EUROPEAN MECHANICS SOCIETY

EUROMECH Colloquium 650
ADDRESSING CHALLENGES IN APPLIED MECHANICS THROUGH ARTIFICIAL INTELLIGENCE APPLICATIONS

Book of Abstracts

Faculty of Mechanical Engineering
University of Belgrade
Belgrade, Serbia
August 27th to 29th, 2025

BOOK OF ABSTRACTS

EUROMECH Colloquium 650

ADDRESSING CHALLENGES IN APPLIED MECHANICS THROUGH ARTIFICIAL INTELLIGENCE APPLICATIONS

Editor:

***Prof. Dr. Nataša Trišović**, University of Belgrade, Faculty of Mechanical Engineering*

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About EUROMECH

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EUROMECH - European Mechanics Society is an international non-governmental non-profit scientific organization.

The European Mechanics Society serves as an organization dedicated to the advancement of science and research within the broad field of mechanics. Recognizing this pursuit as a charitable endeavor, EUROMECH aims to foster a vibrant and collaborative European mechanics community.

To achieve its objectives, EUROMECH undertakes a range of activities designed to stimulate scientific exchange and progress.

These include the organization of European colloquia and conferences covering diverse topics within mechanics, as well as establishing strong connections between researchers and institutions engaged in this and related scientific disciplines.

The society also plays a crucial role in collecting and disseminating relevant information and promoting scientific publications in the field.

Recognizing the importance of future generations, EUROMECH is committed to supporting young scientists and awarding prizes and recognitions to those who make significant contributions.

As a non-profit entity, EUROMECH operates selflessly, focusing solely on the promotion of science for the public benefit.

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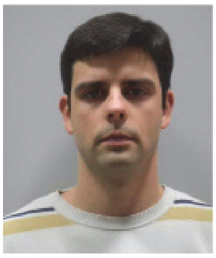

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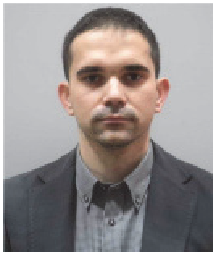

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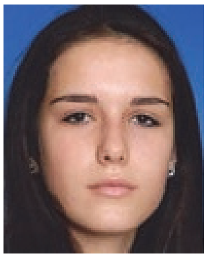

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PREFACE

It is our great honor and pleasure to welcome you to the 650th EUROMECH Colloquium, entitled "Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications", held in Belgrade, Serbia, from August 27 to 29, 2025.

This Colloquium marks a significant milestone, the first-ever EUROMECH event organized in our region and as such, represents a unique opportunity to set the stage for future scientific developments at the intersection of applied mechanics and artificial intelligence. The Colloquium brings together distinguished experts and early-career researchers from over fifteen countries, including Austria, Bosnia and Herzegovina, Bulgaria, Canada, China, the Czech Republic, Germany, Greece, Hungary, Iceland, North Macedonia, Poland, Slovenia, the United Kingdom, the United States and others. This international participation fosters a vibrant and collaborative atmosphere for scientific exchange and innovation.

We are proud to report that the Colloquium features 63 abstracts, including 8 keynote lectures, which far exceed our initial expectations, a clear indication of the growing relevance and appeal of this research field.

Thematically, the Colloquium covers a wide range of disciplines, including general and numerical mechanics, fluid and solid mechanics, biomechanics, robotics, control, and various interdisciplinary and multidisciplinary topics. The contributions address core areas such as AI optimization in mechanical systems, energy harvesting and conversion, AI for material characterization and design, structural health monitoring and damage detection, and AI in vibration analysis and wavelet transform.

The abstracts presented in this book provide an overview of current research efforts, innovative methodologies, and promising applications that demonstrate the transformative potential of artificial intelligence within classical engineering domains. We hope this collection will serve as a valuable resource and source of inspiration for future developments.

All authors who present their work at the Colloquium are invited to submit full-length papers by December 2025. All peer-reviewed and accepted contributions will be published in an edited Springer volume in the first half of 2026, and we are truly grateful to the Springer team for this opportunity.

We extend our sincere gratitude to all keynote speakers, authors, and participants for their valuable contributions. We are especially thankful to the EUROMECH Council for their trust and support, as well as to our co-organizer and host, the Faculty of Mechanical Engineering, University of Belgrade. We also gratefully acknowledge the financial support of the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, as well as our supporters Tim-Invest Ltd., Smart Steel Innovation Ltd., GIR Ltd., Radijator Inženjering Ltd., Aqua Crystal Ltd., and others. Throughout the preparation of the event, we also had the continued support of the Serbian Society of Mechanics, for which we are sincerely thankful.

We look forward to a dynamic and productive exchange of ideas and to new collaborations that will shape the future of AI-driven applied mechanics. I am especially pleased that this Colloquium is organized in close cooperation with my esteemed co-chairpersons, Tamás Mankovits (Hungary), Petar Dimitrov (North Macedonia), Zoltán Major (Austria), and Ana Petrović (Serbia), whose joint efforts contribute to the strong international character of this event.

On behalf of the Organizing Committee,

Nataša Trišović,

Chairperson

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Runar Unnthorsson

Professor at the University of Iceland. His research centers on experimental engineering and product development, with a focus on acoustics, non-destructive testing, energy systems, and battery technology. He has participated in many international projects and was the Principal Investigator of the H2020-funded Sound of Vision, which won the European Union’s Innovation Radar Prize 2018 in the “Tech for Society” category. He has also received recognition for work on aluminium-ion batteries and biomass gasification. Runar has co-founded technology companies and has extensive experience developing practical engineering solutions, from sensory substitution devices to repurposing used EV batteries. With over 24 years of experience applying advanced measurement and AI techniques, his work bridges experimentation and real-world impact, always with the goal of making the world better through sustainable and innovative engineering.

Zdeněk Hadaš

Professor and director of the Institute of Automation and Computer Science at the Faculty of Mechanical Engineering, Brno University of Technology, Czech Republic. He earned his Dipl. Ing. degree in Mechatronics in 2003 and his Ph.D. in Applied Mechanics in 2007. In 2015, he was appointed Associate Professor, and in 2025, he was appointed Associate Professor of Applied Mechanics. His teaching activities include courses in nonlinear dynamics, simulation and modelling, SMART systems and energy harvesting. His main research interests focus on energy harvesting from ambient mechanical vibrations, as well as modelling and simulation of cyber-physical systems. He has led and participated in numerous national and international projects, including FP6, FP7, H2020 and Horizon Europe programs. Professor Hadaš has conducted academic internships abroad, notably at EADS Innovation Works in Munich, Germany. He has authored more than 100 scientific publications, with around 700 citations (excluding self-citations) in Web of Science. He actively promotes knowledge transfer and innovation in engineering education.

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Professor at the Xidian University, China since 2005, research interest covers stochastic dynamics, biological mathematics, and artificial intelligence, with applications in mechanical engineering, materials science. She is leading one National Natural Science Foundation of China (NSFC) and completed two "Belt and Road" Foreign Expert Projects, one NSFC Young Scientists Fund, one Shaanxi Provincial Natural Science Fund, and one China-Serbia Joint Committee on S&T Cooperation Project. She gained the First Prize in Science & Technology from the Chinese Society of Vibration Engineering (2024), the Second Prize from the Shaanxi Society of Vibration Engineering (2018), and the First Prize from Shaanxi Universities (2013). She is Executive Council Members of the Shaanxi Society of Operations Research and Young Statisticians Association under the Chinese Industrial Statistics Society.

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Stanislav Stoykov

Associate Professor at the Institute of Information and Communication Technologies of the Bulgarian Academy of Sciences. He holds a PhD in Mechanical Engineering from the University of Porto, Portugal (2012), an M.Sc. in Applied Mathematics, and a B.Sc. in Computer Science from Sofia University. His research focuses on nonlinear dynamics, bifurcation theory, and finite element methods applied to beams, plates, and shells, as well as 3D structures. He has authored journal and conference papers on the nonlinear vibrations and stability of elastic structures, structural health monitoring, and scalable algorithms for parallel computation of nonlinear responses. His international collaborations include a guest research stay at TU Delft and work with academic institutions across Europe. Dr. Stoykov is also the developer of TOBECS, a tool for beam cross-sectional analysis. His recent work involves applying machine learning techniques to localize damages in beams and plates.

Aleksandar Jeremić

Aleksandar Jeremić received the Dipl. Ing. degree in electrical engineering from the University of Belgrade, Belgrade, Serbia in 1995, Master of Science in Electrical Engineering (MSEE) from The University of Illinois at Chicago in 1997 (advisor: Dr. Arye Nehorai) and Ph.D. in electrical engineering from the University of Illinois at Chicago in 2002 (advisor: Dr. Arye Nehorai). He has authored more than 80 articles in the statistical and biomedical signal processing. His current research interests include small size machine learning techniques for biomedical applications. He was a recipient of the teaching award by McMaster Electrical and Computer Engineering Society in 2018. He supervised/co-supervised 7 Ph.D. students and 18 M.Sc. students at McMaster University and University of Belgrade.

Dávid Huri

Mechanical engineer and simulation expert who is currently serving as an Assistant Professor in the Department of Mechanical Engineering at the University of Debrecen. His research focuses on developing and integrating artificial intelligence-supported optimisation processes into mechanical designs based on structural analysis. His precise approach has motivated him to improve the accuracy of nonlinear simulations of elastomer products, leading him to investigate the calibration process of hyperelastic material models. His work bridges the gap between theoretical modelling and industrial applications, establishing him as a valuable contributor to the academic and engineering communities. In his spare time, he enjoys sports activities that are both physically demanding and intellectually stimulating.

Sandra Klinge

Full Professor and Head of the Chair of Structural Mechanics and Analysis at the Faculty of Transport and Mechanical Systems, TU Berlin. She earned her doctorate and habilitation at Ruhr University Bochum, where she was a DAAD scholarship holder in the international Computational Engineering Master's program. Before joining TU Berlin in 2021, she served as Junior Professor of Computational Engineering at TU Dortmund, where she established her own research group. Her research focuses on numerical methods for simulating heterogeneous materials, particularly multiscale finite element methods for direct and inverse problems, with applications in biomechanics and metal forming. She is involved in the development of advanced methods such as statistical homogenization, isogeometric analysis, and machine learning. Professor Klinge has extensive international collaborations and is the author of a monograph on the application of homogenization theory to mineralized tissue. Her work bridges applied mathematics, engineering, and computational science.

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

AI-driven experimentation: Designing experiments and extracting insights from complex engineering data

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I INTRODUCTION

Experimental mechanics is being reshaped by a wave of new technologies – from advanced sensors to automated data collection systems – resulting in richer, faster, and more complex experiments than ever before. This transformation introduces both new opportunities and new challenges: while the richness of data opens doors to deeper understanding, it also overwhelms traditional methods of experimental design and analysis. The challenge lies not only in the complexity of the data but also in its sheer volume-driven by more sensors, more measurement channels, and increasingly data-intensive techniques such as high-resolution imaging, high-speed video, ultrasonic monitoring, and acoustic emission analysis.

Artificial Intelligence (AI) offers a promising set of tools to assist experimentalists in navigating this complexity – helping to design more effective experiments, extract meaningful insights, and support data-driven decision-making across a wide range of engineering domains. This talk will discuss how AI can be used throughout the experimental process to support the design of experiments and to manage, process, and interpret large and complex datasets.

II GROWING DATA ABUNDANCE IN EXPERIMENTAL MECHANICS

Across many areas of experimental mechanics, the volume, resolution, and frequency of collected data are increasing rapidly. This shift is driven by improvements in sensor technology, multi-channel measurement systems, and the adoption of advanced diagnostic tools. Common areas experiencing this trend include:

- Structural health monitoring and damage detection, where ultrasonic, acoustic emission, and vibration-based methods produce high-frequency, multi-channel data.
- Energy systems and materials testing, where thermal imaging, electrochemical measurements, and high-resolution imaging generate large, multi-scale datasets.

Advanced imaging-based techniques are a major contributor to the growing data abundance in experimental mechanics. For example, high-speed cameras and Digital Image Correlation (DIC) systems are increasingly used in structural and material testing to capture detailed deformation fields and failure processes. These tools enable researchers to study the behaviour of materials, components, and products with great precision, but they also generate large datasets that are difficult to process manually.

While this data richness offers great potential, data alone is not the goal. More is not always better. The true value lies in extracting insight. We want it as quickly and accurately as possible so that it can support better understanding and more informed engineering decisions. Traditional manual workflows are no longer sufficient to handle this scale and complexity, creating a growing need for intelligent, scalable approaches.

III INTEGRATING AI INTO THE EXPERIMENTAL WORKFLOW

Artificial Intelligence offers a range of tools to help researchers and engineers address these challenges. Rather than replacing experimental work, AI is best understood as a way to augment it – enhancing the speed, depth, and quality of insight.AI can support the full experimental workflow:

- Pre-experiment: assisting with test planning, parameter space optimisation, and identifying efficient coverage of experimental conditions.
- During experiments: enabling real-time monitoring, anomaly detection, and adaptive control based on emerging signals.
- Post-experiment: allowing for data cleaning, pattern discovery, high-dimensional clustering, and development of predictive models to guide future testing.

Methods such as supervised learning (e.g. for fault classification), unsupervised clustering (for identifying behavioural patterns), and surrogate modelling (to reduce simulation cost) make it possible to extract value from large experimental datasets. These capabilities can be applied across diverse fields to support innovation and sustainable design.

IV CONCLUSION

AI-enhanced experimentation represents a shift in how engineering data is approached, interpreted, and acted upon. As the complexity and volume of data continue to grow, so does the pressure to extract insight faster and more reliably. Time is critical, experiments are costly, funding is finite, and the competitive pace of research and innovation is accelerating.

By integrating AI into experimental workflows, we can reduce trial-and-error, increase the return on every test run, and move more confidently toward results that matter. Whether the goal is advancing fundamental science or delivering practical solutions, these tools will be essential to staying ahead.

For established researchers, AI offers a way to scale expertise and increase the impact of every experiment. For early-career researchers, it opens exciting new frontiers in how we design, conduct, and learn from physical tests. We are entering a new phase of experimental mechanics – one that is faster, smarter, and more responsive to the challenges of our time.

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The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Perspectives and opportunities for vibration energy harvesting technologies in industrial applications

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I INTRODUCTION

The growing global demand for sustainable technologies increased the focus on developing SMART, Industrial 4.0, and environmental applications with embedded autonomous monitoring and diagnostic units. The operation of modern sustainable systems requires complex monitoring tasks that employ IoT sensing and monitoring units [1]. Developed embedded IoT systems based on modern sensing materials and electronics could be used for long-term sensing to indicate wear, anomalies, or system degradation [2]. Monitoring applications of modern aircraft systems leads to an increase in the opportunity for the development of energy harvesting applications [3].

This contribution is focused on mechanical systems that operate under vibrations and provides a summary of potential physical principles of energy harvesting. The contribution addresses the critical challenges in mechanical energy harvesting technologies and provides an overview of the successful transfer of energy harvesting technology from laboratory specimens to industrial applications.

II KINETIC ENERGY HARVESTING SYSTEMS

Energy harvesting technologies are characterized by converting waste and ambient mechanical vibration into useful electricity. This physical principle is shown in Fig. 1 in the form of a hybrid kinetic energy harvester [4]. Kinetic energy of vibration (green) is transferred into resonance operation, and consequently, this relative movement (red) is converted by electromagnetic (blue) or piezoelectric principle (orange) into electricity.

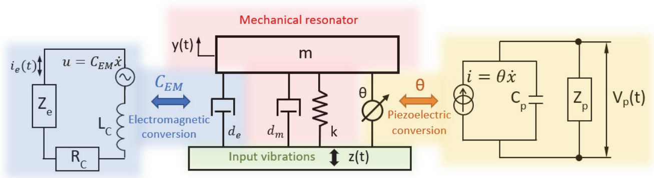

Fig. 1. Hybrid kinetic energy harvesting system; system of mechanical resonator (red), electro-magnetic (blue) and piezoelectric conversion system (orange)

The one degree of freedom mathematical model of mechanical resonator (1) could be used for both piezoelectric and electromagnetic converters, and the consumption of harvested energy is analysed. Both converters could be in different forms and designs, and provide a coupled electro-mechanical system. The model of the piezoelectric composite beam (2) is well understood and described in many papers, such as [5]. The example of a common electromagnetic system (3) is described in publication [6].

III APPLICATIONS OF ENERGY HARVESTING DEVICES

Several thousand journal papers about kinetic energy harvesting systems provide analysis and solutions for energy harvesting devices in a lab environment. However, only a few technical applications with energy harvesting sources provide a fruitful solution for wireless sensor nodes.

Developing energy harvesting technologies provides a novel and autonomous energy source for IoT applications [7] in reporting, monitoring, and diagnostic purposes.Primarilyvibration energy harvesting technology is developed for safe aircraft applications [3]. Significant demands are placed on energy sources for biomedical applications [8].However the promising energy harvesting outputs are reported in operation on a railway infrastructure [9] and environmental sea monitoring [10].

IV ACKNOWLEDGEMENT

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V REFERENCES

[1] H. Elahi, K. Munir, M. Eugeni, S. Atek, P. Gaudenzi, *Energy harvesting towards self-powered IoT devices*, Energies, vol. 13/21, pp. 1–31, 2020.
[2] P. Cawley, *Structural health monitoring: Closing the gap between research and industrial deployment*, Structural Health Monitoring, vol. 17/5, pp. 1225–1244, 2018.
[3] P. Sundriyal, S. Bhattacharya, *Energy harvesting techniques for powering wireless sensor networks in aircraft applications: A review*, in Proc., pp. 55–76, 2019.
[4] H. Ryu, H.J. Yoon, S.W. Kim, *Hybrid energy harvesters: Toward sustainable energy harvesting*, Advanced Materials, vol. 31, 1802898, 2019.
[5] Q.M. Wang, L.E. Gross, *Constitutive equations of symmetrical triple layer piezoelectric benders*, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 46, pp. 1343–1351, 1999.
[6] Z. Hadas, L. Janak, J. Smilek, *Virtual prototypes of energy harvesting systems for industrial applications*, Mechanical Systems and Signal Processing, vol. 110, pp. 152–164, 2018.
[7] O. Rubes, J. Chalupa, F. Ksica, Z. Hadas, *Development and experimental validation of self-powered wireless vibration sensor node using vibration energy harvester*, Mechanical Systems and Signal Processing, vol. 160, 2021.
[8] S. Panda et al., *Piezoelectric energy harvesting systems for biomedical applications*, Nano Energy, vol. 100, 107514, 2022.
[9] Z. Hadas, O. Rubes, F. Ksica, J. Chalupa, *Kinetic electromagnetic energy harvester for railway applications – Development and test with wireless sensor*, Sensors, vol. 22/3, 905, 2022.
[10] M. Carandell et al., *Electromagnetic rolling mass wave energy harvester for oceanic drifter applications*, The European Physical Journal Special Topics, vol. 231/8, pp. 1475–1484, 2022.

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An intelligent algorithm to study the response of stochastic dynamical system

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I INTRODUCTION

Random vibration is a common phenomenon that appears in the field of structural engineering systems, especially when a system is excited by a random loading [1–3]. Correspondingly, the response of such stochastic dynamical systems under random excitation is always a hot issue in understanding the structure performance. Generally, the transient or stationary probability density function satisfied by the system response is used to measure the instantaneous and cumulative impact of random excitation on the systems, which is governed by a FPK equation. Therefore, how to solve the FPK equation is a key problem in analyzing the response of stochastic dynamical systems.

II ABSTRACT PREPARATION GUIDELINES

In this paper, an intelligent algorithm is proposed and applied to solve the stochastic dynamical systems under random excitation. Our attention is focused on the transient solution of the systems under Non-Gaussian excitation. Firstly, we built a neural network by using Logistic probability functions as the basis functions (LBFNN), in which the weighted coefficients are unknown and to be determined. After that, we construct the loss function to be comprised by the constraint from FPK equation and the normalization condition from the weighted parameters. The innovation of our algorithm is that unknown weighted parameters can be obtained by solving a set of algebraic iteration formulas instead of testify by sample data. All results show that this algorithm is not only capable to get transient solutions of the systems under Gaussian white-noise, but also enable us to get the transient solutions in the case of Non-Gaussian excitation.

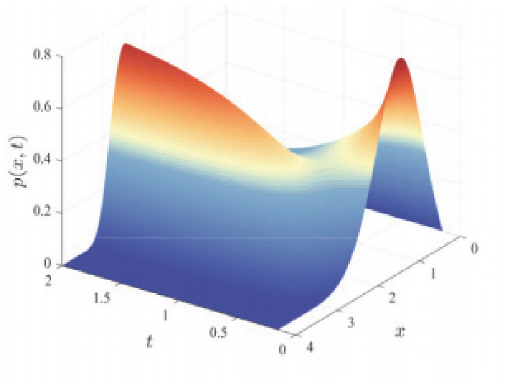

Fig. 1.Transient probability density function of system (1) obtained by LBFNN algorithm under Gaussian excitation

As an example, Consider a first-order stochastic dynamical system

$$\dot{x} = -\rho x + \tau x^3 - \omega x^5 + \frac{k}{x} + W(t) \quad (1)$$

Where ρ, τ, ω, k are positive parameters, $W(t)$ is a Gaussian white-noise excitation with zero mean-value and constant noise intensity. Fig. 1 shows the transient probability density of the system (1) at different times.

Consider a stochastic dynamical system under stationary Non-Gaussian excitation

$$\dot{x} = c_1 x - c_3 x^3 + \sigma U(t) \quad (2)$$

where c_1,c_3,σ are constant, $U(t)$ is a stationary Non-Gaussian random process. Fig. 2. displays the transient joint probability responses of the system (2) under stationary Non-Gaussian excitation.

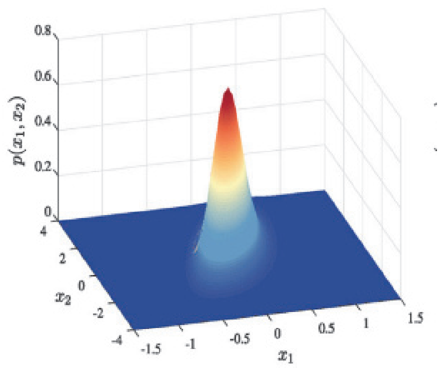

Fig. 2.The transient joint probability responses of the system (2) under stationary Non-Gaussian excitation

III CONCLUSION

The results show that the LBFNN algorithm can obtain the probability density function at any time for both Gaussian or Non-Gaussian excitation.

IV ACKNOWLEDGEMENT

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V REFERENCES

[1] M. Ptak, J. Czmochowski, *Using computer techniques for vibration damage estimation under stochastic loading using the Monte Carlo method for aerospace applications*. Probab Eng Mech, 103452, 2023.
[2] P. Wang, G. Chen, *Invariant behavior of stochastic atmosphere-ocean model with degenerate noise*. J Math Phys, vol. 60/6, 062701, 2019.
[3] A. Cunha, G. Litak, P. Wolszczak, *Effect of stochastic excitation on sub-harmonic solutions in a bistable energy harvester*. AIP Conf Proc 2425/1, 410003, 2022.

EUROPEAN MECHANICS SOCIETY

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

On the use of machine learning for vibration control purposes in metastructures: benefits and challenges

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I INTRODUCTION

The concept of employing distributed tuned oscillatory attachments in the metamaterials and metastructures (MSs) began to evolve at the beginning of the new millennium [1]. However, a widely accepted framework for the specific tuning of these oscillators has not been established yet. Several factors contribute to this shortcoming. Firstly, there exists a broad spectrum of mechanical models for MSs, and a comprehensive framework that integrates all these models is challenging to define. Secondly, MSs are frequently depicted as chains composed of multiple mass-in-mass units with complex forms of the corresponding governing equations. As their analytical treatments are cumbersome, researchers have resorted to utilising numerical methods. The application of data science and machine learning (ML) has open new horizons in this respect. To highlight the beneficial use of ML methodologies for MSs, this work first provides an overview of the state-of-the art regarding their mechanical models and practical realizations, focusing on the type of oscillatory attachments and the resulting responses. Then, the summary of some author's contributions to the field of the design of oscillatory attachments in MSs, achieved with co-workers [2-4] is presented related to their design, specifically targeting objectives beneficial for vibration control.

II ON THE ORIGINAL AND RESEDIGNED METASTRUCTURES

The focus is on a base excited MS that incorporates periodically arranged external units, each containing internal oscillatory attachments. The initial design of these attachments in the MS, labelled here as MS0 (Fig. 1a), aimed to reduce vibrations around the first structural resonance was characterized by uniformity of the form and arrangement of oscillatory attachments [2]. To achieve efficient vibration control around the second or higher resonance, an analytical approach is developed first [3]. Since the values of some parameters were practically unattainable, a procedure involving ML methodology was developed [4]. The initial phase for the latter comprised the creation of a distinct numerical dataset comprising frequency-displacement amplitude diagrams within COMSOL simulation software. Secondly, two specific ML techniques (Support Vector Regression and Artificial Neural Networks) were utilized. Their efficacy and accuracy were assessed, and the surpassing one was detected. In the third phase, the optimization process was undertaken with two optimality criteria. The first one pertained to the region of vibration attenuation, which was defined as the frequency region within which the displacement amplitude of the newly designed MS is lower than that of the original one, surrounding the second modal frequency. This yielded the redesigned MS1 (Fig. 1b), featuring an innovative configuration of three types of oscillatory attachments, whose unique forms and arrangement are neither simple nor intuitively predictable. The second optimality criterion was related to the total width of the frequency ranges that demonstrate vibration reduction around both the first and second frequencies. The redesigned MS2 (Fig. 1c) was obtained to feature uniformly distributed oscillatory attachments of the same shape as those in MS0 but characterised by different dimensions. Both the original and the redesigned MSs were produced using 3D printing technology, as seen in Figure 1a)-c), and subsequently experimentally investigated to validate the benefits of the redesigns obtained by the ML technique for the sake of vibration control.

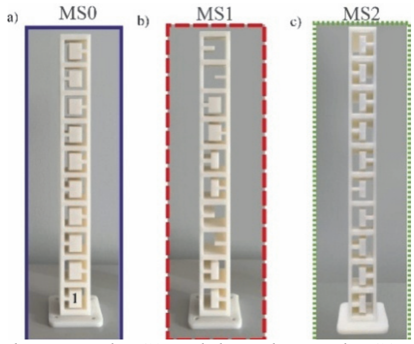

Fig. 1. The original MS0 and the redesigned MS1 and MS2

III CONCLUSION

In addition to outlining a newly developed methodology for implementing ML techniques aimed at reaching a novel design of MSs with oscillatory attachments for the sake of effective vibration control, this study also illustrates their beneficial effects regarding originality and flexibility. Furthermore, this study also highlights specific challenges posed by system dynamics, relevant not only to this particular research but also to the broader field of vibration control.

IV ACKNOWLEDGEMENT

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V REFERENCES

[1] J.C. Ji, Q.T. Luo, K. Ye, *Vibration control based metamaterials and origami structures: a state-of-the-art review*, Mechanical Systems and Signal Processing, vol.161, 107945, 2021.
[2] I. Kovačić, Z. Rakarić, Z. Kanović, V. Rajs, *Metastructure with integrated oscillators of constant, linearly and nonlinearly varying natural frequency*, Frontiers in Physics, vol. 10, 934998, 2022.
[3] I. Kovačić, Lj. Teofanov, Z. Kanović, J. Zhao, R. Zhu, V. Rajs, *On the influence of internal oscillators on the performance of metastructures: Modelling and tuning conditions*, Mechanical Systems and Signal Processing, vol. 205, 110861, 2023.
[4] I. Kovačić, Z. Kanović, V. Rajs, Lj. Teofanov, R. Zhu, *Reaching a desirable metastructures for passive vibration attenuation by using a machine learning approach*, Nonlinear Dynamics, vol. 112, pp. 20661-20676, 2024.

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Application of neural networks to damage detection of beams and plates

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I INTRODUCTION

Beams and plates are thin structures widely used for numerous engineering applications. They often undergo large deformations and severe weather conditions that cause structural damage. The early detection of damages, their localization, and the estimation of their severity are critical for their operation and maintenance. Apart from traditional vibration-based methods, machine learning methods [1] have proven to be more precise, particularly when one deals with noisy data. The current study presents a supervised machine learning strategy for damage localization and severity estimation of the damage that is inspired by vibration-based techniques [2].

II GENERATION OF TRAINIGN DATA

A major part of the process is the generation of appropriate data, which is used to train the neural network. In the current work, the input of the neural network represents the deformed shape of the structure taken at some instant of time from its forced time response. The deformed shape is represented as a vector that consists of the transverse displacements of the deformed shape measured at several locations.

The data is generated numerically by simulating time responses of damaged beams and plates. The equations of motion of these structures are derived by considering Timoshenko's theory for beams and Mindlin's hypothesis for the plate equation of motion. Geometrical nonlinearity is included in both models. Space discretization is performed by the finite element method, and simulations in the time domain are generated by Newmark's time integration scheme. The damage to the structure is modeled by reducing the thickness of one or more finite elements.

Simulations of damages with different severities located along the entire surface of the elastic structure due to external forces with various excitation frequencies are generated. Transverse displacements of the structure are estimated at multiple locations along the surface of the structure and stored at multiple instants of time. This dataset is used to train the neural network [3].

III DAMAGE DETECTION OF NOISY TIME RESPONSES

Noise is unavoidable in real applications, and estimation of the capabilities of the neural network for damage detection of time response vibrations in the presence of noise is essential for their further development.

The deformed shapes from the time responses of the damaged structure are shocked by random noise, which is generated from a normal distribution. Noise with different magnitudes is considered. As expected, the accuracy of the neural network tends to decrease with the increasing magnitude of the noise. Nevertheless, it is shown that with sufficiently large training data, the neural network maintains high accuracy levels for time responses with additional random noise.

IV OPTIMAL LOCATION OF SENSORS

In numerical experiments, one may measure time responses at as many locations as necessary; in real applications, this number is limited. It is essential to obtain a reliable damage detection algorithm with a low number of sensors. The last part of the research deals with a reduction analysis of the number of locations where transverse displacements are measured and stored for further training the neural network. Furthermore, different strategies for the distribution of the sensors, which include non-symmetric locations along the surface of the structure, are investigated.

V CONCLUSION

The capability of neural networks to localize damages and estimate their severity on plates and beams is investigated by generating training data and predicting damages at unknown locations. The neural network achieved high accuracy in localizing damages that were either smaller than or different from those in the training data, i.e., the neural network accurately predicts both known and new damages.

Additionally, the neural network maintained its accuracy even when noise was introduced into the deformed shapes of the damaged structure.

In the absence of noisy data, the neural network demonstrated high accuracy not only in locating the damage but also in determining its severity. Although the estimation of damage severity tends to show higher severities for the cases with introduced noise, the accuracy of locating the damage remained high, highlighting the applicability of neural networks for structural health monitoring in real-world scenarios.

VI ACKNOWLEDGEMENT

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VII REFERENCES

[1] C.R. Farrar, K. Worden, *Structural Health Monitoring: A Machine Learning Perspective*, John Wiley & Sons Ltd, 2013.
[2] S. Stoykov, E. Manoach, *Damage localization of beams based on measured forced responses*, Mechanical Systems and Signal Processing, vol. 151, 107379, 2021.
[3] S. Stoykov, E. Manoach, *Vibration Based Damage Detection of Beams by Supervised Learning Approach*, Recent Trends in Wave Mechanics and Vibrations. Mechanisms and Machine Science, Springer, vol. 125, pp. 827–833, 2023.

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Physics informed neural network for estimation of physiological models

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I INTRODUCTION

One of the most important tasks in biomedical signal processing is related to assisting clinical decision making by health care providers. To achieve this goal, we often utilize inverse models in which a vast amount of information that is available from physiological measurements (electroencephalography, electrocardiography, ultrasound, magnetic resonance imaging, etc.) is reduced to much smaller, but still meaningful, set of parameters.

Depending on the phenomenon of interests the size of data may vary significantly thus affecting what kind of machine learning / artificial neural network techniques are applicable. In the case of limited amount of data (e.g. large patient-to-patient variability) we often need to utilize physics based models in order to compensate for the lack of big data sets.

To this purpose we demonstrate applicability of the proposed technique on two clinical applications in which physics based models are utilized to estimate unknown physiological parameters. First, we demonstrate applicability of physics informed neural network for estimation of the electrical activity of the neonatal cortex using neural networks and finite-element-model of infant skull. Then we demonstrate the applicability of the proposed approach to estimating electromechanical properties of the heart using electrocardiography and tagged magnetic resonance imaging technique.

We evaluate the performance of the proposed techniques for various scenarios for both simulated and real data measurements.\

II FORWARD MODEL

The electro-mechanical activity in human body is modelled adequately using a set of partial differential equations (PDEs) with a particular set of boundary conditions defined by various physical constraints (e.g. intraventricular pressure is used to model boundary stress in elasto-dynamic equations). In addition, depending on the resolution level (micro-, meso- or macroscopic) various electro-mechanic and mechano-electric feedback mechanism may need to be included.

Furthermore, the actual complexity of realistically shaped geometries of organs requires that forward models are obtained by finite-element solvers (e.g. COMSOL ANSYS, etc.)

III INVERSE MODELS FOR CORTICAL ACTIVITY

Using our previously proposed cortical activity model, we model the cortical activity using 256 dipoles placed on the cortical surface. Due to the fact that the geometry is inherently irregular the solution of these equations can only be obtained by using a numerical method such as finite-element method.

We use realistic geometry of the 9 months old infant obtained at The University Children Hospital, University of Belgrade, Serbia. MRI images consisted of 110 axial MR slices with 256x256 size and field of view of 240 mm.

The segmentation and meshing was done using software packages Slicer and Meshlabs that were then imported as STL files in COMSOL finite-element solver.

IV INVERSE MODELS FOR ELECTROMECHNICAL ACTIVITY OF THE HEART

We model the electro-mechanical activity of the heart using elasto-dynamic equations in which the elasticity modules are defined using electro-mechanical feedback model that assumes functional dependence between the stiffness of the heart muscle and Ca+2 ionic currents. The corresponding model accounts for intraventricular pressure by incorporating it as a boundary condition.

The inverse model is defined using tagged magnetic resonance images that enable calculation of the corresponding strain (deformation) and intraventricular pressure (stress). The solution of these inverse models is computationally intensive due to a mesh size and physics informed neural networks (PINN) provide potentially fast solution with a desired level of accuracy.

V REFERENCES

[1] Y.C. Fung, *Biomechanics*. Springer-Verlag, New York, 1987.
[2] J.M. Guccione et al., *Passive material properties of intact ventricular myocardium determined from a cylindrical model*, J. Biomech. Eng., vol. 113, pp. 42–55, 1991.
[3] S. Asadzadeh, T.Y. Rezaii, S. Beheshti, A. Delpak, S. Meshgini, *A systematic review of eeg source localization techniques and their applications on diagnosis of brain abnormalities*. In J Neurosci Methods. ELSEVIER, 2020.
[4] L. Cornette, S. Tanner, L. Miall, A. Childs, R. Arthur, *Magnetic resonance imaging of the infant brain: anatomical characteristics and clinical significance of punctate lesions*. In Arch Dis Child Fetal Neonatal. ELSEVIER, 2002.

Artificial intelligence-supported shape optimization of an automotive rubber bumper

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I INTRODUCTION

In rubber bumper design, the most important mechanical property of the product is the force-displacement curve under compression and its fulfillment requires an iterative design method. Design engineers can handle this task with the modification of the product shape, while the axisymmetric finite element model of the rubber product is an efficient way to evaluate the working characteristics. Using an optimization process in place of a trial-and-error-based mechanical engineering design method can help a company stay competitive in the market if the iteration process can be automated.

II METHODS

This research examines the sequence of steps in the engineering simulation-based design optimisation process at which automation can be increased using artificial intelligence (AI) tools. Fig. 1 identifies two areas of integration. One possibility is to replace time-consuming simulations with machine learning methods, such as neural networks or support vector regression. Additionally, a task-independent process can be achieved using metaheuristic optimisation algorithms, such as simulated annealing, particle swarm optimisation or genetic algorithms, to approach the global optimum. Further development of deep learning algorithms could enable a method to trigger the entire process without human interaction.

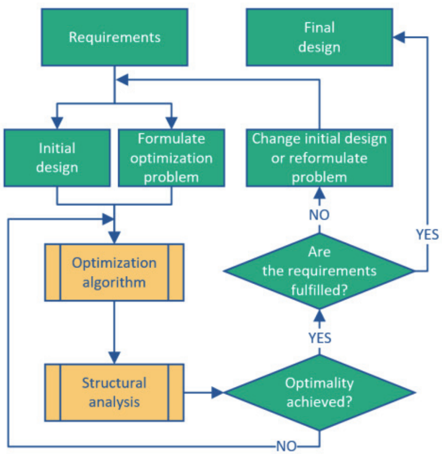

Fig. 2. Design optimization process and the identified sequence of steps for the integration of artificial intelligence methods

The integrability of AI methods was investigated through a two-variable shape optimization problem of a rubber bumper. Given that the geometry, boundary conditions and material behavior can be considered axisymmetric, it is possible to simplify the problem and perform the discretisation with axisymmetric elements. Thus, the calculation of the simulation-based objective function takes less than a minute using any commercial finite element software. The objective function is calculated as the difference between the initial and optimal spring characteristics shown in Fig. 2.

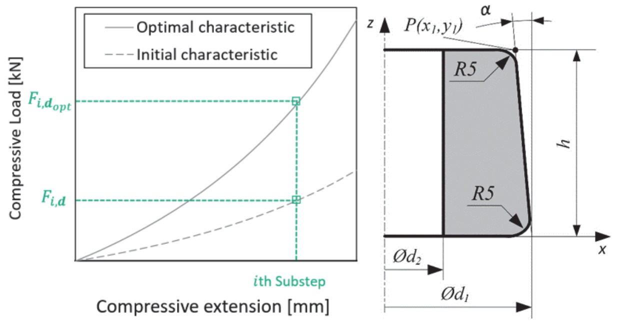

Fig. 1. The working characteristics and section of the rubber bumper

During optimization, the aim is to minimisethe objective function by varying the outer and bore diameters of the rubber bumper

$$E(\boldsymbol{d}_{opt})_{FEA} = \min_{\boldsymbol{d}\in\Omega} E(\boldsymbol{d})_{FEA}, \qquad (1)$$

where the objective function is given by the sum of squared differences

$$E(\boldsymbol{d})_{FEA} = \sum_{i=10}^{100}\left(F_{i,\boldsymbol{d}_{opt}} - F_{i,\boldsymbol{d}}\right)^2, i \in \{10:10:100\}. \qquad (2)$$

Regardless of how the objective function behaves, metaheuristic search techniques can be used to approach the optimal solution; however, task-specific hyperparameter selection is required. The computational cost of the simulation-based objective function evaluation makes it impossible to solve the tuning process in time. The solution devised was to implement a procedure that utilised a support vector regression surrogate model. This procedure was employed for testing and task-specific tuning of the hyperparameters of the simulated annealing algorithm [1]. The novel method has been demonstrated to be capable of solving the optimisation task of the rubber bumper with high accuracy, in a planned timeframe and with high automation.

III CONCLUSIONS

The utilisation of artificial intelligence tools has the potential to enhance automation and reduce the time required for engineering optimisation tasks. The developed procedure has the potential to reduce uncertainty and increase the efficiency of the design cycle, thereby accelerating innovation.

IV ACKNOWLEDGEMENT

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V REFERENCES

[1] D. Huri, T. Mankovits, *Surrogate Model-Based Parameter Tuning of Simulated Annealing Algorithm for the Shape Optimization of Automotive Rubber Bumpers*, Applied Science, 2022.

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New trends for ML-based solution of solid mechanics tasks

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I INTRODUCTION

Machine Learning (ML) and Neural Networks (NN) have proven to be highly versatile and applicable to a broad variety of engineering problems in solid mechanics [1,2]. The present talk gives an overview of recent trends in this field and shows some application examples.

II EXAMPLE I: CANN-DEM FRAMEWORK

A generic NN-approach consisting of the Deep Energy Method (DEM) and Constitutive Artificial Neural Networks (CANN) has been investigated for elastostatic simulations as an alternative to the traditional Finite Element Method (FEM). No explicit material model is required since the CANN replaces analytical expressions describing the material behavior. The approach is trained based on a small number of deformation states and corresponding boundary conditions and can be used in further simulations on a structural level thereafter. The tests presented have applied a two-, a four- and a twelve-parameter CANN for an incompressible and a compressible Neo-Hookean material. The DEM has been conducted with one, four and six deformation states, respectively on 100 sample points as well as for a three-dimensional T-shaped structure.

The achieved results show that the coupled CANN-DEM architecture works robustly and efficiently. This also applies to the process of automatic material identification. The resulting CANN models generalize well for loading conditions which are not part of the training data. Different than observed in some other approaches, consistently good agreements between the trained CANNs and original material models indicate that there is no influence of the CANN initialization on the final results.

III EXAMPLE II: oPINN

A new ML architecture, namely the oscillatory Physics-Informed Neural Network (oPINN) has been introduced for the numerical investigation of oscillating continua. The approach carries out a modal analysis of a structure alongside with the transient analysis.

The numerical validation has been carried out on three different test cases of the wave equation with comparison to analytical approximations of the solution as well as to a numerical reference solution based on the conventional Adams predictor-corrector time stepping scheme. The results show that the reference solution and the oPINN can capture the characteristic behavior of continua subjected to free oscillations as well as to harmonic excitation with good agreement and accuracy. In numerically more challenging cases like a saw tooth displacement, the oPINN demonstrates its higher numerical accuracy emphasized by the consistent conservation of energy. This can be attributed to the iterative solution procedure for all time steps in parallel which enables the use of symmetric difference stencils in time, whereas conventional multi-step algorithm only can apply one-sided difference stencils and are bound by the Dahlquist barriers. For the further optimization of accuracy, an additional contribution to the loss term stipulating the conservation of energy has been suggested and demonstrated to be effective. The relative error of the amplitudes for the sawtooth test case amounts to 7.3%, whereas the relative error stays below 5% for the numerically less challenging test cases.

Moreover, the potential of transfer learning has been investigated. This step results in better accuracy and allows to speed up the calculations for a series of related tasks exploiting the similarity between neighbouring solutions and makes use of the adaptive nature of NN training. The results furthermore show its efficacy in calculating solutions for comparatively stiff problems. The suggested architecture of the NN is designed to obtain the modal properties (eigenfrequencies, eigenshapes, amplitudes) of the structure as well as the transient simulation result.

IV EXAMPLE III: STATISTICAL HOMOGENIZATION

The final example deals with the statistical homogenization methods evaluating the effective response of heterogeneous materials to different cases of loading. A key challenge in applying these methods is the choice of a suitable probability function that accurately captures the material's spatial correlations [5]. To address this open issue, we propose a machine learning based approach to identify a correct two-point correlational descriptor. A combination of neural networks is used to extract the probability functions from the microstructure image focusing purely on the geometry of the given structure. By coupling fully connected neural networks (FCNN) and a convolutional neural network (CNN), both trained simultaneously, our adaptable approach significantly reduces the data requirements, allowing for effective training with a comparably small data set.

V REFERENCES

[1] S. Hildebrand, S. Klinge, *Comparison of neural FEM and neural operator methods for applications in solid mechanics*, Neural Comput. & Applic, vol. 11, pp. 16657–16682, 2024.
[2] S. Hildebrand, S. Klinge, *Hybrid data-driven and physics-informed regularized learning of cyclic plasticity with neural networks*, Mach. Learn.: Sci. Technol., vol. 5, 045058, 2024.
[3] S. Hildebrand, J.G. Friedrich, M. Mohammadkhah, S. Klinge, *Coupled CANN-DEM simulation in solid mechanics*, Mach. Learn.: Sci. Technol., vol. 6, 015038, 2025.
[4] S. Hildebrand, J. Sachsendal, S. Klinge, *Simulating vibrations of continua with oscillatory Physics-Informed Neural Networks (oPINN)*, (submitted).
[5] L. Schmollack, S.Klinge, *A hybrid CNN-FCNN surrogate model for spatial correlations in two-phase composite materials*, (submitted).

CONTRIBUTED TALKS

Deep symbolic regression: challenges and potential in application to constitutive modeling of soft materials

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I INTRODUCTION

Symbolic regression represents a powerful tool of machine learning which allows an unbiased automatized generation of constitutive models for various materials. It is based on an evolutionary procedure and starts with a population set of random mathematical expressions constructed from a user-defined list of allowed basic operators, algebraic functions, predefined independent variables and numerical constants. In comparison to other data-driven methods symbolic regression reproduces a mathematical expression of a strain energy, damage or other constitutive function which can be analyzed, interpreted und easily implemented for example into a finite element code.

II CONSTITUTIVE MODELING OF SOFT MATERIALS BY DEEP SYMBOLIC REGRESSION

Soft materials can be subject to large deformations, demonstrate inelastic and often anisotropic response, which makes their constitutive modeling very challenging. For a long time, it was mostly driven by expert knowledge whereas attention was focused in particular to elastomers, biological tissues and fabrics.

In this contribution, we present some applications demonstrating how effective symbolic regression can be, for example, in modeling elastic and inelastic response of elastomers [1,2]. To this end, a strain energy function of a filled elastomer is formulated in terms of the principal strain invariants and alternatively in terms of the principal stretches. In both cases, the so created hyperelastic model demonstrates very good agreement with experimental data from multiaxial tension tests. The strain energy function in terms of the principal invariants includes as a basis the well-known Mooney-Rivlin model enhanced by some correction terms which play an important role at large deformations. Thus, the proposed procedure also grants new insights into many established and well-known material models.

In the next step, deep symbolic regression is applied to create a damage function describing the Mullins effect in elastomers. The resulting softening model for elastomers shows good agreement with data both artificially created by established material models (see for example reference [3]) and resulting from cyclic tension tests with stepwise increasing amplitude.

III CALCULATION OF TENSOR FUNCTIONS

Another interesting application of deep symbolic regression is the calculation of isotropic tensor functions. Such functions as for example exponential or logarithmic one play an important role in continuum mechanics. For diagonalizable tensors such functions can be computed on the basis of their eigenvalues. However, the calculation of the eigenvalues can be challenging from the numerical point of view especially when they are very close to each other. By means of symbolic regression these tensor functions can be calculated approximately in terms of the principal invariants in very good agreement with the corresponding analytical solutions.

IV CONCLUSIONS

The results presented in this contribution confirm the large potential of deep symbolic regression for various applications in continuum mechanics and especially in constitutive modeling of soft materials. Finally, we also discuss challenges typical for machine learning in general and deep symbolic regression in particular. These are for example overfitting or dealing with sparse or noisy data.

V REFERENCES

[1] R. Abdusalamov, M. Hillgärtner, M. Itskov, *Automatic generation of interpretable hyperelastic material models by symbolic regression*, International Journal for Numerical Methods in Engineering, vol. 124/9, pp. 2093-2104, 2023.
[2] R. Abdusalamov, J. Weise, M. Itskov, *Rediscovering the Mullins effect with deep symbolic regression*, International Journal of Plasticity, vol. 179, 104037, 2024.
[3] R.W. Ogden, D.G. Roxburgh, *A pseudo–elastic model for the Mullins effect in filled rubber*, Proceedings of the Royal Society of London A, vol. 455/1988, pp. 2861–2877, 1999.

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Importance of the loss function for training model-driven neural networks in thermographic image reconstruction

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I INTRODUCTION

Thermographic reconstruction (TR) is a non-destructive evaluation technique that involves applying an initial thermal excitation to the object under investigation. By using infrared cameras to measure the resulting surface temperature changes, the internal structure (IS) of the material can be reconstructed [1]. This process involves solving a large-scale ill-posed linear inverse problem, which requires regularization and the accurate modeling of the thermal diffusion process.

A prominent method for TR is the virtual wave (VW) concept [1], which solves the underlying inverse problem by first converting the surface temperature data to pressure signals, called VWs, which are then used for structural reconstruction with ultrasonic methods. Both steps of this approach involve large-scale ill-posed inverse problems, which we solved with a combination of FISTA-Net and U-Net neural networks (NN) in [2]. This model-driven NN approach inherits the advantages in performance of deep learning and the interpretability of traditional mathematical modeling.

II CONTRIBUTIONS

Due to the parabolic shape of VWs [1], they are inherently tubular by structure, which is an a-priori property that has not been leveraged in previous works on VW reconstruction [2]. As shown in the ground truth example from Figure 1., VWs produced by artifacts at different depths preserve their tubular structure despite the thermal interferences between them. However, the low signal-to-noise ratio (SNR) in real-world measurements significantly impedes the ability of FISTA-Net to separately reconstruct such VWs.

To assure a better differentiation of VWs, we propose to fine-tune FISTA-Net using clDice, a loss metric with proven topology-preserving qualities [3]. Specifically, we re-train the last 10 epochs of the model with the loss function $\mathcal{L}_{total} = \mathcal{L} + \lambda\mathcal{L}_{clDice}$, where $\mathcal{L}$ is the compound training loss used in [2] for training, $\mathcal{L}_{clDice} = \mathrm{clDice}\big(\mathrm{absmax}(\boldsymbol{Y}_p),\ \mathrm{absmax}(\boldsymbol{Y}_{gt})\big)$ is an adapted loss with the soft clDice function from [3] and an additional absolute-maximum normalization of the predicted VWs $\boldsymbol{Y}_p$ and the ground truths $\boldsymbol{Y}_{gt}$, and λ is a weight parameter.

To assess the performance of the proposed approach, we perform an in-depth analysis of both reconstruction steps using the U-Net trained in [2]. We compare the original approach, i.e. setting $\lambda = 0$, with the proposed fine-tuning method. Additionally, we analyze the effects of changing the clDice weight parameter λ. Our experiments demonstrate an increased ability of the fine-tuned model to separately reconstruct VWs, which leads to improvements in the following step as well. A specific example is shown in Fig. 1, where the parameter $\lambda = 300$ was chosen empirically. The re-training process leads to a more differentiated VW reconstruction by FISTA-Net in this test sample, as well as more pronounced defects and less artifacts in the ISs from the subsequent step.

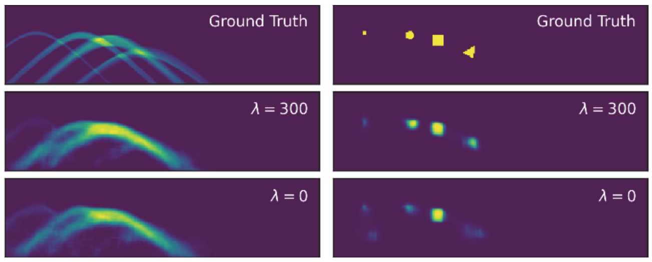

Fig. 1. Test sample reconstruction at 10 dB SNR of VWs (left) and ISs (right) with ($\lambda = 300$) and without clDice ($\lambda = 0$).

III ACKNOWLEDGMENTS

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IV REFERENCES

[1] P. Burgholzer, M. Thor, J. Gruber, G. Mayr, *Three-dimensional thermographic imaging using a virtual wave concept.* Journal of Applied Physics, vol. 121/10, 105102, 2017.

[2] G. Galiger, N. Azadi, B. Lehner, M. Huemer, P. Kovács, *Model-based neural networks for thermographic image reconstruction*, In 2024 IEEE 3rd Conference on Information Technology and Data Science, pp. 1-6, 2024.

[3] S. Suprosanna, J.C. Paetzold, A. Sekuboyina, I. Ezhov, A. Unger, A. Zhylka, J.P.W. Pluim, U. Bauer, B.H. Menze, *clDice-a novel topology-preserving loss function for tubular structure segmentation*, In IEEE/CVF conf. on computer vision and pattern recognition, pp. 16560-16569, 2021.

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through
Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Generative adversarial networks for inverse design of self-deploying structures

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I INTRODUCTION

Morphing structures capable of transforming from a compact configuration to a deployed form are crucial in various fields, such as soft robotics, biomimetic systems and aerospace. A key challenge is the inverse design of these structures, where the target shapes are known, but the design parameters are not. We present a data-driven approach using generative adversarial networks (GANs) to address this challenge.

II METHODOLOGY

Our approach employs a GAN-based model (Fig. 1) to generate design parameters. The generator network takes target shape as inputs and produces the corresponding design parameters, such as geometric configurations and material properties. A critic network evaluates the feasibility of the generated parameters, while the pre-trained simulator ensures the shape accuracy.

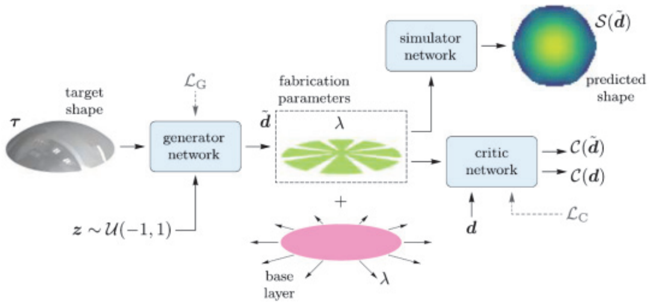

Fig. 1. GAN-based inverse design framework

III RESULTS

The proposed GAN-based method effectively generates design parameters for morphing structures, demonstrating its capability to handle complex inverse design problems. In one application, the method was used to design kirigami composites that self-deploy into target 3D shapes (Fig. 2). This involved generating kirigami patterns and pre-stretch values to achieve complex 3D forms from simple planar designs.

In another instance, we designed soft actuator beams that

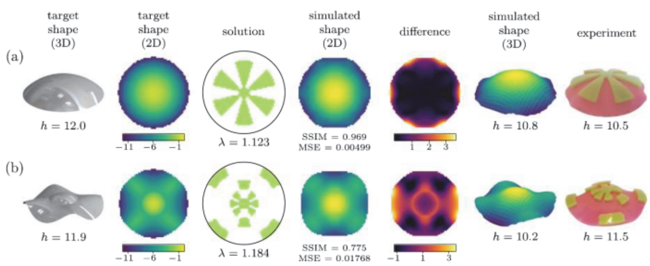

Fig. 2. Results of the inverse design of composite plates

morph into complex shapes and demonstrate target motion. This was achieved by utilizing composites with passive and active layers that morph due to the strain mismatch, resulting from temperature difference. We have established a mechanical analog to heating/cooling by stretching individual active layers. Therefore, we were able to experimentally verify the method by designing target shapes, generating design parameters and comparing fabricated specimens with the target shapes (Fig. 3).

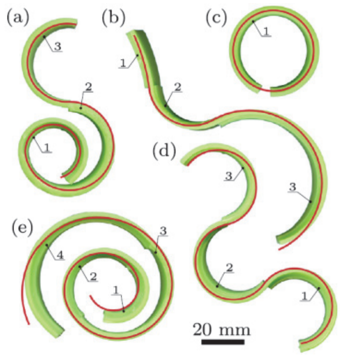

Fig.3. Results of the inverse design of composite beams

IV CONCLUSION

We presented a GAN-based inverse design method for self-deploying structures. The method can generate complex designs for deployable structures and soft robotic actuators. The data-driven approach enables efficient exploration of the design space, offering a promising avenue for the development of advanced morphing structures.

V ACKNOWLEDGMENT

The research results were supported by the Slovenian Research Agency under Grants J2-2499 and J2-4449, as well as by the European Union (NextGenerationEU) under the framework of the GREENTECH project.

VI REFERENCES

[1] T. Brzin, M. Brojan, *Using a generative adversarial network for the inverse design of soft morphing composite beams*, Engineering Application of Artificial Intelligence, vol. 133, 108527, 2024.
[2] T. Brzin, M.K. Jawed, M. Brojan, *Generative adversarial network-based inverse design of self-deploying soft kirigami composites for targeted shape transformation*, Engineering Applications of Artificial Intelligence, vol. 149, 110417, 2025.

Theoretical analysis of galloping energy harvesters

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I INTRODUCTION

With the rapid development of ultra-low power wireless sensors and sensor networks in the framework of Internet of Things, supplying power to these particular devices is quite a challenge when they are installed in the harsh and/or barely accessible environments. This issue has promoted the development of various energy harvesting technologies to resolve the costly and tedious battery replacement problem and provide the sustained power for these wireless devices. Especially, galloping energy harvesting has become a superior choice for solving this issue due to the fact that mechanical vibration energy can be found everywhere[1-2]. This work main discussed the stochastic analysis of galloping energy harvesters.

II MODELLING AND RESULTS

The distributed parameter model of the galloping energy harvester is shown as follows:

$$\ddot{X}(\tau)+(2\xi\omega_1-\alpha_1 v)\dot{X}(\tau)+\omega_1^2 X(\tau) -\gamma Z(\tau)-\frac{\alpha_2}{v}\dot{X}^3(\tau)=F_0\cos(\omega\tau) \tag{1}$$

$$C\ddot{Z}(\tau)+\frac{1}{R}\dot{Z}(\tau)+\frac{Z(\tau)}{I}+\eta\ddot{X}(\tau)=0 \tag{2}$$

where $X(\tau)$ denotes the modal coordinates, $Z(\tau)$ denotes the generated voltage through the electrical resistance, both γ and η are the piezoelectric coupling terms, C is the sum of the piezoelectric capacitance and the electrical capacitance, R denotes the resistance of the system, and I is the electrical inductance. $2\xi\omega_1-\alpha_1 v$ is defined as μ_1, where ξ , ω_1, α_1 and v mean the mechanical damping ratio, the structural natural frequency, the linear coefficients of the galloping force and wind speed respectively. And let k be equal to $-\frac{\alpha_2}{v}$, where α_2 means the nonlinear coefficients of the galloping force.

In order to discuss the steady-state moments can be derived by means of stochastic analysis

$$E[X^2]=\frac{D(\beta c_{11}\gamma(\beta\gamma b_1+b_2)+\omega_1^2\omega_2^2 b_3)}{\omega_1^4(\beta\gamma(\omega_2^2(c_{11}^2+\mu_2^2)+c_{11}\mu_2 a_2)+c_{11}\mu_2 a_3)} \tag{3}$$

$$E[\dot{X}^2]=\frac{D(\beta\gamma c_{11}\mu_2 b_4+\omega_2^2 b_5)}{\beta\gamma(\omega_2^2(c_{11}^2+\mu_2^2)+c_{11}\mu_2 a_2)+c_{11}\mu_2 a_3} \tag{4}$$

$$E[Z^2]=\frac{\beta^2 D(c_{11}\mu_2(-c_{11}^2-c_{11}\mu_2+c_{11}+b_4)+c_{11}\omega_2^2+\mu_2\omega_2^2)}{\beta\gamma(\omega_2^2(c_{11}^2+\mu_2^2)+c_{11}\mu_2 a_2)+c_{11}\mu_2 a_3} \tag{5}$$

where

$$a_1=c_{11}^2+c_{11}\mu_2-c_{11}\omega_1^2+c_{11}\omega_2^2+2\omega_2^2,$$

$$a_2=c_{11}^2\omega_2^2+2c_{11}\mu_2\omega_2^2+\mu_2^2\omega_2^2,$$

$$b_1=-\beta\gamma-c_{11}\mu_2+\mu_2-2\omega_1^2+\omega_2^2,$$

$$b_2=c_{11}\omega_1^2+\mu_2\omega_1^2-\omega_1^4+\omega_1^2\omega_2^2+\frac{\omega_2^4}{c_{11}},$$

$$b_3=\beta\gamma c_{11}+c_{11}\mu_2+2c_{11}\mu_2^2,$$

$$b_4=-\beta\gamma+c_{11}+\mu_2-\omega_1^2+\omega_2^2,$$

$$b_5=\beta\gamma(c_{11}+\mu_2)+\mu_2(c_{11}^2+2c_{11}\mu_2+\mu_2^2).$$

Substituting the expression of $E[\dot{X}^2]$ into the relationship $c_{11}=\mu_1+3kE[\dot{X}^2]$, and taking a cyclic procedure on it, the convergence value of c_{11} and $E[\dot{X}^2]$ can be determined.

III CONCLUSION

By means of the method of moments in stochastic process theory, the exact closed expressions for the mean square voltage and the average output power are derived based on the distributed parameter model of the galloping energy harvester.

IV ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China (Grant No. 12172266)

V REFERENCES

[1] Y. Yang, L. Zhao, L. Tang, *Comparative study of tip cross-sections for efficient galloping energy harvesting*. Applied Physics Letters, vol. 102/6, 064105, 2013.

[2] D. Huang, J. Han, W. Li, et al., *Responses, optimization and prediction of energy harvesters under galloping and base excitations*, Communications in Nonlinear Science and Numerical Simulation, vol. 119, 107086, 2023.

Neuro-fuzzy clustering of lateral and vertical acceleration of railway track: an AI-enhanced approach

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I INTRODUCTION

Modern railway systems require advanced monitoring methods to ensure safety, passenger comfort, and predictive maintenance. Vibrational signals – especially lateral and vertical accelerations – are crucial indicators of track and vehicle condition but are often obscured by environmental noise and operational complexity. This study addresses these challenges by applying an adaptive neuro-fuzzy inference system (ANFIS) to model and predict acceleration trends. The aim is to identify the most influential time-lagged parameters contributing to acceleration signals and explore the integration of artificial intelligence (AI) to enhance diagnostic accuracy.

II METHODS

The methodology employed a simplified measurement method aligned with EN 14363 standards to gather lateral and vertical acceleration data from a diesel train. Accelerometers were installed on bogie frames and car bodies, and signals were collected over segments of 70, 100, and 250 meters. An ANFIS architecture was used to predict future acceleration values based on prior time-lagged inputs. The system combined fuzzy logic's interpretability with the learning capabilities of neural networks. Additionally, AI techniques – such as convolutional neural networks (CNNs), ensemble learning, and adaptive algorithms – were discussed as complementary tools to boost performance in real-time applications.

III RESULTS AND DISCUSSION

Experimental results showed that near-term time-lagged data had the highest predictive value for both lateral and vertical accelerations, with long-term lags proving less relevant. The accuracy of predictions varied with the complexity of measurements, increasing in error with noisier datasets. AI-enhanced ANFIS models confirmed robustness in handling nonlinearity and signal uncertainties. Integration with advanced AI methods such as LSTM and autoencoders was proposed to further reduce noise and enable adaptive, real-time monitoring.

IV CONCLUSION

This study highlights the efficacy of ANFIS in clustering and predicting acceleration data, emphasizing the utility of short-term historical values in dynamic forecasting. The AI-augmented framework holds promise for predictive maintenance, improved ride comfort, and enhanced safety in high-speed rail systems. Future work may include online learning, multi-sensor fusion, and deployment in seasonally frozen or otherwise challenging environments.

V REFERENCES

[1] X. Xi, Y. Li, L. Tang, P. Zhou, *Numerical investigation of vibrational acceleration for a ballasted railway track in cold regions*, Journal of Cold Regions Engineering, vol. 35/4, 04121022, 2021.
[2] J. Li, F. Wang, X. Cheng, *Effect of acceleration and deceleration of a high-speed capsule train on transonic flow and heat transfer in an evacuated tube*, Aerospace Science and Technology, vol. 121, 107321, 2022.
[3] M. Zhang, S.I Kim, J. Park, *Evaluation of railway bridge integrity using acceleration data and semi-supervised machine learning*, Engineering Structures, vol. 269, 115229, 2023.
[4] Y. Chen, P. Zheng, D. Wu, L. He, *Experimental investigation on train-induced ground vibration at embankment and under-crossing tunnel interfaces*, Transportation Geotechnics, vol. 29, 100675, 2023.
[5] A. Shams, A. Mahmood, *Advances in adaptive neuro-fuzzy inference systems (ANFIS) for structural health monitoring*, IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 51/12, pp. 6985–6998, 2021.

EUROPEAN MECHANICS SOCIETY

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Periodic and stochastic transversal excitation on the elastically connected nano-plate and nano-shell

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I INTRODUCTION

Curvatured surfaces of elastically connected nano-elements find a crucial role in various medical and nanotechnological applications. These systems can be adapted to different locations. The radius of curvature in such systems plays a key role in the amplitudes of oscillations, with all other parameters of the coupled system and periodic excitation being the same.

II ANALYSIS OF THE NANO-SYSTEM WITH PERIODIC AND STOCHASTIC TRANSVERSAL EXCITATION

The paper presents numerical study of forced vibration of an orthotropic nano-system consisting of nano-plate and a doubly curved shallow nano-shell elastically interconnected by Winkler-type layer, Fig. 1.

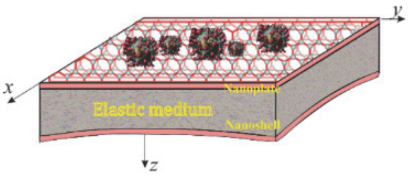

Fig. 1. Physical model of the double graphene nano-system composed of nano-plate and nano-shell and coupled by Winkler-type elastic layer

Utilizing the Eringen constitutive elastic relation [1] and Novozhilov linear shallow shell theory [2], we derive a system of four coupled nonhomogeneous partial differential equations (PDEs) describing the forced transverse vibrations of the system [3]. The forced vibration analysis is conducted using modal analysis [4] and simulated for two types of transverse loads: periodic and stochastic.

The coupled nonhomogeneous ordinary differential equations ODEs for the time modes of the transverse vibrations, which describe the forced vibrations of the nano-system are presented in detail by (60-64) in Ref. [4]. Also, ODEs can be presented in the concise matrix form:

$$\mathbf{M}\{\ddot{\mathrm{S}}\} + \mathbf{K}\{\mathrm{S}\} = \{\mathrm{F}\} \quad (1)$$

where $\{\mathrm{S}\}$ contains time functions for four transversal displacements and **M** and **K** are mass and stiffness matrices which contains mass, extensional and bending stiffness, respectively. The transverse load $\{\mathrm{F}\}$ is presented either as the uniformly distributed surface harmonic load, see expression (83) in Ref. [3] or as stochastic excitation in the form of real-noise.

According to discretized form of ODEs (1) describing the forced transverse vibrations of the system extensively shown in [3] the simulation scheme is generated in MATLAB software where numerical comparisons for two different transverse loads are presented in Fig. 2.As an example of stochastic process numerical calculations are done for real-noise process defined by the following equation:

$$d\xi(t) = -\alpha\xi(t)dt + \sigma_r dW(t) \quad (2)$$

where α and σ_r are constants and $dW(t)$ is standard Wiener process. This process is simulated according to the program code for real-noise process simulation suggested which was used and successfully confirmed in [5].

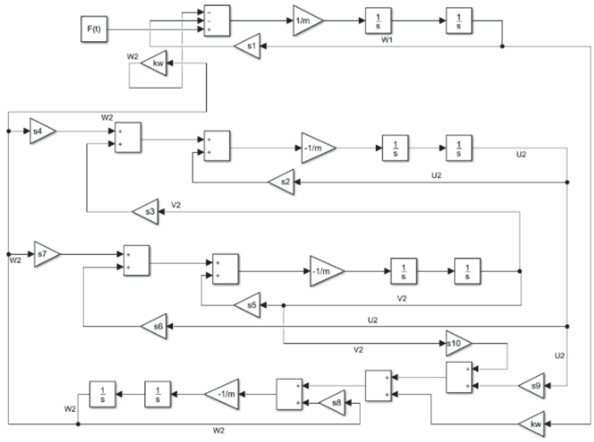

Fig.2. Simulation scheme according to model described by ODEs (1) taking into account influence of transverse force

III CONCLUSION

This study uses simulations to compare the actual response of a coupled curved system to various external stimuli. By analyzing these stimuli, we can optimize the system's response and identify the most suitable amplitudes based on the selected optimization parameter, which is the radius of curvature.

IV ACKNOWLEDGEMENT

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V REFERENCES

[1] A.C. Eringen, *Nonlocal continuum field theories*, International Journal of Mechanical Sciences, Springer Science and Business, 2002.

[2] M. Amabili, *Nonlinear vibrations and stability of shells and plates*, New York: Cambridge University Press, 2008.

[3] M.S. Atanasov, I.R. Pavlović, J. Simonović, C. Borzan, A. Păcurar, R. Păcurar, *Forced Dynamics of Elastically Connected Nano-Plates and Nano-Shells in Winkler-Type Elastic Medium*, Applied Sciences, vol. 15(5), 2765, 2025.

[4] S.G. Kelly, *Mechanical vibrations: theory and applications*, Cengage learning, 2012.

[5] I. Pavlović, R. Pavlović, I. Ćirić, D. Karličić, *Dynamic stability of nonlocal Voigt–Kelvin viscoelastic Rayleigh beams*, vol. 39, pp. 6941-6950, 2015.

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Wavelet-based feature extraction and AI techniques for acoustic event detection in urban environments

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I INTRODUCTION

The increasing demand for efficient environmental noise monitoring systems calls for intelligent solutions capable of identifying and classifying diverse sound sources in complex urban soundscapes. This study presents an AI-based approach for sound event recognition and classification in urban environments, with a particular focus on the application of wavelet transform techniques for advanced vibration and acoustic signal analysis.

II WAVELET-BASED FEATURE EXTRACTION AND AI TECHNIQUES FOR ACOUSTIC EVENT DETECTION

In this work, a supervised classification system is developed by combining digital signal processing with machine learning algorithms. Key features are extracted from audio signals using wavelet transform, enabling time-frequency domain analysis essential for capturing transient and non-stationary characteristics of acoustic events. These features are then utilized as input to machine learning models for accurate classification of sound events. The performance of various feature sets is evaluated to determine the most effective parameters for class-specific recognition.

In continuation, this research builds upon existing frameworks such as the SONYC project [1] and other embedded systems for sound recognition [2], by introducing a hybrid feature extraction scheme combining wavelet transform with commonly used techniques such as MFCC, Mel Spectrogram, and Chromagram. The fusion of these features into a unified vector improves classification performance across multiple machine learning models including Random Forest, SVM, and Naïve Bayes classifiers. The dataset used comprises ten categories of urban noise events, allowing for a comprehensive evaluation of the system's detection capabilities. The integration of AI-driven classification with advanced signal processing tools presents a scalable and efficient model for future smart city deployments. In addition to the research, by using several feature extraction techniques as an input to machine learning algorithm, the researchers in [3] have studied which set of features will give highest efficiency of the system when classifying urban noise. By applying hyperparameter optimization on the machine learning algorithms, the designed AED/C system results with higher predictive accuracy results so it would be suitable for practical application. By using several datasets of environmental sound classes, the researchers in [4,5] have examined and visualized the wavelet-based feature as an input in CNN network.

III CONCLUSION

The resulting Acoustic Event Detection and Classification (AED/C) system demonstrates strong potential for integration into intelligent sensor networks, enabling automated environmental noise control through precise source identification. This reduces the need for human intervention and enhances the efficiency of urban noise management strategies. The results suggest that multi-feature approaches combined with interpretable ML models offer a reliable pathway to achieving robust, real-time acoustic monitoring solutions in dense urban environments.

IV REFERENCES

[1] J.P. Silva, C. Bello, O. Nov, R.L. Dubois, A. Arora, J. Salamon, *Sonyc: A system for monitoring, analyzing, and mitigating urban noise pollution*, Communications of the ACM, 62/2, pp. 68-77. 2019.

[2] D. Hollosi, G. Nagy, R. Rodigast, S. Goetze, P. Cousin, *Enhancing wireless sensor networks with acoustic sensing technology: use cases, applications & experiments*, In 2013 IEEE International Conference on Green Computing and Communications and IEEE Internet of Things and IEEE CPS Computing. IEEE, pp. 335-342, 2013.

[3] S. Domazetovska, D. Pecioski, V. Gavriloski, H. Mickoski, *IoT smart city framework using AI for urban sound classification*, In INTER-NOISE and NOISE-CON Congress and Conference Proceedings, Institute of Noise Control Engineering, vol. 265/5, pp. 2767-2776, 2023.

[4] Y. Lee, S. Lim, IY. Kwak, *CNN-based acoustic scene classification system*. Electronics, 10/4, p. 371. 2021.

[5] K. Wakayama, S. Saito, *CNN-transformer with self-attention network for sound event detection*. In ICASSP 2022-2022 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP). IEEE. pp. 806-810, 2022.

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Effects of handling an imbalanced dataset on the accuracy of supervised machine learning classifiers

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I INTRODUCTION

In fault diagnostics, class imbalance in the training data can significantly compromise the effectiveness of supervised machine learning classifiers. A dataset can be characterized as imbalanced if a significant predominance of one or more classes over others is present. Using an imbalanced dataset for training a supervised machine learning classifier may result in a biased classifier that performs well on the predominant classes but makes errors when encountering minority classes. In this paper, the effect of handling an imbalanced dataset on the performance of supervised machine learning classifiers is analyzed, with a focus on vibration-based fault diagnostics.

II EFFECTS OF HANDLING AN IMBALANCED DATASET ON THE ACCURACY OF SUPERVISED MACHINE LEARNING CLASSIFIERS

This paper proposes a methodology for balancing the Mafaulda dataset [1-4], which consists of measured vibration signals under six operating conditions: normal, imbalance, vertical and horizontal misalignment, faulty underhang, and overhang bearing. The number of data files that consist of measured vibration signals during normal machine operation is represented by less than 50% of the mean value of the number of data files recorded across all other machine states, characterizing this database as imbalanced [5]. This may reduce the accuracy in recognizing defect-free conditions and increase the possibility of false alarms. To evaluate the effects of handling an imbalanced dataset on the accuracy of supervised machine learning classifiers, both versions, the original (imbalanced) and the balanced one, are used to train classification models. Each version of the dataset is properly prepared, analyzed, and feature extraction is performed. In order to reduce the dimensionality of the input vectors of the extracted features, the Sequential Selection algorithms (SSA) method is used. The obtained feature vectors from both versions of the dataset are used to train and test three supervised machine learning classifiers: a support vector machine (SVM) classifier, a random forest (RF) classifier, and a k-nearest neighbors (kNN) classifier. Classification accuracy and confusion matrices are obtained for each model using the 10-fold cross-validation method.

III CONCLUSION

The output of the paper gives an evaluation of the impact of handling an imbalanced dataset on the accuracy of the applied supervised machine learning classifiers. The comparison of the performance between the models trained on the imbalanced and balanced datasets shows how addressing class imbalance can affect the robustness and reliability of the created classifiers. The results of this paper emphasize the importance of proper data preparation and organization in increasing the overall classification accuracy.

IV REFERENCES

[1] *MaFaulda - Machinery Fault Database*. [Online]: http://www02.smt.ufrj.br/~offshore/mfs/page_01.html.

[2] A.M. Matheus, M.L.F. Ribeiro, L.N. Sergio, A.B.S. Eduardo, *Improved Similarity-Based Modeling for the Classification of Rotating-Machine Failures*, Journal of the Franklin Institute, 2017

[3] D.P. Viana, D.Z. Lopez, R.D., A.A. Lima, T.D.M. Prego, S.L. Netto, E.A. Silva, *The influence of feature vector on the classification of mechanical faults using neural networks*, IEEE 7th Latin American Symposium on Circuits & Systems, pp. 115-118, 2016.

[4] SpectraQuest, Inc.
[Online]. Available: http://www.http//spectraquest.com/

[5] N.V. Chawla, *Data mining for imbalanced datasets: An overview*. Data mining and knowledge discovery handbook, pp.875-886, 2010.

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through
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Baseline-free damage detection method based on vibration with tunable resolution for composite laminates

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I INTRODUCTION

Composite laminates have attracted much attention in advanced engineering structures, while issues on assessing the unavoidable damage and defects in these structures still confront with many challenges.

Among the various structural health monitoring (SHM) and non-destructive testing (NDT) methods, vibration-based damage detection methods are widely applied in composite structures, for their great capabilities in evaluating global integrity of the target structure[1], [2].Many efforts have been made to explore and improve the sensitivity of vibration-based damage detection method. By using two-dimensional continuous wavelet transform (2D CWT)to analyze the responses, the defects in composite plates can be visualized[3]. However, these researches did not deeply discuss about the selection of 2Dwavelet function and the effects of wavelet parameters, which heavily ignores the flexibility of 2D CWT.

In this paper, a baseline-free damage detection method based on vibration with tunable resolution is proposed by using 2D CWT for multiscale damage detection in composite laminates.

II DAMAGE DETECTION METHOD BASED ON 2D CWT

Based on the central finite difference approximation and 2D CWT, a baseline-free damage detection method is proposed. The flowchart of the proposed method to get the damage index is elaborated in Fig. 1.

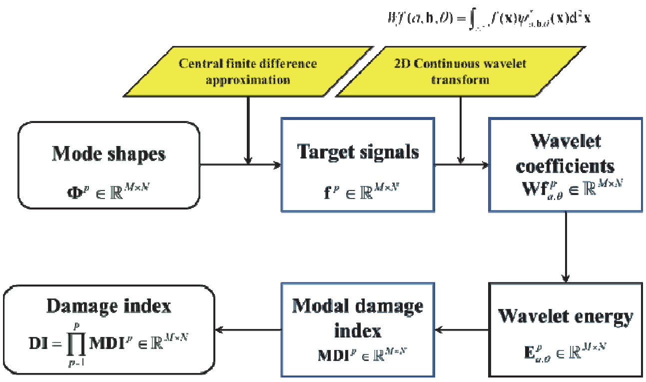

Fig. 1. Flowchart of the proposed damage detection method.

III RESULTS AND DISCUSSIONS

To validate the capability of the proposed method, both numerical simulations and laboratory experimental tests on composite laminates are conducted in this study. Here, a carbon fiber-reinforced plastic (CFRP) composite laminate with dimensions of 800 × 800 × 3.2 mm^3 and stacking sequence of $[45/-45/0/0/-45/90/45/0]_s$ is considered. There are two defects with the same stiffness reduction but different damage sizes as shown in Fig. 2.

By considering various scaling parameters of 2D CWT, the sensitivity to the smaller defect (Damage II) and the greater defect (Damage I) can be switchable as shown in Fig. 3 (a) and (b). Moreover, by considering multiple scaling parameters of 2D CWT, defects with different damage sizes can be visualized as shown in Fig. 3 (c).

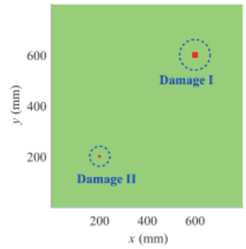

Fig. 2. Dual damage in composite laminate.

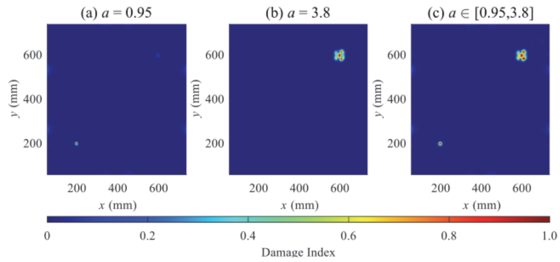

Fig. 3. Damage index with different scaling parameters.

IV CONCLUSIONS

In this paper, a baseline-free damage detection method with tunable resolution is developed for composite laminates. By deeply considering the property and flexibility of2D CWT, the smallest detectable size of damage can be estimated, and the tunable resolution of identification can be realized to meet the requirement in practice.

In summary, the proposed method provides a novel and robust vibration-based technique for damage identification in composite laminates, which has great developing potential and application prospect in on-line detection of various sizes of defects or damage in plate-like structures.

V ACKNOWLEDGEMENT

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VI REFERENCES

[1] P. Chaupal, P. Rajendran, *A review on recent developments in vibration-based damage identification methods for laminated composite structures: 2010–2022*, Compos. Struct., vol. 311, 116809, 2023.

[2] W. Fan, P. Qiao, *Vibration-based damage identification methods: A review and comparative study*, Struct. Health Monit., vol. 10/1, pp. 83–111, 2011.

[3] J. Zhou, Z. Li, J. Chen, *Application of two dimensional Morlet wavelet transform in damage detection for composite laminates*, Compos. Struct., vol. 318, 117091, 2023.

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Modeling and simulation of a hybrid piezoelectric–electromagnetic system for vibration energy harvesting

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I INTRODUCTION

Energy harvesting is the process of accumulating electrical energy from naturally available sources, such as mechanical vibrations, with the aim of supporting the energy autonomy of low-power devices that require between a few µW and several tens of mW. Such devices are essential for applications in the Internet of Things (IoT), autonomous structures, biomedical devices, and wearable technologies. Mechanical-to-electrical energy conversion can be achieved through methods such as the piezoelectric effect and electromagnetic induction, each offering distinct efficiencies and operational characteristics. Since environmental vibrations are typically random, low-frequency, and time-varying, optimizing the design of energy harvesters is critical to improving conversion performance. Hybrid systems demonstrate advantages by combining both conversion mechanisms, enabling more efficient utilization of vibrations. Modeling and simulation are crucial preliminary steps before prototype construction, allowing for system analysis, correction, and optimization. The resulting models will serve as the foundation for developing an experimental prototype.

II MODELING AND SIMULATION OF A HYBRID PIEZOELECTRIC–ELECTROMAGNETIC SYSTEM FOR VIBRATION ENERGY HARVESTING

This study presents the modeling and simulation of a hybrid energy harvesting system that combines piezoelectric and electromagnetic conversion mechanisms to improve energy conversion efficiency. The system consists of a cantilever-type mechanical structure integrated with a piezoelectric patch (lead zirconate titanate, PZT) and an electromagnetic generator operating according to Faraday's law of induction. Piezoelectric materials are valued for their lightweight, flexible design and the ability to be integrated onto various surfaces without significantly affecting the structural dynamics [1]. Electromagnetic generators, characterized by simple construction and effective performance at low load impedance, complement the piezoelectric components [2,3].

An analytical model of the cantilever beam, mathematical models of the piezoelectric and electromagnetic transducers, as well as a multiphysics simulation of the entire hybrid system were developed. Finite element modeling and simulation were performed using the COMSOL Multiphysics software to predict and optimize the physical behavior of the system. The results show that the piezoelectric element generates up to 1.5 mW of power at an optimal load of 50 kΩ, while the electromagnetic generator achieves 3 mW at 1000 Ω, both at a natural frequency of 11 Hz. The hybrid approach improves adaptability to variable vibration conditions and significantly enhances the overall harvested energy [4].

Piezoelectric transducers, due to their ability to directly convert mechanical stress into electrical voltage, are particularly efficient under high-frequency, low-amplitude conditions. Their lightweight and compact construction makes them suitable for integration onto a wide range of structures. In contrast, electromagnetic transducers are more efficient for low-frequency, high-amplitude vibrations. Their simple construction and lower load impedance make them suitable for systems with higher power requirements.

III CONCLUSION

Hybrid energy harvesting systems present a promising approach for enhancing the efficiency of mechanical-to-electrical energy conversion. By combining piezoelectric and electromagnetic mechanisms, it is possible to maximize power output and ensure a more stable energy supply for low-power autonomous devices. Modeling and simulation are critical steps toward system optimization, providing a foundation for future experimental prototypes and practical applications. The integration of these two technologies into a hybrid system demonstrates significant improvements in energy efficiency and broadens the range of applicable frequencies. Furthermore, the developed models and simulations confirm that careful design and optimization are essential for the maximum utilization of mechanical vibrations. Future work will focus on experimental validation of the models and the development of prototypes tailored for specific real-world applications.

IV REFERENCES

[1] H.S. Tae, H. Sinichi, K.J. Hyung, B.K. Se, S. Daniel, *Piezoelectricity harvesting system has piezoelectric element that is equipped in movable structure with external force, so that external force is delivered to movable structure for generating electric power*, Hyu Holdings, Seedenertech Co Ltd., 2020.

[2] I. Ahmad, L.M. Hee, A.M. Abdelrhman, S.A. Imam, M.S. Leong, *Hybrid vibro-acoustic energy harvesting using electromagnetic transduction for autonomous condition monitoring system*, Energy Convers. Manage. vol. 258, 115443, 2022.

[3] J. Cuji, L. Mendoza, G. Brito, C. Gordon, *Portable electromagnetic energy harvesting system*, in 1st Congress on Sustainability, Energy and City (CSECity) University Tecnologica Indoamerica, Ambato, Ecuador, 2021.

[4] Z.Q. Liu, S.Y. Li, S.Q. Lin, Y.X. Shi, P. Yang, X.Y. Chen, Z.L. Wang, *Crystallization-induced shift in a triboelectric series and even polarity reversal for elastic triboelectric materials*, Nano Lett., vol. 22/10, pp. 4074–4082, 2022.

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Analysis of loss factors in passenger car motion using artificial intelligence

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I INTRODUCTION

Due to increasingly stringent environmental regulations in the automotive industry, reducing fuel consumption has become a matter of paramount importance. Optimizing fuel consumption and ensuring the efficient use of available energy resources are essential prerequisites for sustainable development. Fuel economy can primarily be improved by minimizing the losses that occur during vehicle operation; therefore, accurately identifying these loss factors is crucial in both the design and operation of vehicles. Among the various forms of resistance encountered during motion, rolling resistance and aerodynamic drag are particularly significant.

II OBJECTIVE AND METHOD

This research aims to experimentally identify the primary sources of energy loss during passenger car operation and to characterize the vehicle's energy behavior based on the results. The analysis was conducted using measurements performed under both elevated conditions and real-world road scenarios. The collected data were evaluated using artificial intelligence-based methods. This approach enables the quantification of engine power required to overcome specific resistance forces, thus supporting more efficient vehicle design and operation. The vehicle's engine power, speed, and resistance values were monitored under various gear positions and speed intervals. The data collection protocol was based on SAE J1263, adapted to the available measurement conditions.

III THEORETICAL BACKGROUND

Operational losses during vehicle motion can generally be categorized into four main types: rolling resistance, aerodynamic drag, inertial resistance, and grade resistance. Rolling resistance refers to the energy loss caused by the contact between the tire and the road surface and is influenced by factors such as tire construction, temperature, and internal pressure. Aerodynamic drag results from air movement around the vehicle and increases proportionally to the square of the speed. Inertial resistance stems from the forces related to acceleration or deceleration, while grade resistance results from gravitational forces acting when the vehicle moves uphill.

IV MATERIALS AND METHODS

Experiments were conducted under two conditions: elevated position and on-road driving. Data collection was performed using an ELM327 OBD-II Bluetooth device and an Android-based application. The test vehicle was a Suzuki Liana 1.6 (2005), with 78 kW engine power, a frontal area of 2.25 m^2, and a drag coefficient (Cd) of 0.5.

V RESULTS AND DISCUSSION

The analysis revealed that rolling resistance dominates at lower speeds, while aerodynamic drag becomes increasingly significant at higher velocities. Graphical evaluations clearly showed the relationship between engine power, speed, and gear position in both lifted and real-world driving conditions. The experiments demonstrated that a consistent proportionality exists between the two test conditions, and the elevated state measurements provide valuable reference for estimating real losses. The measured data align well with values reported in the literature, confirming the reliability of the experimental method.

VI CONCLUSION

Accurately identifying the loss factors that occur during the movement of passenger cars contributes significantly to reducing fuel consumption. The measurement methods applied in this research are suitable for reliably determining rolling and aerodynamic resistance. By combining theoretical background with field experiments and intelligent data analysis, this study provides a reliable methodology to evaluate loss factors affecting passenger car motion. The findings support further research in reducing fuel consumption and improving vehicle efficiency, while offering an accessible and replicable framework for similar investigations in the automotive sector.The use of artificial intelligence enhanced the accuracy of data interpretation, offering a practical and replicable methodology for further studies on vehicle loss optimization.

VII REFERENCES

[1] U. Hammarström et al., *Road surface effects on rolling resistance – coastdown measurements with uncertainty analysis in focus*, 2009.
[2] B. Świeczko-Żurek et al., *Rolling Resistance and Tire/Road Noise*, 2015.
[3] B. Wiegand, *Estimation of the Rolling Resistance of Tires*, 2016.
[4] Y. Wicaksana et al., *Determining Rolling Resistance Coefficient*, 2011.
[5] T.D. Gillespie, Fundamentals of Vehicle Dynamics (Society of Automotive Engineers) pp. 116-117, 1992.
[6] *SAE Road load measurement and dynamometer simulation using coastdown techniques* (SAE J1263, Society of Automotive Engineers), 2010.
[7] U. Sandberg et al., *Rolling resistance – Basic information and state-of-the-art on measurement methods (Models for Rolling Resistance in Road Infrastructure Asset Management Systems (MIRIAM))* p. 12, 2011.

Fuzzy Lyapunov approach for adaptive system control

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I INTRODUCTION

For the efficient speed control of DC motors, this paper combines Model Reference Adaptive Control (MRAC) and Fuzzy Logic (FL). The proposed approach ensures stability and good system performance for various desired speeds and undesired disturbances.

II MODEL OF THE PLANT AND CONTROL ALGORITHM

A DC motor with an additional load on the output shaft in the shape of a disk is used as the object. Its linear equation is obtained by combining electrical and mechanical quantities, from which the transfer function is easily found in the form of $W(s) = \frac{0.1284}{0.0021s+0.084}$.

Precise control of dynamic systems requires strategies that ensure stability and fast response under changing operating conditions. MRAC uses adaptive gain control to ensure that the system output y follows a reference model y_m until the tracking error e is eliminated [1]. The tuning of the MRAC algorithm parameters can be done using the Lyapunov approach [2]. It is necessary to choose the Lyapunov function V so that it is positive definite and its derivative is negative definite, Eq. (2). Since there is no universal method for choosing the Lyapunov function [3], in this paper, it is chosen as:

$$V(e,\theta_1,\theta_2) = \frac{1}{2}\left(e^2 + \frac{1}{b\gamma}(b\theta_2 + a - a_m)^2 + \frac{1}{b\gamma}(b\theta_1 - b_m)^2\right) \quad (1)$$

where a, b, a_m, and b_m are all positive coefficients of the plant and reference model, respectively; θ_1 and θ_2 are adjustable parameters with derivatives defined as $\dot{\theta}_1 = -\gamma y_d e$ and $\dot{\theta}_2 = -\gamma y e$ with the desired output y_d and for tuning parameter $\gamma>0$. To find the tuning parameter γ, instead of the trial and error method, which is quite time-consuming, a more advanced approach, i.e., FL, is employed. The fuzzy controller structure is based on an open-source implementation licensed under the MIT License [4]. Error and its derivative are selected for the fuzzy inputs, and each is defined by two Gaussian membership functions centered at ±100 with a large standard deviation of 70; although symmetrically placed, the functions are not evenly spaced across the input range. To find γ, a zero-ordered Takagi–Sugeno (TS) fuzzy inference system is employed, combining rule-based logic with predefined constant outputs selected from the singleton set {–150, –100, –50, 0, 50, 100, 150}.

III RESULTS AND DISCUSSION

To evaluate the effectiveness of the developed controller, several representative simulations with sine and step disturbances were performed, as well as with two different defuzzification factors. The most illustrative case is shown in Fig. 1. The system tracks the desired output accurately with fast settling time and minimal overshoot. After the step signal disturbance $d(s)$ with a magnitude of 0.5 at t=1s, a brief deviation occurs, followed and the output stabilizing rapidly, confirming the controller's robustness and effective disturbance rejection. The control signal is denoted by $c(t)$ and represents the output of the fuzzy regulator applied to the system. Four different objective functions are calculated: Integral Square Error (ISE) = 0.1777, Integral Absolute Error (IAE) = 0.1903, Integral Time-weighted Absolute Error (ITAE) = 7.6328, and Integral Time-weighted Square Error (ITSE)=7.6425. Low values across all error metrics indicate fast and accurate tracking.

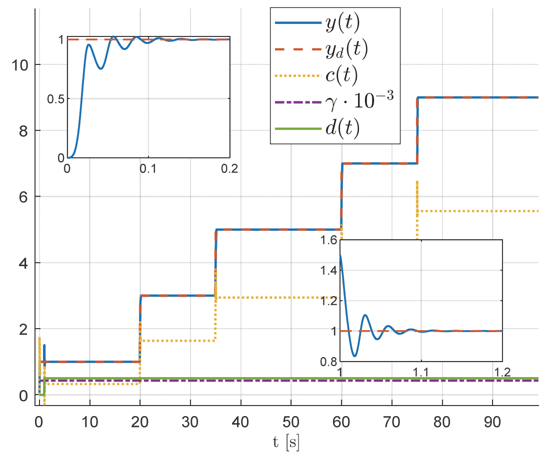

Fig. 1. System response with fuzzy controller

IV CONCLUSION

This paper presents a TS fuzzy-enhanced Lyapunov rule applied to a specific engineering problem. The proposed control technique effectively stabilizes the system and ensures robustness under various disturbances. The use of multiple error criteria validates the controller's efficiency, making it a promising solution for advanced adaptive control applications.

V ACKNOWLEDGEMENT

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VI REFERENCES

[1] D.D. Dinakin, P.O. Oluseyi, *Fuzzy-Optimized Model Reference Adaptive Control of Interacting and Noninteracting Processes Based on MIT and Lyapunov Rules*, Turkish Journal of Engineering, vol. 5/4, pp. 141-153, 2021.

[2] D. Gupta, A. Kumar, V. Kumar Giri, *Investigations on MIT and Lyapunov Rule-Based Modified MRAC for Noninteracting and Interacting Two-Tank Coupled Systems*, FME Transactions, vol. 52/2, pp. 305-318, 2024.

[3] K.J. Astrom, B. Wittenmark, *Adaptive Control*, USA: Addison-Wesley, 1989.

[4] https://github.com/AlfianFadliPramadhan/Fuzzy-PID-DC-Motor-Matlab-Simulink

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Parameter-dependent fractal spectra in quasiperiodic metastructures with elastic and rigid segments

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I INTRODUCTION

Periodic structures exhibit unique dynamic behaviors that are strongly influenced by their structural organization. The structural periodicity leads to wave phenomena similar to those in crystallography, including Bragg scattering and band gap formation. These engineered systems, known as metastructures, allow enhanced control over mechanical wave propagation and have been widely studied for applications such as vibration suppression, energy harvesting, and non-invasive testing. By carefully designing and tessellating unit cells, advanced effects can be achieved. Notably, these dynamic phenomena remain robust despite small structural irregularities. This robustness enables the introduction of deterministic disorder through controlled variations in design parameters, creating quasiperiodic structures. Such systems often show spatial localization of vibrational modes, confining energy to specific regions. This tunable behavior supports the development of intelligent structures, offering innovative solutions in various engineering domains.

II ANALYTICAL MODEL AND DISCUSSION

The analyzed metastructure consists of tessellated unit cells, each comprising a Timoshenko beam with a rigid body attached at its right end [1-3]. A quasiperiodic pattern is introduced, with a quasiperiodicity parameter θ, which governs the variation of selected material and geometric properties [4-7].

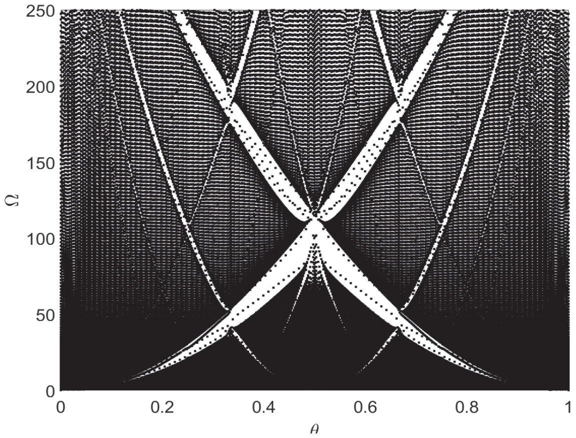

Fig. 1. Fractal spectrum resembling the Hofstadter butterfly for a system composed of 200 unit cells.

An analytical model is developed using the transfer matrix method, and the natural frequencies of a finite structure with n unit cells and free-free boundary conditions are computed using the bisection method. By plotting the normalized natural frequencies as a function of θ, a fractal spectrum resembling the Hofstadter butterfly is obtained [7]. In structures with a relatively small number of unit cells, discrete frequency branches appear within the band gaps, corresponding to natural frequencies at which wave localization occurs [6,7]. As the number of unit cells increases, the system exhibits characteristics of an infinite structure, and continuous lines appear within band gaps, indicating the presence of edge modes [6,7]. These results will be further validated through frequency response analysis and mode shape visualization to confirm wave localization, showing increased amplitude at the structure's ends [4-7].

III CONCLUSION

Although quasiperiodic structures are fundamentally aperiodic, they still exhibit band gaps. By plotting natural frequencies versus the quasiperiodicity parameter, a fractal spectrum resembling Hofstadter's butterfly was observed. Within the band gaps, discrete natural frequencies appear, indicating wave localization. To validate this, the frequency response function and mode shape visualization **are employed**. Quasiperiodic metastructures offer promising applications, enabling adaptive and efficient mechanical systems.

IV ACKNOWLEDGEMENT

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V REFERENCES

[1] M.I. Hussein, M. Ruzzene, M. Leamy, *Dynamics of Phononic Materials and Structures: Historical Origins, Recent Progress, and Future Outlook*, Applied Mechanics Reviews, vol. 66, 040802, 2014.
[2] A. Obradović, S. Šalinić, D.R. Trifković, N. Zorić, Z. Stokić, *Free vibration of structures composed of rigid bodies and elastic beam segments*, Journal of Sound and Vibration, vol. 347, pp. 126-138, 2015.
[3] N. Rosić, D. Karličić, M. Cajić, S. Adhikari, M. Lazarević, *Wave propagation in tailored metastructures consisting of elastic beams and rigid bodies*, Philosophical Transactions of the Royal Society A, vol. 382, 20230362, 2024.
[4] M. Gupta, M. Ruzzene, *Dynamics of Quasiperiodic Beams*, Crystals, vol. 10, 1144, 2020.
[5] M. Gei, *Wave propagation in quasiperiodic structures: stop/pass band distribution and prestress effects*, International Journal of Solids and Structures, vol. 47, pp. 3067-3075, 2010.
[6] R.K. Pal, M.I.N. Rosa, M. Ruzzene, *Topological bands and localized vibration modes in quasiperiodic beams*, New Journal of Physics, vol. 21, 093017, 2019.
[7] X. Ni, K. Chen, M. Weiner, D.J. Apigo, C. Prodan, A. Alu, E. Prodan, A.B. Khanikaev, *Observation of Hofstadter butterfly and topological edge states in reconfigurable quasi-periodic acoustic crystals*, Communications Physics, vol. 2, 55, 2019.

Application of artificial intelligence in testing conformity with Benford's law in chaotic dynamical systems

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I INTRODUCTION

Benford's Law, a logarithmic distribution of leading digits, has proven useful in domains such as fraud detection, natural sciences, and numerical data validation. Despite its widespread empirical success, its application to data generated by chaotic dynamical systems remains a relatively unexplored area. Given the sensitive dependence on initial conditions and long-term unpredictability of chaotic systems, the question arises whether their numerical outputs inherently align with Benford's distribution.

II METHODOLOGY

In this study, we simulate data from canonical chaotic systems including Lorenz, Hénon and Rössler systems, across a range of parameter values. Lorenz system is of the form:

$$\dot{x}(t) = \sigma\left(y(t) - x(t)\right), \quad (1)$$

$$\dot{y}(t) = r\,x(t) - y(t) - x(t)\,z(t), \quad (2)$$

$$\dot{z}(t) = x(t)\,y(t) - b\,z(t), \quad (3)$$

where (σ, r, b) is the set of parameters. Hénon system is of the form:

$$x_{n+1} = y_n + 1 - a\,x_n^2, \quad (4)$$

$$y_{n+1} = b\,x_n, \quad (5)$$

where a and b are two parameters. Rössler system is of the form:

$$\dot{x}(t) = -y(t) - z(t), \quad (6)$$

$$\dot{y}\,(t) = x(t) + a\,y(t), \quad (7)$$

$$\dot{z}(t) = b + z(t)(x(t) - c), \quad (8)$$

with set of parameters (a, b, c).

We examine whether the leading-digit distributions of these datasets conform to Benford's Law by computing the empirical digit frequencies and comparing them with theoretical Benford proportions using statistical distance metrics such as the chi-square and Kullback-Leibler divergence.

Furthermore, we develop machine learning models, primarily decision trees and support vector machines, to classify datasets as either Benford-conforming or non-conforming. These models are trained on statistical features derived from digit distributions, capturing subtle patterns beyond conventional statistical testing.

III RESULTS AND DISCUSSION

Our findings suggest that conformity to Benford's Law in chaotic systems is influenced by system parameters and numerical representation. AI classifiers demonstrate strong accuracy in distinguishing Benford-consistent behavior, often outperforming classical statistical tests in complex scenarios. Notably, models can detect latent regularities linked to the underlying dynamics of the system, providing new insights into how chaos and numerical structure interact.

The integration of AI tools in this analysis enables both a refined classification process and the potential to uncover unexpected symmetries in chaotic data. This supports the broader idea that intelligent systems can augment theoretical studies in nonlinear dynamics.

IV CONCLUSION

This work establishes a novel connection between dynamical systems theory and data science, illustrating how AI can deepen our understanding of the numerical properties of chaotic systems. Beyond the scope of Benford's Law, the methodology developed here opens promising avenues for applying AI to other structural analyses in complex systems.

V REFERENCES

[1] F. Benford, *The law of anomalous numbers*, Proceedings of the American philosophical society, vol 78/4, pp. 551-572, 1938.
[2] V. Rajić, J. Stanojević, W. Li, N. Trišović, *Testing conformity with Benford's Law in chaotic dynamical systems*, Technical Gazette, vol 32/3, pp. 1032-1039, 2025.
[3] C.R. Tolle, J.L. Budzien, R.A. LaViolette, *Do dynamical systems follow Benford's law?*, Chaos: An Interdisciplinary Journal of Nonlinear Science, vol 10/2, pp. 331-336, 2000.

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AI-driven optimization of biomechanical models for personalized prosthetic design and performance enhancement

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I INTRODUCTION

The development of prosthetic limbs has advanced significantly with the integration of computational tools that enable precise modelling of human biomechanics. Within this context, artificial intelligence (AI) has emerged as a pivotal technology, enabling the creation of prosthetic systems that are not only structurally optimized but also capable of mimicking complex human movements with a high degree of accuracy. In medical physics, where the quantitative analysis of biological systems underpins design and therapeutic innovation, AI enhances the ability to model and simulate musculoskeletal dynamics critical to prosthetic function. Artificial intelligence (AI) is emerging as a transformative tool in the field of medical physics, particularly in the design and development of advanced prosthetic systems. This study explores the integration of AI-driven methodologies in the modelling, simulation, and optimization processes central to prosthetic development. By leveraging AI algorithms such as machine learning, deep learning, and generative design, medical physicists can create personalized prosthetic solutions that closely mimic natural biomechanics. In particular, AI enhances the accuracy of finite element modelling for stress-strain analysis, predicts patient-specific gait dynamics, and supports the development of lightweight yet mechanically robust prosthetic components.

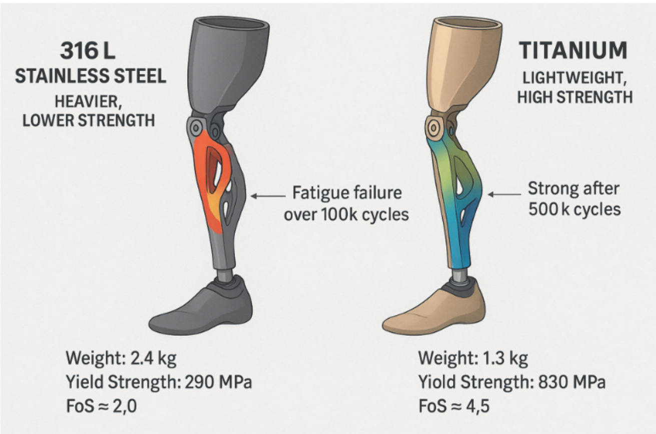

Fig. 1. Comparison titanium vs. 316L

II CONCLUSION

This study demonstrates the transformative potential of artificial development. By integrating AI-driven predictive models with motion capture, EMG data, and medical imaging, we successfully developed a biomechanics-informed framework capable of accurately estimating joint torques, muscle forces, and load distributions. These predictions were instrumental in optimizing prosthetic design, enabling significant reductions in weight and material usage while maintaining structural integrity and functional performance. The use of AI not only streamlined the simulation and design process but also facilitated the creation of more personalized, adaptive prosthetic systems. Experimental validation, both in laboratory settings and real-world user trials, confirmed the effectiveness of the AI-informed designs in enhancing gait efficiency, comfort, and overall mobility. In conclusion, if budget permits, Titanium (Ti-6Al-4V) is the superior choice for a final, wearable transfemoral prosthesis – offering greater patient comfort, long-term durability, and strength for high-stress activities (Fig. 1). However, for early-stage development, prototyping, or lab-based FEA trials, 316L stainless steel remains a more accessible and cost-effective alternative.

III ACKNOWLEDGEMENT

I would like to express my sincere gratitude to Maximilian Aaron Jelačić for his invaluable assistance in AI modelling for this project. His contributions played a pivotal role in the development and optimization of biomechanical models, significantly enhancing the effectiveness of AI-driven approaches for personalized prosthetic design and performance improvement.

IV REFERENCES

[1] V.C. Georgopoulos, A. Malousi, C.D. Stylios, A. Tzavaras, *Artificial intelligence in orthotics and prosthetics: A review of recent advances and future directions*, Journal of Rehabilitation and Assistive Technologies Engineering, vol. 6, pp. 1–13, 2019.

[2] H. Huang, F. Zhang, L.J. Hargrove, Z. Dou, D.R. Rogers, K.B Englehart, *Continuous locomotion-mode identification for prosthetic legs based on neuromuscular–mechanical fusion*, IEEE Transactions on Biomedical Engineering, vol. 58/10, pp. 2867–2875, 2011.

[3] J. Zhang, P. Fiers, K.A. Witte, R.W. Jackson, K.L. Poggensee, C.G. Atkeson, S.H. Collins, *Human-in-the-loop optimization of exoskeleton assistance during walking*, Science, vol. 356/6344, pp. 1280–1284, 2017.

[4] P.B. Shull, D.D. Damian, *Haptic wearables as sensory replacement, sensory augmentation and trainer–A review*, Journal of NeuroEngineering and Rehabilitation, vol. 12/1, 59, 2015.

[5] M. Côté, P. Boissy, *Biomechanical modeling of gait and its application to prosthetic development: A review*, Medical Engineering & Physics, vol. 78, pp. 1–12, 2020.

[6] Z. Jelačić, R. Dedić, *Designing and 3D Digital Development of a Prosthetic Prop Based on the Example of a Human Foot*, New Technologies, Development and Application VII NT 2024. Lecture Notes in Networks and Systems, vol 1069. Springer, Cham., 2024.

[7] Z. Jelačić, R. Dedić, *Reference Tracking of the Robotic Above-Knee Prosthetic Leg with Actuated Knee and Ankle Joints Using Robust Control*, CMBEBIH 2019. IFMBE Proceedings, vol 73. Springer, Cham., 2020.

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Multi-robot collaboration through AI-powered prompts

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I INTRODUCTION

The complexity of programming and coordinating multiple robotic systems has long been a significant barrier to widespread adoption of robotic automation [1]. Traditional multi-robot programming requires extensive knowledge of robotic kinematics, motion planning algorithms, and complex coordination protocols. Recent advances in large language models (LLMs) have opened unprecedented opportunities for natural language human-robot interaction [2], representing a paradigm shift toward intuitive, accessible robotic programming that can be utilized by non-technical users.

This work presents a comprehensive investigation of multi-robot collaboration using AI prompts, implemented within the Arctos Studio Pro simulation environment. Our system leverages Google's Gemini AI model to interpret natural language commands and translate them into executable Python code for robotic coordination. The integration of conversational AI with robotic systems represents a democratization of robotic control that has profound implications for manufacturing, logistics, healthcare, and service industries.

II METHODOLOGY

A novel three-layer architecture is introduced consisting of: (1) a PyQt5-based user interface layer providing comprehensive graphical interfaces for robot control and 3D scene visualization, (2) a Python command execution engine serving as the core command processing bridge between user interface and robotic operations, and (3) a Google Gemini AI-powered natural language processor that converts conversational commands into executable Python code.

The command interpretation accuracy can be modeled using a probabilistic framework that accounts for linguistic ambiguity and execution complexity:

$$P(S|C) = \alpha \cdot P(I|C) \cdot P(E|I) \cdot P(R|E) \quad (1)$$

where P(S|C) represents the probability of successful task execution given command C, P(I|C) is the probability of correct command interpretation, P(E|I) is the probability of successful code execution given correct interpretation, P(R|E) is the probability of successful robot execution given valid code, and α is a normalization factor accounting for system-specific constraints.

Experimental evaluation compares direct command sequences with generalized natural language instructions across six different robotic coordination scenarios: Direct Sequential, Generalized NL, Complex Coordination, Assembly Tasks, Synchronized Movement and Dynamic Manipulation. Each scenario was executed 20 times across different environmental conditions, totaling 120 experimental trials. Through extensive testing it was achieved task completion rates of 96.7% for direct commands and 89.2% for generalized prompts.

Pick-and-place operations demonstrated highest interpretation accuracy, while spatial navigation and coordination commands showed increased error rates due to linguistic ambiguity and complex spatial relationships, as shown in Fig. 1.

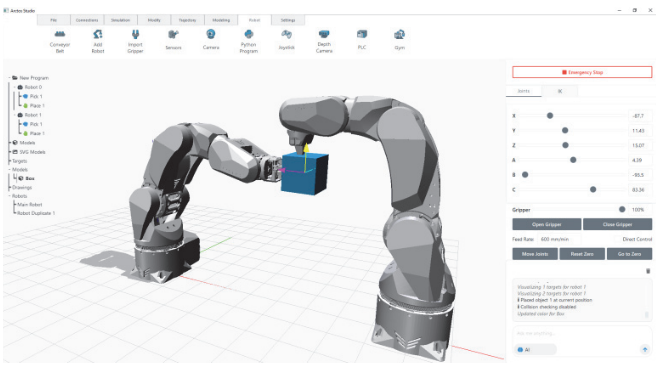

Fig. 1. Multi-robot task execution showing two robotic arms performing coordinated pick-and-place operations during experimental trials.

III CONCLUSION

The results strongly support the feasibility of AI prompt-based robotic coordination as a pathway toward democratizing advanced robotics capabilities. The three-layer architecture successfully integrates user-friendly interfaces with powerful AI processing to create an intuitive robotic control system. Key contributions include: (1) novel three-layer architecture for AI-driven robotic control, (2) comprehensive experimental evaluation with quantitative performance metrics, (3) mathematical framework for modeling command interpretation accuracy, and (4) detailed error analysis and classification system.

The system enables rapid prototyping capabilities, reducing development time from hours to minutes for typical scenarios, and provides educational value through AI explanations that offer transparent insights into robotic operations. Future work will focus on addressing current limitations through enhanced context awareness, multimodal integration, formal safety verification, and scalability improvements for larger multi-robot networks.

IV REFERENCES

[1] B. Siciliano, O. Khatib, *Springer Handbook of Robotics*, 2nd ed., Springer, Heidelberg, 2016.
[2] S. Tellex, T. Kollar, S. Dickerson, M.R. Walter, A.G. Banerjee, S. Teller, N. Roy, *Understanding natural language commands for robotic navigation and mobile manipulation*, Proceedings of the 25th AAAI Conference on Artificial Intelligence, pp. 1507–1514, 2011.
[3] A. Sarajlić, L. Banjanović-Mehmedović, *AI-Driven Human-Robot Interaction for a 3D-Printed Robotic Arm Using Gemini AI and ROS*, 24th Intern. Symposium INFOTEH-JAHORINA, 2025.

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Machine learning-based prediction of equivalent shear modulus in AS4/Epoxy laminates

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I INTRODUCTION

Accurate prediction of mechanical properties in composite laminates is essential for the design and analysis of advanced aerospace and structural components. In particular, estimating the equivalent in-plane shear modulus ($G_{xy}eq$) in orthotropic composite materials, such as AS4/Epoxy, is a complex task due to anisotropy, heterogeneous microstructures, and nonlinear fiber-matrix interactions. Conventional approaches based on classical laminate theory and micromechanics, although widely accepted, often require detailed modeling, material calibration, and significant computational effort.

In this study, we present a data-driven methodology that leverages machine learning (ML) algorithms to predict the equivalent shear modulus of AS4/Epoxy composite laminates based on key material design variables. The inputs to the predictive model include the fiber volume fraction (V_f) and a set of five fiber orientation angles representing various lamination schemes. These inputs serve as descriptors of the laminate architecture, while the output is the equivalent shear modulus as derived from a combination of high-fidelity experiments and theoretical estimates.

The theoretical framework is grounded in the generalized Hooke's Law for orthotropic materials, which establishes a relationship between stress and strain via a reduced stiffness matrix. For the specific case of laminated composites, equivalent shear properties were initially approximated using classical micromechanical models that account for the contributions of both fiber and matrix constituents. This hybrid dataset, composed of theoretical and experimental entries, was used to train and validate several supervised ML algorithms, including linear regression, polynomial regression, and ensemble methods.

Among the models tested, Random Forest Regression (RFR) demonstrated superior performance in terms of predictive accuracy and generalization. The RFR model constructs an ensemble of decision trees, each trained on a random subset of the input data and features, and aggregates their predictions to yield a robust estimate of G_xy^eq. Mathematically, the output of the ensemble is given by:

$$\hat{y} = \frac{1}{N}\sum_{k=1}^{N} T_k\,(\boldsymbol{X}) \quad (1)$$

where y^ is the predicted shear modulus, T_k represents the k^{th} decision tree in the forest, N is the number of trees, and X is the input feature vector comprising V_f and the five orientation angles. The model's loss function is defined as the mean squared error between predicted and actual values:

$$\text{MSE} = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2$$

where y_i and $\hat{y}_i$ denote the true and predicted values of the shear modulus for each sample in the dataset, respectively. The model was trained using 80% of the data, while 20% was reserved for testing. Hyperparameter tuning was performed using grid search and 5-fold cross-validation to optimize the number of trees, maximum depth, and minimum samples required for a node split.

Evaluation metrics indicate that the Random Forest Regression model achieves a coefficient of determination (R^2) of 0.923 on the test set, with a mean absolute error (MAE) below 0.15 GPa. The residuals were symmetrically distributed around zero, suggesting minimal bias in the predictions. Feature importance analysis revealed that the fiber volume fraction and the first two fiber orientation angles had the most significant influence on the predicted values, underlining their critical role in tailoring shear performance in composite laminates.

II CONCLUSION

In conclusion, the results demonstrate the viability of machine learning, particularly Random Forest Regression as a predictive tool for estimating the in-plane equivalent shear modulus of fiber-reinforced polymer composites. This approach enables rapid screening of laminate designs without the need for extensive finite element simulations or experimental campaigns. The study offers a foundational step toward integrating AI-driven models into composite material design workflows, with potential extensions to include environmental effects, multiscale modeling, and inverse design optimization.

III REFERENCES

[1] R. M. Jones, *Mechanics of Composite Materials*. CRC Press, 1999.
[2] I. Goodfellow, Y. Bengio, A. Courville, *Deep Learning*, MIT Press, 2016.
[3] T. Hastie, R. Tibshirani, J Friedman, *The Elements of Statistical Learning*, Springer. Bishop, C. M., 2006.
[4] C.M. Bishop, *Pattern Recognition and Machine Learning*, Springer, 2006.

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Real-time simulation of combustion processes using artificial neural networks

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I INTRODUCTION

Internal combustion engines are sources of increased pollution of atmospheric air, water sources and soil with harmful substances. The development of reliable methods for calculating the amount of toxic and harmful substances emitted into the atmosphere in various engine operating modes is important to identify ways to reduce emissions of harmful substances. The rapid prediction of critical internal combustion engine (ICE) parameters is essential for advancing real-time control and development of digital twins. This study investigates the capabilities of artificial neural networks (ANN), trained on high-fidelity simulation data, to accurately and efficiently predict in-cylinder combustion characteristics across varying engine conditions.

II METHODOLOGY

The integration of artificial intelligence (AI), particularly artificial neural networks, in engine modelling offers the potential to accelerate predictive analysis and optimization of ICE performance. Traditional high-fidelity simulations deliver accuracy at the expense of computational cost, often limiting their use for real-time applications. By training ANN surrogates on validated simulation data, it is possible to achieve rapid, accurate predictions that support next-generation engine development and digital twins [1].

An in-house thermodynamic simulation model of a spark-ignition engine is validated against industry-standard software, GT-Suite (1D code) and Ansys Forte (3D code including detailed chemistry and turbulence effects) using consistent engine geometry and fuel properties. The thermodynamic model is shown to predict peak cylinder pressures within ±1.7% of both commercial packages, while overall pressure–crank angle profiles displayed strong agreement. As detailed in [1], the computational time for a single simulation varied significantly across platforms: Ansys Forte required approximately 12 hours per case, and GT-Suite completed each case in about one minute, while the in-house thermodynamic code produce results in only 8 seconds per case. This efficiency made ideally suited for generating large, high-fidelity datasets needed for ANN training.

The developed model is used to systematically vary compression ratio, equivalence ratio and engine speed, generating a comprehensive dataset of peak cylinder pressure and crank angle of peak pressure. This dataset enabled supervised training of an artificial neural network to serve as a surrogate predictor.

Following training, the ANN surrogate exhibited excellent performance across the engine speed range (1000–3000 rpm), with a maximum absolute deviation of +1.35% for peak cylinder pressure and +1.23% for the crank angle of peak pressure, and minimum errors below −0.25% and −1.8%, respectively. Critically, the ANN is able to deliver instantaneous predictions effectively reducing the computation time for a single case from seconds (in-house code), minutes (GT-Suite) or hours (Ansys Forte) to less than one millisecond. Fig. 1 visualizes the close correspondence between ANN and reference simulation data.

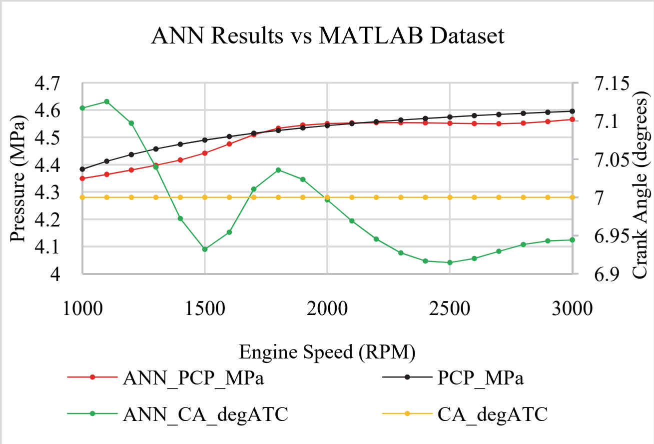

Fig. 1. Comparison of ANN predictions and dataset values for peak cylinder pressure and crank angle of peak pressure over a range of engine speeds.

This extraordinary speed-up makes the ANN surrogate highly suitable for real-time applications, large-scale parametric studies, and rapid optimization, all while retaining the accuracy and trends of the underlying physics-based model.

III CONCLUSION

The results indicate that ANN trained on validated simulation data provide not only highly accurate predictions of key combustion parameters in internal combustion engines but also a transformative increase in computational efficiency. This approach offers substantial advantages for real-time engine control, system optimization, and the practical implementation of digital twins in future ICE research and development. The model developed can potentially be used for the development of comprehensive models capable of predicting not only the combustion process, but also the cycle-to-cycle variability and the knock tendency under various engine operating conditions.

IV REFERENCES

[1] R. Benhadj-Djilali, A. Gulevskis, K. Volkov, *Development and validation of predictive simulation models for internal combustion engines*, Proceedings of the 12th European Combustion Meeting (ECM), Edinburgh, United Kingdom, 8-11 April, 2025.

[2] J.B. Heywood, *Internal Combustion Engine Fundamentals*, McGraw-Hill, 1988.

[3] A.T. Kirkpatrick, *Internal Combustion Engines: Applied Thermosciences*, Wiley, 2021.

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Data-driven multiscale simulation of two-phase flows with non-spherical particles

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I INTRODUCTION

The traditional approach to simulation of particle laden flows is to use the semi-empirical relations for the drag coefficient. Such dependencies usually have the form of a dependence of the drag on the non-dimensional flow quantities. However, semi-empirical relationships for the drag coefficient do not consider the actual shape of particle, unsteady and other effects. Data-driven approach combining fluid dynamics with machine learning technique is applied to better understand, predict and control fluid flows with non-spherical particles in propulsion system.

II METHODOLOGY

Many of the known methods for modelling two-phase flows use models based on calculation of trajectories of sample particles or continuum models, which are convenient for modelling individual phenomena, but are of little use for describing complex transient processes and the resulting multi-scale structures. A significant difference between multi-scale modelling of two-phase flows and other problems is that in this case the model at the microlevel is continuous, and not a model based on the particle method [1].

AI is applied to overcome limitations of traditional numerical methods, especially in terms of computational cost, data-driven modeling and capturing complex physics across scales [2]. Traditional multiphase CFD relies on empirical correlations or semi-theoretical closure models. AI can replace or augment these with neural networks trained on high-fidelity data (DNS). It involves the use of a database that is prepared in advance using calculations performed for the required range of parameters. This improves the accuracy and ensures the stability of calculations, as well as reduces the amount of computer memory for storing the database in a wide range of conditions. In general, the use of a prepared database and high-precision interpolation algorithms significantly reduces the overall calculation time and solves the problem of mismatch, since in this case all dependencies are obtained from calculations of particle evolution at the micro-level.

Mathematical models and computational algorithms cover three scale levels: macroscopic, mesoscopic and microscopic. At the macro level of detail, the flows of solid fuel combustion products are described. At the micro level, the non-spherical shape of agglomerate particles formed during fuel combustion is taken into account [3]. The agglomerate consists of aluminium droplets that have varying amounts of aluminium oxide present on their surface in the form of oxide slaps (Fig. 1). At the mesoscopic level, the interaction of particles of condensed combustion products with the turbulence of the carrier flow is added. The introduction of the mesoscopic level into consideration allows to trace the detailed behaviour of individual particles as they move in the propellant channel, taking into account the specified distributions of velocity and temperature of the gas flow.

The implementation of a multi-scale method involves identifying a number of spatial/temporal levels characteristic of a particular problem. At each of these levels, a coordinate system is selected. The connection between the micro-, meso-, and macro-levels is achieved using a representative volume element (RVE). Selecting an RVE and determining its properties is a non-trivial task. RVE features are determined at the micro-level by the components of micro-stresses and micro-strains. Mesoscopic stresses are determined by averaging over the RVE volume using homogenization methods.

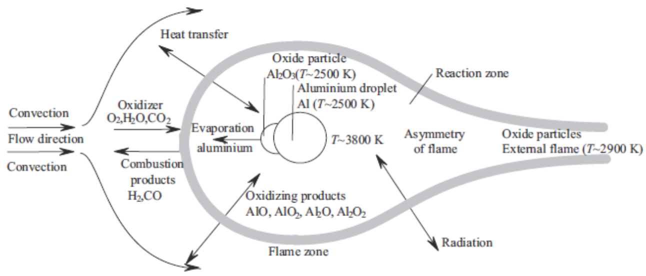

Fig. 1. Physical and chemical transformations of aluminium particles

III CONCLUSION

In order to address challenges pertaining to the investigation of propulsion systems and the modelling of two-phase flows, a multi-scale approach is developed and implemented. The multi-scale approach uses three levels of detail (macro-, meso- and micro-levels). Based on the developed approach, modelling of two-phase flows with metal-oxide agglomerates representing drops of molten metal with metal oxide particles attached to their surface is carried out, which are formed in the charge channel and.

Using AI to predict the drag coefficient is a powerful and growing research area in CFD, especially when dealing with complex geometries and non-spherical particles. Traditional methods to determine drag coefficient rely on experiments, analytical models or high-fidelity simulations (DNS). AI offers a fast, accurate, and generalizable alternative useful in simulation of two-phase flows with non-spherical particles.

IV REFERENCES

[1] D. Drikakis, M. Frank, G. Tabor, M*ultiscale computational fluid dynamics*, Energies, vol. 12, 3272, 2019.

[2] J.M. Gimenez, S.R. Idelsohn, E. Onate, R. Lohner, *Multiscale approach for the numerical simulation of turbulent flows with droplets*, Archives of Computational Methods in Engineering, vol. 28, pp. 4185–4204, 2021.

[3] V.N. Emelyanov, I.V. Teterina, K.N. Volkov, *Dynamics and combustion of single aluminium agglomerate in solid propellant environment*, Acta Astronautica, vol. 176, pp. 682–694, 2020.

Physics-informed neural networks for intelligent railway sensing system assessment

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I INTRODUCTION

The assessment of railway sensing systems is a current challenge in predictive maintenance. However, the complexity of rail loading by passing trains introduces nontrivial modeling difficulties. Ksica presents the smart system for railway monitoring [1]. Machu presents piezoelectric sensing system measured rail strain [2]. These approaches present rail strain data measurement, which contains a lot of information about the passing train as well as about the railway infrastructure condition.

This work presents Physics-Informed Neural Network (PINN) for analyzing measured data from a railway sensing system. For comparison, a standard Neural Network (NN) model was used. To validate the model estimations, a finite element method (FEM) model was employed to simulate train loads at various speeds. The FEM model was also used for training PINN and generating data for the NN.

II MODEL FORMULATION AND SIMULATION SETUP

The locomotive selected for the simulation was the Skoda 58E, and the rail type used was 49E1. The finite element model (FEM) was formulated as a single-layer discrete beam model with elastic supports. This method allows for future extensions to model discontinuities while maintaining low model complexity [3]. Both the rail pad and ballast were modeled using linear spring-damper elements, supporting the rail at sleeper positions. The mass of sleepers was added to the corresponding rail nodes. The train was represented by a moving force vector, which progressed gradually from node to node using a ramp function. The velocity of the model was parameterized in the range of 1 to 10 m/s to evaluate the system's dynamic response under varying operational speeds. Longer rail segments increase the node count, reducing numerical efficiency. Therefore, it is necessary to reduce the problem size using modal decomposition. By applying modal decomposition, the problem is reduced to 70 independent linear systems, which collectively represent the overall system. This approach allows each mode to be normalized independently.

Both PINN and NN models shared the same architecture, consisting of one input layer, three hidden layers, and one output layer. The hyperbolic tangent (Tanh) activation function was used throughout. The loss function for the NN was based solely on the difference in simulated modal coordinates. In contrast, the PINN approach also incorporated information about the first and second derivatives, computed using automatic differentiation.

III RESULTS

The model represents the dynamic behavior of the railway track and enables extrapolation of estimated data to velocity ranges beyond those used during training. Fig.1 presents a comparison between the numerical simulation, NN, and PINN results for the modal component q_{10} at a velocity outside the training range. Noticeable differences are evident among the approaches; the PINN estimation more accurately captures the underlying trends due to its loss function incorporating derivative terms.

In contrast, the NN approach allows for the integration of measured data, which can be highly beneficial in many scenarios. The most robust strategy involves combining both methods to leverage their respective strengths. By tuning both models and identifying hyperparameters that ensure convergence, a more resilient and accurate model can be developed. This hybrid model could then be extended to parametrize additional input variables, such as train type and subgrade condition.

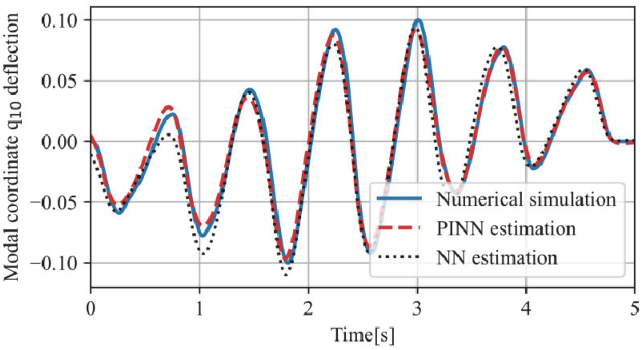

Fig. 1. Estimated deflection by PINN and NN compared with numerical simulation for 11 m/s passing train

IV CONCLUSION

This abstract presents the PINN model designed to estimate train track deformation in response to a passing train. Both the PINN and standard NN models demonstrated the ability to predict responses beyond the range of the training data. Therefore, future research should focus on combining these approaches to leverage the strengths of each. Training shallow NNs capable of representing the complex behavior of large finite element models holds significant potential for real-time signal analysis.

V ACKNOWLEDGEMENT

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VI REFERENCES

[1] F. Ksica, O. Rubes, J. Kovar, J. Chalupa, Z. Hadas, *Smart sensing system for railway monitoring*, Proceedings of the 20th International Conference on Mechatronics - Mechatronika, Pilsen, Czech Republic, pp. 1–6, 2022.
[2] Z. Machu, F. Ksica, Z. Hadas, M. Kratochvilova, J. Podrouzek, *Sensing rail system with piezoelectric elements*, MM Science Journal, vol. 2021, pp. 4230–4237, 2021.
[3] H. Askarinejad, M. Dhanasekar, *A multi-body dynamic model for analysis of localized track responses in vicinity of rail discontinuities*, Int. J. Struct. Stab. Dyn., vol. 16, 1550058, 2015.

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Analysis of the effect of geometric constraints on the optimal synthesis of planar mechanisms conducted by using metaheuristic algorithms

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I INTRODUCTION

Analysis and synthesis of mechanisms form the foundation of the process of designing solutions that must meet the predefined requirements of end users in terms of mechanism motion precision. Thus far, numerous methods that enable the designer to find solutions for various mechanism design problems under corresponding conditions and within corresponding constraints have been developed. Recently, there has been an increasing reliance on new metaheuristic methods [1] that, with the development of artificial intelligence, enable the designer to achieve the desired output faster and more efficiently. However, to achieve a high-quality output, it is essential to conduct a detailed analysis of the mechanism, as the basis of research, that will enable the prescribed motion to be generated. Therefore, special attention in this paper has been devoted to defining the equations with precision and the analysis of the effect of the constraints and conditions that lead to faster convergence to the global optimal solution and the minimal deviation of the output behavior from the desired behavior of the mechanism.

II PROBLEM DESCRIPTION

The second section contains a description of the type of mechanism on which the analysis of the effect of geometric constraints is tested, as well as the definition of the variable parameters, constraints and objective function. The paper considers particularly an analytical representation of the position and arrangement of the mechanism links. Specifically, various frames of reference (coordinate systems) have been constructed to describe the position or the location of the points on the trajectory; the paper also examines the effect of these frames of reference on the output values obtained through the synthesis of the mechanisms. Previous research has established that there is no unique solution to a mechanism. By introducing the constraints concerning the dimensional relationships between the mechanism links, different configurations of mechanisms capable of completing the given task are obtained. Taking this into consideration, it can be concluded that the primary responsibility of the designer is to determine which optimal solution is the best, where 'optimal' does not always encompass the same conditions but depends on the predefined problem.

III OPTIMAL SYNTHESIS OF PLANAR MECHANISMS

For the purpose of mechanism synthesis, the authors have used the metaheuristic algorithm DE-MPA, which has proven to be an excellent tool for the optimal synthesis of planar mechanisms in the authors' experience [2]. For each predefined problem of the planar mechanism, a large number of variables have been optimised. By adopting this approach to analysis and synthesis, the configuration of mechanisms that pass through certain positions of prescribed precision points with high motion accuracy can be obtained.

IV CONCLUSIONS

The content of this paper ought to contribute to the field of mechanism synthesis from the perspective of determining the optimal solution, allowing for the implementation of conditions and constraints that directly affect their practical application. It also lays the foundation for further research on the development of tool that could facilitate the user's access to mechanism synthesis by enabling new, more developed methods and offering a greater number of different optimal solutions.

V REFERENCES

[1] Y-H. Kang, J-W. Lin, W-C. You, *Comparative Study on the Synthesis of Path-Generating Four-Bar Linkages Using Metaheuristic Optimization Algorithms*, Applied Sciences, vol. 12/15, 7368, 2022.

[2] A. Nikitović, N. Dučić, Z. Jeli, R. Bulatović, I. Atanasovska, *Dimensional synthesis of a four-bar linkage for closed-path generation performed by the differential evolution algorithm combined with the marine predators algorithm*, Mechanics Based Design of Structures and Machines, 1–29, 2025.

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AI-based fatigue delamination detection and classification in thermoplastic coupons using C-Scan imaging

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I INTRODUCTION

Fatigue damage detection in composite aircraft structures is crucial due to the harsh operational environments that subject aircraft components to cyclic loads, causing damages such as matrix cracking, delamination, and fiber breakage [1]. Damage if undetected, can compromise structural integrity of aircraft structures. Thermoplastic composites are increasingly used in aerospace structures due to their increased toughness, impact resistance, and recyclability [2]. Among various non-destructive evaluation (NDE) techniques, C-scan ultrasonic imaging plays a vital role by providing high-resolution, through-thickness visualization of internal defects and damage. It is particularly effective in detecting delamination, offering quantitative information on damage size, location, and severity. Moreover, the integration of C-scan imaging into routine inspection protocols enhances the overall effectiveness of structural health monitoring systems in aerospace composite structures.

This work implements machine learning tools to develop an automated, image-based approach aiming to:

i. Quantify delamination as a function of fatigue cycles,
ii. Classify fatigue states from delamination features, and
iii. Predict fatigue life from delamination growth trends.

II METHODOLOGY AND RESULTS

Thirteen coupons made from the thermoplastic PAEK/T700 composite material with a quasi-isotropic lay-up were subjected to interrupted tension-tension fatigue (R = 0.1), with C-scan images collected across intervals of 10,000 cycles. A dataset of 190 C-scan images was created. Fig. 1 shows a representative C-scan image.

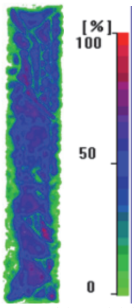

Fig. 1. C-scan image of coupon 10 at 200,000 cycles and colormap.

Each C-scan image was processed using the OpenCV and Pillow image processing libraries. HSV color thresholding was applied to isolate green (delamination) and blue (raw material) regions. Pixels were counted to compute the delamination. Principal Component Analysis (PCA) [3] was performed on delamination percentage metrics to reduce feature dimensionality. KMeans clustering (k=3) was used to group fatigue states into "Early", "Mid", and "Late" stages based on PCA space. A Random Forest model [4] achieved over 98% accuracy in predicting fatigue stage labels. The PCA diagram, shown in Fig. 2, successfully reduces dimensionality while preserving important variance tied to fatigue stage. Moreover, a clear clustering and a gradual transition from Early to Late stage were observed.

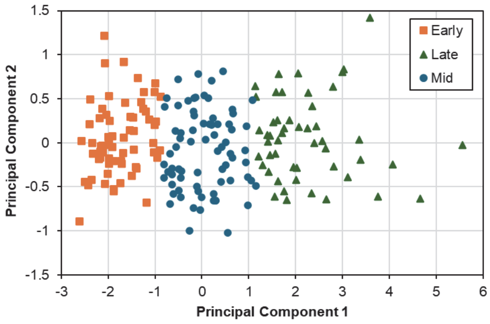

Fig. 2. PCA of delamination features across fatigue cycles.

For each coupon, a linear regression model was also fitted to predict delamination percentage versus fatigue cycles. The slope of the regression line represents the delamination growth rate. A separate regression was then used to model fatigue life as a function of growth rate.

III CONCLUSIONS

It is shown that delamination increases progressively with fatigue cycles and can be quantified accurately using C-scan image segmentation. PCA reveals clear trends in delamination growth and enables effective visualization of fatigue progression. KMeans clustering and Random Forest classification achieved high accuracy in identifying fatigue stages. A strong inverse correlation exists between delamination growth rate and fatigue life, enabling predictive modeling. This integrated image-based pipeline supports non-destructive monitoring and early life prediction for structural health management.

IV REFERENCES

[1] Sp. Pantelakis, K. Tserpes, *Revolutionizing Aircraft Materials and Processes*, Springer, 2020.
[2] N. Tsivouraki, S. Fassois, K. Tserpes, *On the random vibration-based progressive fatigue damage detection and classification for thermoplastic coupons under population and operational uncertainty*, Composite Structures, vol. 349, 118254, 2024.
[3] I.T. Jolliffe, *Principal Component Analysis*, Springer Series in Statistics, 2002.
[4] L. Breiman, *Random Forests*, Machine Learning, vol. 45, pp. 5–32, 2001.

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Predictive fatigue management in commercial aviation using AI tools: a study on the Airbus fleet

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I ABSTRACT

In the highly regulated and safety-critical aviation industry, the structural integrity of aircraft is of paramount importance. Ensuring that airframes and mechanical systems remain within safe operating limits over their entire service life is not only essential to flight safety but also central to the operational efficiency and economic sustainability of commercial airline operations. Among the various degradation mechanisms that affect aircraft systems, mechanical fatigue stands out as one of the most persistent and potentially dangerous. It is characterized by the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. Over thousands of flight cycles, even minute stress variations – such as those experienced during take-off, turbulence, pressurization, and landing – can accumulate, leading to the initiation and propagation of cracks in critical components such as wing root fittings, fuselage frames, engine pylons, and landing gear assemblies.

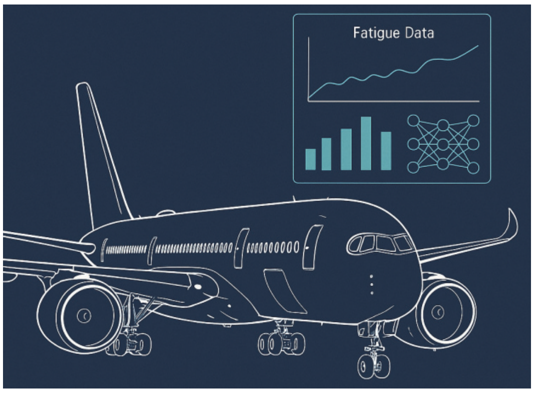

Fig. 1

What makes fatigue particularly insidious is its silent and incremental progression. Often undetectable during early stages without specialized inspection, fatigue can advance until it compromises the load-bearing capacity of a component, increasing the likelihood of catastrophic failure. This risk is compounded by the limitations of traditional maintenance strategies, which often rely on rigid, time-based inspection schedules rather than real-time assessments of component health. Such reactive approaches can lead to either premature maintenance – resulting in unnecessary downtime and cost – or late interventions that may fail to prevent in-service failures. The result is a delicate balance between ensuring safety and minimizing disruptions and cost.

In response to these challenges, this study explores a novel, data-driven approach to fatigue management, illustrating how artificial intelligence (AI) can be harnessed to shift the paradigm from reactive to predictive maintenance. Focusing on a case study involving an Airbus fleet of the fictional airline "Petar Air", the research showcases the deployment of an integrated AI system composed of three complementary technologies: computer vision for image-based crack detection, time-series deep learning models for Remaining Useful Life (RUL) prediction, and natural language processing (NLP) for extracting hidden insights from maintenance logs. Through the fusion of these AI tools, "Petar Air" was able to continuously monitor structural health, anticipate fatigue-related failures well in advance, and optimize maintenance scheduling based on actual component condition.

The result was a marked reduction in fatigue incidents, a decline in unplanned maintenance interventions, and measurable cost savings – demonstrating that intelligent automation not only improves safety but also delivers tangible operational benefits. This case exemplifies how the aviation industry can benefit from integrating AI into safety-critical workflows and sets a precedent for broader adoption across fleets and aircraft types.

II ACKNOWLEDGEMENT

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III REFERENCES

[1] O. Ronneberger, P. Fischer, T. Brox, *U-Net: Convolutional Networks for Biomedical Image Segmentation*, In Medical Image Computing and Computer-Assisted Intervention (MICCAI), pp. 234–241, 2015.
[2] S. Hochreiter, J. Schmidhuber, *Long short-term memory*, Neural Computation, vol. 9/8, pp. 1735–1780, 1997.
[3] J. Devlin, M.-W. Chang, K. Lee, K. Toutanova, *BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding,* In Proceedings of NAACL-HLT 2019, pp. 4171–4186, 2019.
[4] Y. LeCun, Y. Bengio, G. Hinton, *Deep learning*, Nature, 521/7553, pp. 436–444, 2015.
[5] J. Wang, Y. Ma, L. Zhang, R. X. Gao, D. Wu, *Deep learning for smart manufacturing: Methods and applications*, Journal of Manufacturing Systems, vol. 48, pp. 144–156, 2019.
[6] IBM Corporation, *IBM Maximo Application Suite*, https://www.ibm.com/products/maximo, 2021.
[7] R. Zhao, R. Yan, Z. Chen, K. Mao, P. Wang, R. X. Gao, *Deep learning and its applications to machine health monitoring*, Mechanical Systems and Signal Processing, vol. 115, pp. 213–237, 2019.
[8] I.M. Baltruschat, L. Steinmeister, H. Nickisch, M. Grass, A. Saalbach, H. Koesling, *Comparative study of deep learning approaches for detection of abnormalities in chest radiographs*, Radiology: Artificial Intelligence, 2/5, e190080, 2020.

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Application of deep symbolic regression for approximation problems in statistical mechanics

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I INTRODUCTION

In this study, the Deep Symbolic Optimization (DSO) algorithm is used to derive precise approximations for both the extension-force relationship of the Worm-Like Chain (WLC) model and a non-Gaussian probability distribution function for polymer chain length. The latter one is based on Kuhn and Gruen's non-Gaussian statistical theory [1]. Existing approximation methods in literature frequently yield complex equations that deviate from analytical solutions, thus limiting their practical utility. The objective of this work is to identify a set of simple yet accurate approximations that effectively characterize polymer extension models.

The proposed expressions for the WLC extension-force dependency achieve a very small relative error within the relevant variable range, enabling direct application to fit force-extension curves in molecular force spectroscopy experiments. A comparative analysis with recently suggested methods [2] reveals that the DSO-based approach surpasses traditional techniques in accuracy while preserving equation simplicity. Furthermore, we introduce novel approximations for the non-Gaussian probability distribution function of polymer chain length [3], expanding its applicability across a wider spectrum of chain segment numbers. This enhancement allows for more precise modeling of the behavior of polymers.

II CONCLUSION

In conclusion, this study demonstrates the effectiveness of the Deep Symbolic Optimization (DSO) algorithm in deriving concise and accurate analytical approximations for complex polymer models. The improved accuracy and simplicity of the proposed expressions make them suitable for experimental applications where computation resources and time are limited. These results underscore the potential of symbolic regression techniques in advancing the modeling capabilities for polymers and rubbers.

III ACKNOWLEDGEMENT

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IV REFERENCES

[1] W. Kuhn, F. Grün, *Beziehungen zwischen elastischen Konstanten und Dehnungsdoppelbrechung hochelastischer Stoffe*, Kolloid-Zeitschrift, vol. 101, pp. 248-271, 1942.
[2] R. Petrosyan, *Improved approximations for some polymer extension models*, Rheologica Acta, vol. 56, pp. 21-26, 2017.
[3] E. Darabi, M. Hillgärtner, M. Itskov, *An amended approximation of the non-Gaussian probability distribution function*, Mathematics and Mechanics of Solids, vol. 28/2, pp. 521-532, 2023.

EUROPEAN MECHANICS SOCIETY

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Realistic 3D design and modelling of human leg and foot for laboratory testing and FEM simulation

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I INTRODUCTION

The goal was to be that a human foot and the lower part of the be reproduced as realistically as possible to run clinical laboratory tests. After the 3D design and the 3D scanning of the tissue had been made, the 3D printer with the typically applied bone replacement material, "bone cement," was to be used for the reproduction of the bone structure of the leg and foot. When the printing process had been finished, the human tissue was to be reproduced, for which printing or casting methods could be applied. When the reproduction was ready, the laboratory tests were to be conducted.

II APPLICABLE METHODS AND MATERIALS

The procedure relies on a complex CT scanner, which maps the person's bone structure and displays tissues in the images. As a CT device, it enables 3D image analysis and allows for precise dimensional assessments. Additionally, we have a 3D scanner capable of generating a 3D mesh of a person's soft tissue outer surface, composed of triangles, which serves as a starting point in the design software. Using the information generated so far, the design software can combine the resulting surfaces to produce a 3D reconstruction that includes both bone structures and soft tissues. Once the complete reconstruction model has been finished, it will be used for 3D printing after the slicing and preliminary model preparation steps have been completed for body part reconstruction. Initially, the bone structure will be printed by a 3D printer located in the biomechanical laboratory of the University of Debrecen, and bone cement will be utilized as the raw material. After the complex assembly of the 3D-printed bone structure has been finalized, the layer-by-layer preparation of the soft tissues can be initiated. This can be accomplished either through 3D printing or by form-filling casting with a two-component material. Upon completion of the reconstruction process, both the finite element method (FEM) model and simulations can be created. Simultaneously, laboratory tests can be performed to obtain more accurate results for various applications.

III RESULTS

The remodeling process will have been completed with the preparation of the 3D foot model, and the remodeling will have reached its conclusion through 3D printing.

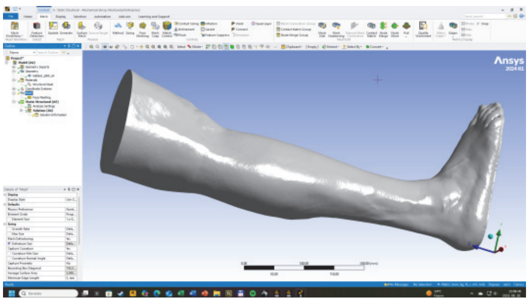

Fig. 1. Scanned model for meshing

IV CONCLUSION

As a result of these processes and tests having been endured with success, information, burdened by its complexity, becomes available concerning the behavior of the bone structure's stress level gradient and the responses of tissue. Moreover, intricate and overwhelming data about the relentless stress across various segments of the human leg and foot shall be optimised. Thus, the form and other oppressive parameters of the final product may be refined to impose greater comfort upon those who wear and use it.

V ACKNOWLEDGEMENT

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VI REFERENCES

[1] F. Nimmervoll, U. Çakmak, M. Reiter, *Studying Force Patterns in an Alpine Ski Boot and Their Relation to Riding Styles and Falling Mechanisms*, Frontiers in Sports and Active Living, vol. 3, 2021.

[2] M. Kainz, S. Haudum, E. Guillén, O. Brüggemann, R. Höller, H. Frommwald, T. Dehne, M. Sittinger, D. Tupe, Z. Major, G. Stubauer, T. Griesser, I Teasdale, *3D Inkjet Printing of Biomaterials with Solvent-Free, Thiol-Yne-Based Photocurable Inks*, in Macromolecular Materials and Engineering, Wiley-VCH GmbH, vol. 309/5, 2024.

[3] D. Laresser, M. Miron, M. Kracalik, F. Baudach, Z. Major, *Analysis of the Rotation Bending Test Method and Characterization of Unidirectional Carbon Fiber-Reinforced Polycarbonate Tapes at Processing Temperatures*, in Polymers, vol. 16/3, 2024.

[4] P. Stelzer, B. Plank, J. Maurer, Z. Major, *Process-induced failure mode transition of compression molded discontinuous carbon fiber composites: From coupon to component level*, in Composites Part B: Engineering, vol. 242, 2022.

[5] P. Stelzer, B. Plank, Z. Major, *Mesostructural simulation of discontinuous prepreg platelet based carbon fibre sheet moulding compounds informed by X-ray computed tomography*, in Nondestructive Testing and Evaluation, 2020.

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Finite element analysis and machine learning based design of latticed hip implant stem

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I INTRODUCTION

Due to the increase in hip implant surgeries over the last few decades, the design and manufacturing methods have also been improving in order to create the optimal design that suits each individual patient and minimizes the need for revision surgery.

This study investigates the design of hip implant stem from titanium alloy and designed with lattice structures, furthermore produced by additive manufacturing. A surrogate model of the latticed implant stem was developed to replace time-consuming finite element calculations of the very complicated structure. Machine learning was used to predict the mechanical response of the implant stems with different design parameters. In the knowledge of the mechanical properties, the surgeon has the information which design fits the best to the patient.

II MATERIALS AND METHODS

Due to its excellent features, Ti6Al4V is commonly used for lattice structure manufacturing because it is a lightweight material with good specific mechanical properties and high corrosion resistance [1].
For the validation of the initial finite element surrogate model implants were additively manufactured for executing laboratory compression tests. The manufacturing of the implant stem was performed with EOS M290 (Electro Optical System, Munich, Germany) 3D printer installed and operated at the University of Debrecen.

There are numerous load models for hip implants. In this research the Bergmann's standard was followed considering the stumbling case [2]. For a patient with 60 kg the loading case is introduced in Fig. 1.

III RESULTS AND DISCUSSION

A series of finite element calculation was made for different design parameters of the lattice design (strut thickness, strut length, shell thickness) and the for certain patient weights using the surrogate model. The mechanical properties (total deformation, maximum stress, total strain energy) were than collected. These results were the input of the machine learning procedure to predict the material response for a large number of variation of implant stem designs.

IV CONCLUSIONS

A database for additively manufactured Ti6Al4V lattice-structured hip implant stem was established considering three lattice design parameters and also the patient's weight. The procedure was based on the finite element analysis and machine learning. This database provides information about the mechanical response of the implant by simulating the implant working conditions. The results of the current research give the possibility to the surgeons to select a patient-specific solution.

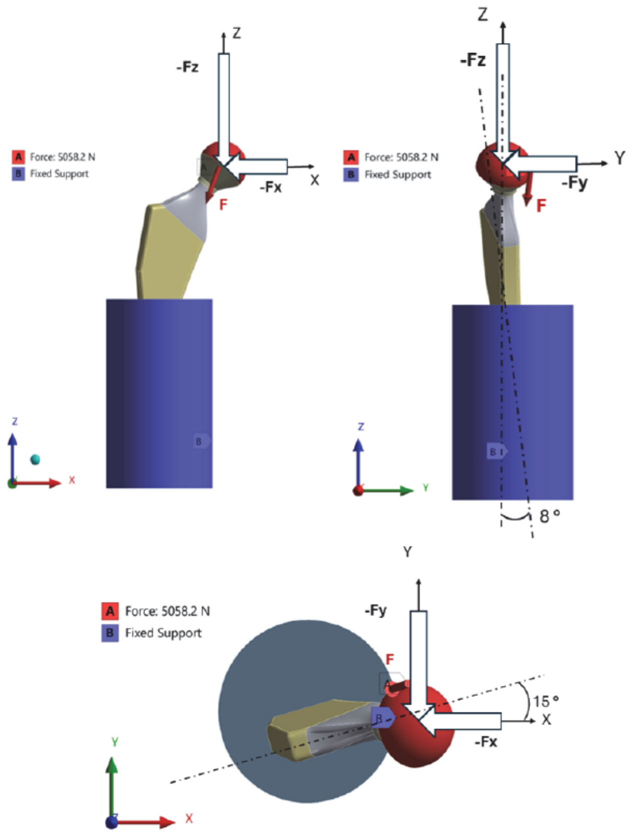

Fig. 1. Loading case for a patient with 60 kg

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VI REFERENCES

[1] F. Bartolomeu et al., *Mechanical Properties of Ti6Al4V Fabricated by Laser Powder Bed Fusion: A Review Focused on the Processing and Microstructural Parameters Influence on the Final Properties*, 2022.
[2] G. Bergmann et al., *Realistic loads for testing hip implants*, Biomed. Mater. Eng., vol. 20/2, pp. 65–75, 2010.

EUROPEAN MECHANICS SOCIETY

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Application of artificial neural networks for aerodynamic coefficient prediction of a CST parameterized airfoil

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I INTRODUCTION

Aerodynamic optimization of airfoil geometries utilizing methods such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) has become a standard procedure in recent years [1]. These optimization routines typically involve a parametric description of the geometry and require repeated aerodynamic evaluations. Since these numerical analyses (especially CFD) can be computationally very expensive, Artificial Neural Networks (ANN) have increasingly been adopted to provide fast and accurate surrogate models for aerodynamic analysis [2,3].

II METHODOLOGY

Class Shape Transformation (CST) [4] was used to parameterize the airfoil geometry using 6 shape parameters: 3 for the upper (w_{1u}, w_{2u}, w_{3u}) and 3 for the lower airfoil surface (w_{1l}, w_{2l}, w_{3l}). While more parameters could allow greater shape complexity, a reduced set was to limit the total number of airfoil configurations needed for training. In addition to the specified parameter ranges (Table 1.), geometric feasibility constraints were imposed to eliminate unrealistic airfoil shapes.

Aerodynamic analyses were performed using XFOIL, a panel method solver often used in optimization procedures due to its computational efficiency. Simulations across a range of Reynolds numbers and angles-of-attack to obtain the corresponding lift (Cl), drag (Cd) and moment (Cm) coefficients were performed.

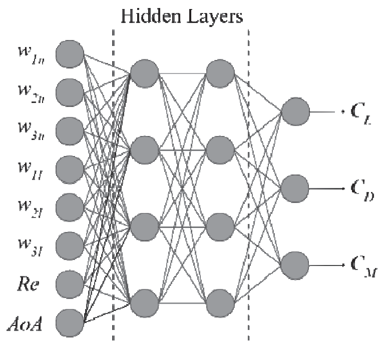

Fig. 1. Feed forward ANN architecture

A feed forward ANN with two hidden layers containing 20 and 10 neurons respectively was trained to learn the nonlinear mapping between the input parameters and aerodynamic coefficients (Fig.1). The ANN was trained using a supervised learning from the obtained dataset via a regression type network (fitnet in Matlab). The Levenberg-Marquardt optimization algorithm with automatic validation was used for the training while all inputs and outputs were normalized prior to ensure better convergence during backpropagation. ANN with different number of layers and neurons, optimization algorithms etc. were tested as well, to compare the accuracy and check for over/underfitting. For the training, dataset with more than 20,000 different airfoils and more than 1 million data points was used.

Table 1. Input variables for the ANN training dataset:

Input Variable	Domain
w_{1u}, w_{2u}, w_{3u}	(0.1:0.5), (0:0.6), (0.0:0.4)
w_{1l}, w_{2l}, w_{3l}	(0.1:0.5), (0.0:0.6), (0.0:0.4)
Re	(100k, 300k, 500k, 1M)
A-o-A	(-5:15)

III RESULTS

The performance of the ANN was assessed using the Mean Squared Error (MSE) and the correlation between predicted and reference values. An MSE of 0.00202 was achieved, indicating strong predictive capability. Furthermore, the ANN predictions were compared with XFOIL results for test cases not included in the training set. The comparisons showed good agreement in most cases, demonstrating the generalization ability of the model.

IV CONCLUSION

ANN were developed to model for relationship between the aerodynamic coefficients and CST parameters of a parameterized airfoil geometry. The ANN was able to capture complex nonlinear interactions between shape parameters, Re numbers, angle of attack and aerodynamic coefficients. The resulting model provides a rapid evaluation tool suitable for use in preliminary design and optimization studies. For future work, high-fidelity CFD data will be incorporated to improve prediction accuracy, especially for configurations where XFOIL fails to converge.

V ACKNOWLEDGEMENT

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VI REFERENCES

[1] T. Ivanov, A. Simonović, N. Petrović, V. Fotev, I. Kostić, *Influence of selected turbulence model on the optimization of a Class-Shape Transformation parameterized*, Thermal Science, vol. 21/3, pp. 737-744, 2017.

[2] L. Jichao, D. Xiaosong, M. Joaquim, *Machine Learning in Aerodynamic Shape Optimization*, Progress in Aerospace Sciences, vol. 134, pp. 1-50, 2022.

[3] M.S. Khurana, H. Winarto, A.K. Sinha, *Application of Swarm Approach and Artificial Neural Networks for Airfoil Shape Optimization*, 12th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Vitoria, Canada, pp. 1-15, 2008.

[4] B. Kulfan, *Universal Parametric Geometry Representation Method*, Journal of Aircraft, vol. 45/1, pp. 142-158, 2008.

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

AI-based finger counting in viscous fingering dynamics

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I INTRODUCTION

Viscous fingering, a hydrodynamic instability occurring when a less viscous fluid displaces a more viscous one, forms complex, branched patterns in confined geometries such as Hele-Shaw cells. Accurate quantification of these fingers – particularly their number and evolution over time – is critical for understanding pattern formation, fluid interface dynamics, and for validating theoretical and numerical models. In this work, we present an AI-based approach for real-time finger counting in a flat, rigid-walled Hele-Shaw cell. By applying convolutional neural network (CNN) trained on experimental image datasets, we demonstrate reliable detection and temporal tracking of viscous fingers in radial geometries. Our method enables automatic feature extraction and pattern recognition, eliminating the need for manual frame-by-frame inspection, which is time-consuming and prone to human error.

II AUTOMATIC FINGER COUNTING USING CNN AND PEAK DETECTION FROM IMAGEJ IMAGES

Viscous fingering in a radial Hele-Shaw cell produces complex, unstable interfaces that form finger-like protrusions. Quantifying the number of fingers as a function of time, $N(t)$, is essential for understanding the dynamics of interfacial instabilities and validating theoretical models. In this work, we present a method that combines classical image processing with deep learning, using images obtained from the ImageJ software to determine the number of fingers automatically and accurately.

The experimental setup involves radial injection of air into a viscous fluid (glycerol) between two parallel plates. Videos of the evolving interface are processed using ImageJ, where individual frames are extracted as grayscale image sequences. Each frame represents a time step in the evolution of the fingering pattern. The images are preprocessed – contrast-enhanced, cropped, and resized – and then analyzed using a two-step method: radial peak detection and convolutional neural network (CNN) validation.

First, each binary image is transformed from Cartesian to polar coordinates centered on the injection point. The radial profile of the interface, $R(\theta)$, is extracted by identifying the outermost boundary pixel for each angle θ. Local maxima in $R(\theta)$, corresponding to finger tips, are identified using standard peak detection algorithms. The number of peaks gives an initial estimate of the finger count, $N_1(t)$, but this method can be sensitive to merging fingers, and interface roughness.

To correct for these issues, a CNN is trained to predict the number of fingers directly from the original images. The CNN takes a preprocessed image as input and outputs a scalar prediction $N_{CNN}(t)$. The network is trained using a dataset of manually labeled frames, with a mean squared error loss function. The final count is determined by either correcting the raw count with the CNN output or combining both using a weighted average.

This hybrid approach ensures robustness across various image qualities and fluid regimes, significantly improving the accuracy and reliability of finger counting in experimental studies. The method enables efficient, automated analysis of fingering dynamics and is adaptable to other radial pattern-forming systems.

III CONCLUSION

We presented a reliable method for automatic finger counting in radial viscous fingering experiments using ImageJ-based image processing combined with a convolutional neural network. The approach begins with peak detection on the polar-transformed interface to estimate finger count and refines this using a CNN trained on labeled experimental images. This hybrid method improves accuracy by correcting for merging fingers, noise, and imaging artifacts. It eliminates manual counting, enables high-throughput analysis, and adapts well to different image qualities and fluid regimes. The technique is generalizable to other pattern-forming systems and offers a valuable tool for experimental studies of fluid instabilities. Future improvements may include temporal modeling to track finger dynamics and extension to non-radial geometries.

IV ACKNOWLEDGEMENT

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V REFERENCES

[1] P.G. Saffman, G.I. Taylor, *The penetration of a fluid into a porous medium or Hele-Shaw cell containing a more viscous fluid*, Proceedings of the Royal Society of London, Series A. Mathematical and Physical Sciences, vol. 245/1242, pp. 312–329, 1958.

[2] G.M. Homsy, *Viscous fingering in porous media*, Annual Review of Fluid Mechanics, vol. 19/1, pp. 271–311, 1987.

[3] O. Ronneberger, P. Fisher, T. Bronx, *U-Net: Convolutional Networks for Biomedical Image Segmentation*, Medical Image Computing and Computer-Assisted Intervention (MICCAI), 9351, pp. 234–241, 2015.

[4] W. Bai, W. Zhang, M. Bai, *Deep learning in fluid mechanics: A review*, Mathematics and Computers in Simulation, vol. 187, pp. 429–451, 2021.

[5] A. Huerre, V. Miralles, M.-C. Jullien, *Finger width selection in radial viscous fingering*, Physical Review E, vol. 90/3, 033011, 2014.

Foundation models in engineering & hard sciences

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I INTRODUCTION

Artificial intelligence (AI) is increasingly central to research in engineering and the hard sciences, where it enables new approaches to simulation, prediction, and data analysis. At the core of this transformation are **foundation models** – large, pretrained systems designed for reuse across many tasks – which are rapidly replacing narrow, task-specific tools [1]. Their adoption raises key questions about who uses them, how they are used, and which model characteristics drive uptake. Understanding these dynamics is essential for evaluating the evolving scientific method, the accessibility of AI infrastructure, and the reproducibility of findings in high-stakes domains like physics, materials science, and engineering. Yet, despite their growing importance, the diffusion and characteristics of foundation models in these disciplines remain poorly mapped [2]; this study provides the first large-scale empirical analysis of how such models are adopted across engineering and the hard sciences.

II METHODS AND RESULTS

To systematically understand the adoption of foundation models in engineering and the hard sciences, we developed the *FutureTech AI in Science Database*, a large-scale resource linking pretrained AI foundation models to scientific publications that cite or apply them [3]. Our database includes 1,942 foundation models released before the end of 2024, curated from public repositories, institutional leaderboards, and research literature. For each model, we recorded metadata including origin, number of trainable parameters, and openness classification (open, restricted-access, or unreleased). Open models are defined by the availability of downloadable and modifiable weights, while restricted-access models are only usable via API, and unreleased models lack any public deployment. These metadata allow for detailed tracking of model dissemination, accessibility, and influence.

To identify scientific usage, we queried the full Semantic Scholar Academic Graph and S2ORC full-text corpus for citations or mentions of these models [4], capturing 269,000 unique papers with explicit references. Each mention was contextualized with a three-sentence window around the model citation and classified by intent into one of three categories: (1) background citation, (2) usage without customization, and (3) customization through fine-tuning or architectural modification. This classification was performed using OpenAI's GPT-4.1-mini model [5], which achieved high accuracy and enabled distinction between superficial mentions and substantive methodological applications. Among models that were substantively used or customized, 61% of instances involved open-weight models, 35% lacked documented access information, and only 4% involved closed or restricted-access models.

The resulting dataset reveals strong adoption patterns across engineering and hard science domains (Fig. 1). Among all cited models, five dominate methodological usage: ResNet-152 (ImageNet), ResNet-110 (CIFAR-10), VGG16, AlexNet, and Faster R-CNN with a VGG19 backbone. These are all vision models, widely used for tasks such as image classification, object detection, and feature extraction, particularly in mechanical engineering, biomedical imaging, and materials science. Their continued prevalence, despite newer transformer-based alternatives, reflects their accessibility, low computational overhead, and deep integration into existing toolchains and educational pipelines. The most frequently used models tend to fall within the 10–100 million parameter range, followed by those with 1–10 million, and then 100 million to 1 billion parameters – highlighting a practical preference for mid-scale models that balance performance with usability (Fig. 1).

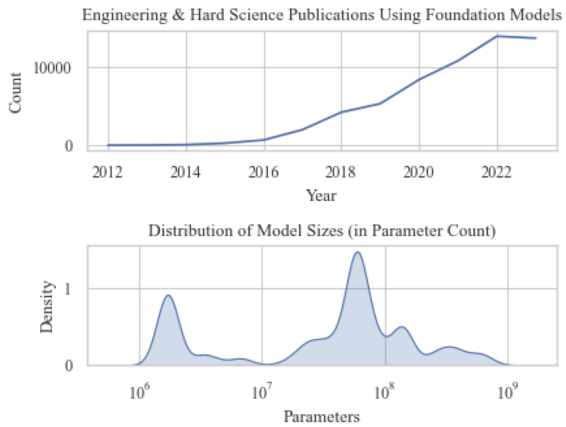

Fig. 1. Trends of foundation model use: over time and model scale.

III CONCLUSION

Our results reveal a steep, year-on-year surge in foundation-model use across engineering and the hard sciences, led by well-established vision architectures and smaller contingents of language and multimodal systems, with uptake strongest for mid-scale models (10–100 M parameters), then smaller, and finally very large models. By mapping these trends, and showing that openness, stability, and community familiarity outweigh raw size or novelty, we supply an empirical baseline for infrastructure, funding, and policy choices aimed at equitable, reproducible AI-enabled discovery.

IV ACKNOWLEDGEMENT

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V REFERENCES

[1] R. Bommasani et al., *On the opportunities and risks of foundation models*, arXiv preprint arXiv:2108.07258 , 2021.
[2] L. Cao, *AI science and engineering: a new field*, IEEE Intelligent Systems, vol. 37/1, pp. 3-13, 2022.
[3] A. Trišović et al., *The AI Frontier: Transformative Role of Foundation Models Across Scientific Disciplines,* Ongoing work, 2025.
[4] R. Kinney et al., *The semantic scholar open data platform*, arXiv preprint arXiv: 2301.10140, 2023.
[5] A. Hurst et al., *Gpt-4o system card*, arXiv preprint arXiv: 2410.21276, 2024.

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through
Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

AI-Driven Multi-Objective Optimization of a Planetary Gearbox: a genetic algorithm and surrogate models approach

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I ABSTRACT

The optimization of planetary gearboxes remains a challenging task due to the inherently complex interactions between geometric parameters, loading conditions, and performance constraints. In this paper, we present a methodology that integrates genetic algorithms (GAs) [1] with artificial intelligence (AI)-driven surrogate modeling to minimize the weight of a single-stage planetary gearbox while satisfying critical design constraints. Specifically, the constraints are formulated based on allowable values for root stress and pitting resistance, in accordance with ISO standards for gear design [2]. To address the computational expense of determining the efficiency of a gearbox, we propose a deep neural network (DNN)-based surrogate model trained on a comprehensive dataset derived from previous analyses [3]. The trained DNN enables rapid and accurate prediction of efficiency, allowing its integration directly into the GA-based optimization loop. The resulting multi-objective optimization framework, combining evolutionary search techniques with AI-enhanced predictive models, demonstrates the ability to produce lightweight gearbox designs that meet stress constraints and maintain high efficiency.

II CONCLUSION

This study shows that it is possible to use genetic algorithms and deep neural network-based surrogate models together to optimize a single-stage planetary gearbox for multiple objectives. The proposed framework solves the main problems of high computational cost and enforcing constraints, making it possible to create high-quality, lightweight gearbox designs that meet both mechanical integrity and efficiency standards. A DNN surrogate model for gearbox efficiency was made to mimic the semi-analytical model previously developed by the authors. This significantly accelerated the optimization process, making it feasible to evaluate large populations across many generations in the GA framework. The method shown here shows that DNNs could be useful for approximating complex engineering models, especially when direct simulation is too expensive in terms of computing power.

This hybrid evolutionary-AI framework demonstrates rapid convergence to lightweight planetary gearbox designs that meet both structural and efficiency requirements. The findings represent a step toward future research into generalization across power-dense gearbox applications and effective data-driven design tools for mechanical transmission systems.

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IV REFERENCES

[1] D.E. Goldberg, *Genetic Algorithms in Search, Optimization, and Machine Learning*, Addison-Wesley, 1989.
[2] ISO 6336: *Calculation of load capacity of spur and helical gears*.
[3] I Goodfellow, Y. Bengio, A. Courville, *Deep Learning*, MIT Press, 2016.
[4] M. Sedak, B. Rosić, *Multi-Objective Optimization of Planetary Gearbox with Adaptive Hybrid Particle Swarm Differential Evolution Algorithm*, Applied Sciences, vol. 11/3, 1107, 2021.

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Development of an internal pressure test setup for multi-mode monotonic and cyclic testing of polymers

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I INTRODUCTION

The mechanical performance of polymeric materials under realistic service conditions is a growing focus in development of components which are under pressure during operation such as future hydrogen systems [1]. To better realize real-life loading conditions, a new specimen geometry and testing fixture had to be developed, to support mechanical multi-mode testing while under the influence of internal pressurization. This study targets the development, testing and evaluation of sintered thermoplastic Polyurethane (TPU) and Polyamide12 (PA12) specimens as well as the clamping device for a simple test setup for normal testing machines respectively. The primary goal is to enable monotonic and cyclic testing under axial and torsional loads, with and without elevated internal pressure.

II METHODS

The test setup allows for monotonic and cyclic axial-torsional loading under controlled internal pressure with specimen geometries that are compatible with standard tensile and axial-torsional machines. Experimental characterization at both ambient and elevated pressures is possible. Examined specimens are fabricated using selective laser sintering (SLS) for PA12 and TPU. Additional specimens of special molded polyurethane rubber are currently milled. Additionally, from the molded TPU cylinders, 3D-printing filament will be cut using a lathe subsequently and printed via Filament Deposition Modeling (FDM). Preliminary pressurization was performed using dried pressurized air. Initial testing results indicate an influence of internal pressurization on mechanic loading capability and longevity of the specimens. Under tensile loading and elevated internal pressure, TPU showed greater deformation at lower loads. The test results additionally indicate an increased displacement at the moment of material failure. In Fig.2, the Force-Displacement-Diagram is illustrated. The red line represents the specimen at increased internal pressure of 4 bar. The black curve shows the specimen behavior at ambient pressure. Cyclic testing also revealed a pronounced increase in the fatigue behavior, compared to the unpressurized specimens under certain loading conditions [2]. PA12 offers more linear material response and better dimensional stability under both ambient and elevated pressure conditions.

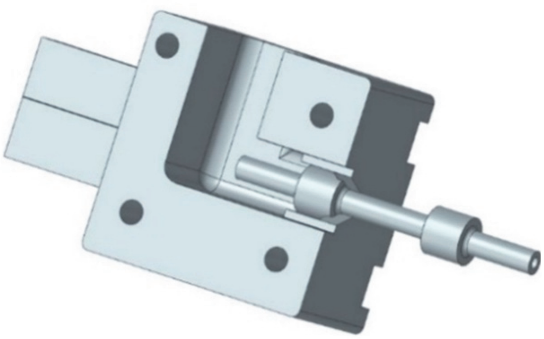

Fig. 1. Specimen for axial torsional testing and part of clamping device for standard tensile testing clamps.

The developed fixture for this type of specimen allows for fast and easy specimen mounting as well as specimen change. The specimens are securely fastened for tensile, compression and rotational loading conditions and allow for a quick connection of pressure hoses and adapters for the pressurization. These insights are intended to guide future testing under the influence of hydrogen or other gases and support the design of polymeric components subjected to mechanical and pressure induced loading [3].

In Fig.1, the 3D CAD model of the test specimen secured inside the clamping device is shown, where the top of the setup has been removed for visualization purposes.

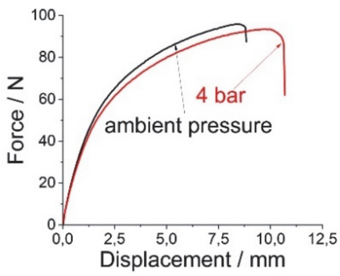

Fig. 2. Comparison of tensile stress-strain behavior for a thermoplastic Polyurethane material with and without internal pressurization.

III CONCLUSION

A test setup was successfully developed to characterize polymeric specimens produced both via additive manufacturing, as well as specimens turned on a lathe. The specimen and testing jig allow for repeatable and precise monotonic and cyclic multi-mode axial and torsional testing at variable internal pressures. The test setup was specifically engineered for compatibility with standard tensile testing machine grips. The differences observed between PA12 and TPU highlight the importance of selection of the right material for applications in pressurized environments. The test setup developed in this work provides a robust baseline for future testing in various environments, such as compressed hydrogen and other gases or mediums.

IV REFERENCES

[1] H.U. Khalid, M. Che Ismail, N. Nosbi, *Permeation Damage of Polymer Liner in Oil and Gas Pipelines: A Review*, Polymers, vol. 12/10, 2307, 2020.

[2] F. Rouhani, J. Wurster Pazin, B.A. Young, Q., Liu, S.S. Velankar, *Inelastic effects in bulge formation of inflated polymer tubes*, Soft Matter, vol. 20/19, pp. 4152–4164, 2024.

[3] P. Krishnan, M.S. Abdul Majid, A.J. Yi, M. Afendi, S. Yaacob, A.G. Gibson, *An automated portable multiaxial pressure test rig for qualifications of glass/epoxy composite pipes*, Science and Engineering of Composite Materials, vol. 25/2 pp. 243–252, 2018.

EUROPEAN MECHANICS SOCIETY

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Evaluation of the compressive properties of different 3D-printed Ti6Al4V lattice structures

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I INTRODUCTION

Additive manufacturing technology, initially used only for the production of geometric prototypes, is now increasingly being used for the manufacture of finished products and customised tools. Accordingly, the models produced must meet the dimensional accuracy, material, and mechanical requirements of the end product in a number of areas (e.g., aerospace, automotive, dentistry, and medical applications).

Lattice 3D-printed materials are transforming musculoskeletal surgery by enabling the creation of lightweight, porous, and patient-specific implants that enhance bone regeneration and mechanical performance. These structures replicate the natural architecture of bone, promoting osseointegration while minimizing stress shielding, a common issue with traditional solid implants. In bone defect repair, such as those caused by trauma or tumor resection, lattice implants can be customized to match the porosity and stiffness of the surrounding bone, ensuring optimal load distribution and healing. For joint reconstruction, particularly in hip arthroplasty, porous acetabular cups made with lattice designs improve biological fixation, reducing the risk of implant loosening over time.

The objective of the present research project was to evaluate the effective compressive modulus of different shaped lattice structures that could be used in custom-made implants.

II MATERIALS AND METHODS

The creation of a compression test specimen model was undertaken in 3-matic anatomical CAD design software (Materialise, Leuven, Belgium) for the purpose of material testing. The clamping part of the model consists of a solid cylinder with a diameter of 9 mm and a height of 35 mm, while the head part is comprised of a cylinder with a height of 5 mm and a diameter of 10 mm. The construction of the head part was executed from the space lattice characteristic of the test specimen.

The lattice structured specimens were printed using an EOS M290 (EOS GmbH, Krailling, Germany) DMLS metal 3D printer from Ti6Al4V titanium alloy, which is a potential raw material for 3D-printable implants.

The compression tests were performed on a solid and six distinct grid types (stochastic, cylindrical, cubic, Shwarz-D, Shwarz-P, tetrahedron), with five samples per group. The measurements were obtained with a speed of 1 mm/min using an Instron 8874 (Instron, Norwood, Massachusetts, USA) biaxial material testing machine, which is available at the Biomechanical Material Testing Laboratory, University of Debrecen.

III RESULTS AND CONCLUSION

The findings of the measurements demonstrated among other results a strong correlation between the porosity and the effective compressive modulus with a correlation coefficient of 0.80 (Fig 1.).

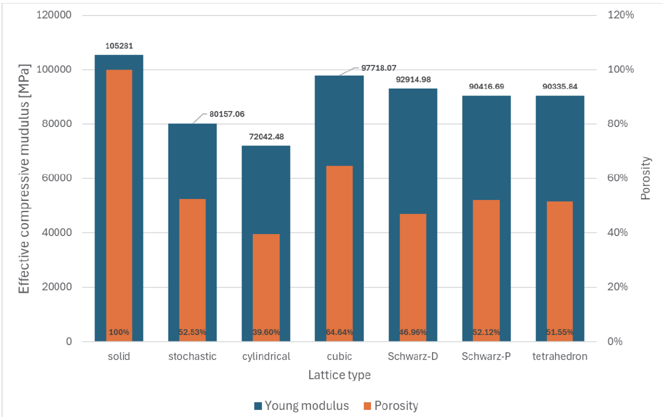

Fig. 1. The effective modulus and the porosity for the different lattice types

IV ACKNOWLEDGEMENT

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V REFERENCES

[1] Á.É. Kovács et al., *Comparative Analysis of Bone Ingrowth in 3D-Printed Titanium Lattice Structures with Different Patterns*, Materials, vol. 20, pp. 3861, 2023.

[2] L.Y. Chen et al., "*dditive manufacturing of metallic lattice structures: Unconstrained design, accurate fabrication, fascinated performances, and challenges*, Mater. Sci. Eng., vol. 146, pp. 100648, 2021.

[3] Y. Zhao et al., *Impact of density on the mechanical performance of Ti-6Al-4V lattices fabricated by additive manufacturing*, Mater. Lett., vol. 306, pp. 130-134, 2022.

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Stochastic reconstruction and simulation of heterophasic microstructures using random field models

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I INTRODUCTION

Heterophasic material blends, such as polymer composites, exhibit complex microstructures that critically affect macroscopic properties. Simulating such systems requires statistically realistic 3D representations of their internal morphology. This work proposes a computational pipeline using Gaussian Random Fields (GRFs) and Fast Fourier Transform (FFT) methods to reconstruct and analyze representative volume elements (RVEs) for mechanical simulations [1]. Finite-element method (FE) simulations are conducted using Digimat-FE with an FFT solver to efficiently estimate the effective quasistatic properties of the composite based on the phase morphology and volume fractions.

II METHODS

We generate 3D microstructures using stationary GRFs with Matérn covariance kernels [2] to control the spatial correlation and morphology of inclusions:

$$C(r) = \frac{2^{1-\nu}}{\Gamma(\nu)}\left(\frac{\sqrt{2\nu}r}{l}\right)^{\nu} K_{\nu}\left(\frac{\sqrt{2\nu}r}{l}\right) \quad (1)$$

where C(r) is the covariance function, Γ is the gamma function [3], ν the smoothness, l the correlation length, and $K\nu$ the modified Bessel function of the second kind [4]. FFT-based spectral methods are employed for efficient field generation, exploiting the periodic boundary conditions to solve in the frequency domain. The field is thresholded to match a target inclusion volume fraction ϕ, producing a binary segmentation of matrix and inclusion phases. The generated voxel models (up to 256^3 resolution) are simulated using FFT-based solvers such as Digimat-FE under quasi-static strain-controlled loading. A three-phase microstructure system with inclusion volume fractions ranging from 20% to 35% is investigated. The matrix phase is modeled as elastoplastic, while inclusions represent linear elastic phases. Transversely isotropic scaling of correlation kernels mimics anisotropy due to processing. In Fig. 1, the microstructure morphologies of examined materials are shown together with their 3D stochastic reconstructions.

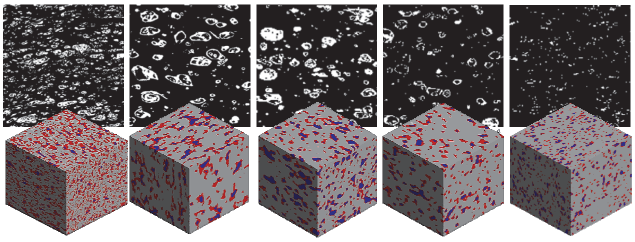
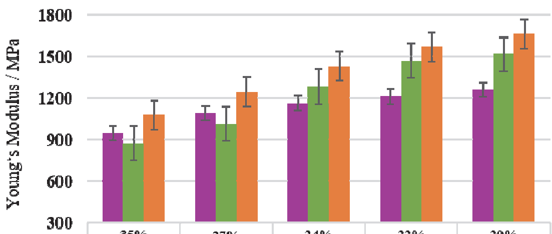


Fig. 1. 3D-Stochastic reconstructions of reference materials with 35%, 27%, 24%, 22%, 20% soft elastic interphase respectively.

III RESULTS AND DISCUSSION

The reconstructed 3D RVEs successfully capture key morphological descriptors, such as phase distribution, anisotropy, and particle connectivity. Full-field simulations using Digimat-FE reveal the stress–strain behavior of examined materials under quasistatic loading. The results highlight the influence of inclusion morphology and orientation on the mechanical response, particularly in regimes near yield and post-yield softening. To validate the computational framework, simulation results are compared with experimental stress–strain curves obtained from tensile tests on injection-molded samples of identical composition. A strong correlation is observed between predicted and measured mechanical properties, particularly in terms of initial stiffness and yield stress, confirming the representativeness of the stochastic microstructure generation. In Fig. 2, the averaged experimental results are compared to their numeric counterparts.



	35%	27%	24%	22%	20%
Experiment n=10	950.00	1089.27	1164.89	1209.81	1259.72
Simulation 90°	877.00	1013.00	1284.00	1470.00	1516.00
Simulation 0°	1077.00	1244.00	1431.00	1570.00	1663.00

Fig. 2. Simulated vs. experimental stress–strain curves for heterophasic composites with different volume fractions of soft interphase.

IV CONCLUSION

The integration of GRF-based reconstruction and FFT solvers presents a scalable, physics-informed framework for analyzing heterophasic material systems. The approach supports material design by enabling rapid virtual testing and optimization of mechanical properties based on controlled microstructure parameters. This framework can be extended with AI-driven surrogate modelling and inverse optimization algorithms to accelerate the discovery of optimal microstructures through data-driven exploration.

V REFERENCES

[1] U. Khristenko et al., *A statistical framework for generating microstructures of two-phase random materials: Application to fatigue analysis*, Multiscale Modeling and Simulation, vol. 18.1, pp. 21–43, 2020.
[2] M.G. Genton, *Classes of kernels for machine learning: a statistics perspective*, Journal of Machine Learning Research, pp. 299–312, 2001.
[3] P.J. Davis, *Leonhard Euler's Integral: A Historical Profile of the Gamma Function: In Memoriam: Milton Abramowitz*, The American Mathematical Monthly, vol. 66, no. 10, pp. 849–869, 1959.
[4] Z.-H. Yang, Y.-M. Chu, *On approximating the modified Bessel function of the second kind*, Journal of Inequalities and Applications, 2017.

Taguchi–AI approach for process optimization in composite manufacturing

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I ABSTRACT

Composite materials are integral to high-performance applications in aerospace, automotive, and energy sectors due to their lightweight and superior mechanical properties. However, their manufacturing processes, especially those involving thermoset prepregs and filament winding, are sensitive to a range of parameters such as resin content, temperature, and pressure. Traditional optimization methods often fall short in managing the complex interactions between these variables.

This paper presents an integrated approach combining the Taguchi method and Artificial Intelligence (AI) to optimize key process parameters in composite manufacturing.The study focuses on enhancing the quality and performance of fiber-reinforced polymer composites by minimizing experimental effort while maximizing process efficiency. The Taguchi method is employed to design robust experiments and identify the most influential factors affecting composite properties such as fiber content, resin impregnation quality, and curing behavior. AI techniques, including regression models and neural networks, are then used to analyze the data, uncover complex nonlinear relationships, and refine predictive accuracy. Experimental validation is conducted using a filament winding setup with thermoset resin systems, demonstrating improvements in mechanical performance and material consistency. The proposed hybrid Taguchi–AI framework offers a powerful tool for smart manufacturing, enabling informed decision-making and adaptive process control in advanced composite production.

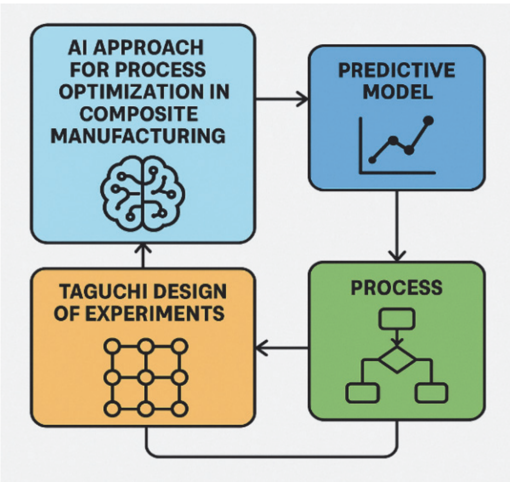

Fig. 1. AI-Driven Process Optimization Flow in Composite Manufacturing

The methods and results presented in this work provide valuable insight into how gsm measurements can be effectively utilized for optimizing the impregnation process. The optimized prepregs exhibit mechanical properties suitable for a wide range of structural applications, confirming the potential of this approach in advanced composite manufacturing.

This paper covers three technologies for manufacture of composites: Impregnation plant, FW and AFP.

Table 1. Important dates:

Impregnation Plant	Coats dry fibers or fabrics with resin (prepreg production)	Dry fibers, fabrics → prepreg	Controlled resin content, consistent prepreg quality
Filament Winding (FW)	Continuous fiber winding over a rotating mandrel with resin application	Tow (wet or prepreg)	High fiber volume fraction, automation-friendly
Automated Fiber Placement (AFP)	Automated placement of tows/tapes with heat and compaction	Prepreg tows/tapes	Precise fiber orientation, minimal waste, high speed

II REFERENCES

[1] Y. Liu, X. Zhang, L. Gao, *Artificial intelligence for materials science: A review of recent applications and prospects*, Materials & Design, vol. 198, 109326, 2021.
[2] O. Torkul, S. Altuntas, M.H. Torkul, *Application of artificial neural networks in predicting the mechanical properties of fiber-reinforced polymer composites*, Composites Part B: Engineering, vol. 92, pp. 471–477, 2016.
[3] R.K. Roy, *A Primer on the Taguchi Method*, Society of Manufacturing Engineers. ISBN: 978-0872638648, 2010.
[4] L. Karunamoorthy, K. Kanthavel, *Optimization of process parameters using Taguchi method and ANOVA for gear material*, Materials & Design, vol. 29/6, pp. 1041–1049, 2008.
[5] M. Kumar, K.A. Khan, *Effect of resin content on mechanical behavior of glass fiber reinforced epoxy composite laminates*, Materials Today: Proceedings, vol. 18, pp. 2413–2422, 2019.

Review of CAD/CAE softwares used in AI optimization of mechanical systems

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I INTRODUCTION

The integration of Artificial Intelligence (AI) into engineering design processes has emerged as a transformative force in mechanical system development. Conventional CAD (Computer-Aided Design) and CAE (Computer-Aided Engineering) tools are being enhanced with AI capabilities to streamline optimization workflows, accelerate simulations, and explore complex design spaces that were previously intractable. This paper provides a comprehensive review of major CAD/CAE platforms and their roles in AI-driven optimization, with an emphasis on their technical capabilities, integration options, and typical use cases in applied mechanics.

II CAD/CAE PLATFORMS AND AI INTEGRATION

Traditional CAD tools, such as SolidWorks, AutoCAD, CATIA, and Siemens NX, have long served as the backbone of mechanical design, offering robust geometry modeling, parametric design, and integration capabilities. On the CAE front, ANSYS, Abaqus, COMSOL Multiphysics, and Altair HyperWorks are widely utilized for finite element analysis (FEA), computational fluid dynamics (CFD), and multi-physics simulations.

Several CAD/CAE platforms now embed AI modules or offer APIs and scripting interfaces (e.g., Python, MATLAB, or C++) to enable the integration of external AI tools. For instance, ANSYS integrates with AI-based optimization libraries through its Workbench platform, supporting Design of Experiments (DOE), response surface modeling, and genetic algorithms [1]. Dassault Systèmes' CATIA and 3DEXPERIENCE platform offer machine learning capabilities for predictive modeling and generative design [2]. Siemens NX leverages AI to automate repetitive design tasks and uses topology optimization integrated with neural network algorithms for faster convergence [3].

From a methodological standpoint, AI optimization in mechanical systems design typically follows a workflow comprising data acquisition, model training, design space exploration, and optimization. Surrogate modeling techniques – such as kriging, radial basis functions, and neural networks – are used to approximate the behavior of mechanical systems under different design parameters, significantly reducing simulation costs [4].

Interfacing AI with CAE simulations presents both opportunities and challenges. One major challenge lies in the generation of high-quality training data from expensive simulation runs. Techniques such as active learning and transfer learning are being explored to reduce the number of required simulations while maintaining model accuracy [5]. Another challenge is the interpretability of AI models in engineering applications. The integration of explainable AI (XAI) techniques is emerging as a vital area of research, particularly for safety-critical applications in aerospace and automotive engineering [6].

Notably, open-source environments like OpenFOAM for CFD and Code_Aster for FEA are gaining traction in the research community due to their adaptability for AI-driven workflows. These tools can be seamlessly integrated with AI libraries such as TensorFlow, PyTorch, and scikit-learn, fostering rapid experimentation with novel optimization algorithms [7]. Furthermore, platforms like Simcenter HEEDS, modeFRONTIER, and OptiSLang provide dedicated environments for multi-disciplinary design optimization (MDO), bridging the gap between simulation and intelligent design exploration [8].

The review also highlights the emergence of AI-native design paradigms such as generative design and inverse design, where AI algorithms autonomously generate optimized mechanical structures based on user-defined constraints and objectives. These paradigms are increasingly supported in commercial tools such as Autodesk Fusion 360 and nTopology, pointing toward a future in which the human designer collaborates with AI agents in a co-creative process [9].

III CONCLUSION

The convergence of CAD/CAE software and AI optimization techniques represents a significant advancement in mechanical systems engineering. As AI continues to mature, its integration with CAD/CAE environments will not only accelerate the design cycle but also pave the way for innovation in applied mechanics.

IV REFERENCES

[1] ANSYS Inc., *ANSYS Workbench User Guide*, Retrieved from https://www.ansys.com, 2023.
[2] Dassault Systèmes, *CATIA and AI-powered Generative Design*, Retrieved from https://www.3ds.com, 2023.
[3] Siemens Digital Industries Software, *NX CAD and Topology Optimization Overview*,
Retrieved from https://www.plm.automation.siemens.com, 2023.
[4] A.I Forrester, A. Sobester, A.J. Keane, *Engineering Design via Surrogate Modelling: A Practical Guide*, Wiley, 2008.
[5] T. Lookman, P.V. Balachandran, D. Xue et al., *Active learning in materials science with emphasis on adaptive sampling using uncertainties for targeted design*, npj Computational Materials, vol. 5/21, 2019.
[6] W. Samek, T. Wiegand, K.R. Müller, *Explainable Artificial Intelligence: Understanding, Visualizing and Interpreting Deep Learning Models*, arXiv preprint arXiv:1708.08296, 2017.
[7] H. Jasak, *OpenFOAM: Open Source CFD in Research and Industry*, International Journal of Naval Architecture and Ocean Engineering, vol. 1/2, pp 89–94, 2009.
[8] Altair Engineering Inc. *OptiSLang for Process Integration and Design Optimization*, Retrieved from https://www.altair.com, 2023.
[9] Autodesk Inc. *Generative Design in Fusion 360*, Retrieved from https://www.autodesk.com, 2023. .

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The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Influence of defects on sheet molding compounds – A hybrid ICME approach

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I INTRODUCTION

State-of-the-art integrated computational material engineering (ICME) approaches commonly couple processing simulations with a structural component analysis. In compression molding of carbon fiber reinforced sheet molding compounds (CF-SMC) a certain number of voids in different shapes and sizes have been observed according to [1] and [2]. Those are individual for each manufactured component. Micro- and macrostructural defects in general, alter the final structural performance of the component and can act as potential crack initiators [1, 2]. With the aim to provide a framework to consider both, local fiber orientation and individual void distributions, this work suggests a hybrid ICME approach based on a two-step homogenization of the local material properties. An analysis of a novel CF-SMC brake caliper was used in a first proof-of-concept study, where monotonic tests were performed, to validate the generated numerical results. The CF-SMC brake caliper component was developed to replace its metallic counterpart in motorcycles. Therefore, a complex thermomechanical loading profile must be withstand by the component [3].

II MATERIAL AND EXPERIMENTAL METHODS

The commercially available Forged Molding Compound STR120N131 from Mitsubishi Chemical Corporation (Tokyo, Japan) was the material of choice to manufacture the brake caliper geometry in a compression molding process. Carbon fiber bundles consisting of 15k TR50S carbon fibers with a length, width and thickness of 25.4 mm, 8 mm and 0.115 mm, respectively, are embedded in a vinyl ester resin to form the desired CF-SMC.

To determine the void size and distribution in each individual caliper half, non-destructive X-ray computer tomography (XCT) measurements were performed by utilizing the TomoScope XS Plus (Werth Messtechnik GmbH, Gießen, Germany). The mechanical test setup used to subsequently test the quasi-static caliper opening is depicted in Fig. 1.

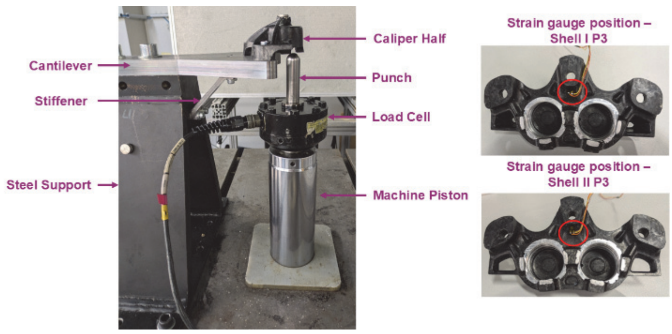

Fig. 1. Illustration of the fully assembled caliper opening test setup, mounted on the MTS 852 Damper Test System. Furthermore, the positions of the attached strain gauges on both caliper halves for the third prototype (P3) are shown and encircled in red.

A steel tripod supports a 20 mm thick cantilever on which the corresponding caliper is mounted during the measurement. A 10 kN load cell was utilized to record the force while the displacement-controlled movement of the punch was conducted by the cylinder of the MTS 852 Damper Test system (MTS Systems Corporation, Eden Prairie, MN, USA).

III RESULTS AND CONCLUSION

The experiments revealed a similar component stiffness for all tested specimens while different strain distributions were observed between the two halves of the caliper. In terms of the average void content, the caliper half which is supposed to be mounted on the fork of the motorcycle, shows a lower value compared to the other half with 8.93% and 12.21%, respectively. However, the void content does not correlate with the maximum aspect ratio of the void shape. A comparison with the hybrid ICME approach showed a good correlation at the beginning of the loading situation while differences in the resulting strain were observed, up to 32%, when damage occurred in the simulations. The damage was considered by a 3D Tsai-Wu criterion implemented by a user material subroutine into Abaqus/Standard.

IV ACKNOWLEDGEMENT

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V REFERENCES

[1] A. Kapshammer, S. Huemer-Kals, K. Zulueta, P. Fischer, Z. Major, *An Advanced Compression Molding Simulation and Validation of a Thick-Walled Carbon Fiber Sheet Molding Compound Brake Caliper*, Journal of Manufacturing and Materials Processing, vol. 9/4, 137, 2025.

[2] M. Mehdikhani, L. Gorbatikh, I. Verpoest, S.V. Lomov, *Voids in fiber reinforced polymer composites: A review on their formation, characteristics, and effects on mechanical performance*, Journal of Composite Materials, vol. 53/12, pp. 1579–1669, 2019.

[3] A. Fidler, K. Zulueta, A. Kapshammer, A. Altemirov, M. Stiefmann, S. Huemer-Kals, P. Fischer, Z. Major, *Carbon-Fiber Reinforced Sheet Moulding Compound in Brakes: Design and Simulation of a Lightweight Motorcycle Brake Calliper*, Proceedings of the Eurobrake 2023: Europe's Braking Technology Conference & Exhibition, Barcelona, Spain, 12–14 September, 2023.

Inteligent machines in predictive maintenance processes

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I INTRODUCTION

Given that the concept of intelligence can be identified with empirical hypotheses of predicting things based on experience, in information technology, intelligence can be identified with the positive processing of databases created by human action. Although a large number of authors believe that computer systems can independently learn from data without the need for explicit programming, the empirical database, especially in the world of engineering, indicates the synergy of human action with developed machine learning algorithms. In this sense, the authors of this paper believe that the "bold" view of the concept of artificial intelligence is precisely a mental trait that consists of the ability to learn from experience, adapt to new situations, grasp and understand new situations and use acquired knowledge in interaction with the environment.

II MAINTANANCE AND PREDICTION

Maintenance predictions using intelligent algorithms, respecting the very concept of maintenance and prediction, can be of exceptional importance for technical systems. As is known, the maintenance process itself can be viewed through the following three characteristic elements: maintenance costs, readiness and availability. Since it is necessary to increase the output characteristics and stability of the system during operation, especially from the point of view of effectiveness, the behavior of the system can be graphically depicted in the following figure.

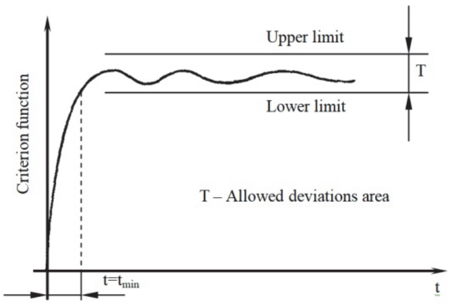

Fig. 1. System behavior model

System effectiveness represents the probability that the system will successfully enter into operation and perform the criterion function in the designed time and given environmental conditions [1]. Practically, system effectiveness encompasses the technological and management process related to the determination, measurement and control of system characteristics. The above clearly indicates the synergy of numerical data, empirical norms and mathematical processing models. The most common approach to determining system effectiveness can be expressed in mathematical form as:

$$E_S(t) = G(t)R(t)FP, \tag{1}$$

where, $G(t)$ is the system readiness, $R(t)$ is the system reliability and FP is the functional system convenience [2].

It is known that system readiness is a measure of the state of the system in terms of the efficiency of entering into action and achieving system output values at the level of allowed deviations of the set criterion function at a certain, given time and given environmental conditions. It is obvious that readiness can be defined in several ways, depending on the specific goals of the analysis, but in general case the following applies:

$$G(t) = \frac{t_r}{t} = \frac{t_r}{t_r + t_o} = \frac{\sum t_{ri}}{\sum t_{ri} + \sum t_{oi}}, \tag{2}$$

where t_r is time in operation (cumulative till time *t*), t_o is time in failure (cumulative till time *t*) and *t* is the total time of observation.

We can see that the longer the time intervals in operation, or the shorter the time in failure is, the greater is the effectiveness of the system, especially from the aspect of mathematical prediction models. It is known that prediction is the process of forecasting future events, states or results based on the analysis of existing data, knowledge or patterns that, based on the previous text, we can find in the synergy of effectiveness and experience parameters. The prediction methodology involves a systematic approach to building, validating and applying models for the forecast of future events or states. Mathematical prediction models are formal models that use mathematical methods and algorithms for data analysis and forecasting future values. The most common mathematical prediction models can be statistical models, machine learning models, Bayes models and numerical models [3,4]. The paper presents the interaction of machine learning models in the maintenance process without explicit programming.

III CONCLUSION

Basic advanced maintenance models, prediction models and practical applications of the aforementioned models are presented in the paper. By integrating the previous systems into the machine environment as the largest area of technology, the authors believe that it is possible to maintain synergy between the system requirements and the general response of the same in real operating conditions.

IV ACKNOWLEDGEMENT

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V REFERENCES

[1] J. Todorović, *Maintainability Engineering*, IIPP Institute, Belgrade, ISBN: 86-84231-11-2, 2006, in Serbian.
[2] D. Zelenović, J. Todorović, *Effectiveness of mechanical systems*, Naučna knjiga, Belgrade, ISBN: 86-23-43057-3, 1990, in Serbian.
[3] J. Jocković, *Time series forecasting – Models and models selection*, MSc paper, University of Belgrade, Faculty of Mathematics, 2016, in Serbian.
[4] A.M.L. da Silva et al., *Application of Monte Carlo simulation to generating system well-being analysis considering renewable sources*, 2004 International Conference on Probabilistic Methods Applied to Power Systems, Ames, IA, USA, pp. 439-444, 2004.

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Optimization of material handling machines with a sustainability focus, using graph neural networks

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I INTRODUCTION

Material handling systems are composed different machines mainly in a modular concept. To define an optimal structure of them requires complex planning task using a wide range of necessary expertise. Operation environment can also be complex and effects the machines' operation in a various ways. Our current research focuses on the applicability of artificial intelligence in warehouse material systems. Our attention turned to the Graph Neural Networks (GNN) and particularly Message Passing Neural Networks (MPNN). After developing a theoretical model for the problem description (see [1]), current paper focuses on the development of a special MPNN structure, which describes functional features and relations of the system components, and able to process the necessary material flows. The proposed structure can calculate the sustainability related parameters of the to be analyzed system which is our final KPI for the judgement of the systems operation.

II PAPER STRUCTURE

First, the paper outlines the most important trends in material handling. It particularly focuses on the concept of reconfigurability, which is a cornerstone of sustainable systems. In current rapidly changing economic environment, quick and large-scale changes are required in the activities of manufacturing companies, which also have an impact on their material handling. This section includes sustainability relevant parameters of material handling systems, which are as follows:

- Energy Consumption
- Green House Gas Emission
- D. Elasticity of Energy consumption on volume Change
- Operational Cost without energy consumption
- Ergonomics

In the second chapter, we discuss the applicability of GNN publications to our case. We found that there was no similar research in this specific area, so we could only find useful references from very distant areas. As in material handling systems there are several different material flows, we could find analogy with traffic flows (see [2]) analysis using MPNN. GNN networks can be a versatile artificial intelligence tool. Kosasih et al. in their paper used graph neural networks for even reasoning purposes in the supply chain area [3]. This can be relevant also to our case, because material handling is analogous to transport processes in supply chains. The authors point out that before the knowledge base van be built, an ontology must be defined.

In the third section the developed ontology for material handling systems is presented in Figure 1. There are six different main functional nodes in the ontology: mobile material handling machine, stationary / installed material handling machine, material flow control, data interface, modules and areas.

Based on the ontology in section four a knowledge graph is created for the to be analyzed use case. This is a heterogeneous graph, as it has two layers, the above described ontology and a material flow layer. Both operate on the basis of MPNN, but using different message structures. The second one connects the material handling machine modes. For the optimization purpose there are alternative branch nodes between them. These can work in a digital or analogous way and follow the principle of reinforcement learning. There is also place for adding expert knowledge in the form of rules to the Area nodes. The sustainability KPIs are calculated only for the nodes with relevance.

This complex method will be demonstrated via an example material handling system.

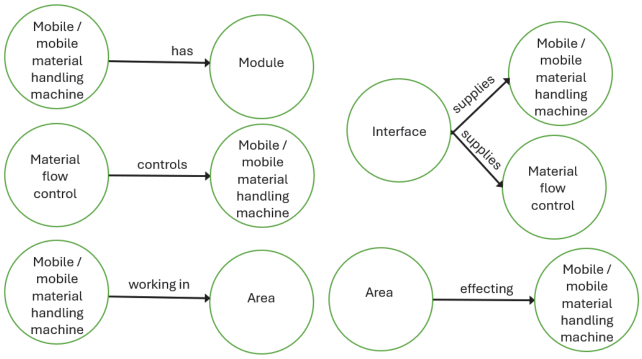

Fig. 1. Ontology for material handling MPNN application

III CONCLUSION

The paper presents a multi-step method for the application of MPNN in material handling system. Main advancement of the method that it is capable for automatic optimization of material flows using both expert knowledge and an AI structure.

IV REFERENCES

[1] G. Bohács, H.M. Sadida, *Integrating Material Handling Machines into an AI-Focused Framework*, Advances in Science and Technology, vol. 165, pp. 263-269, 2025.

[2] A. Prabowo, H. Xue, W. Shao, P. Koniusz, F. Salim, *Message Passing Neural Networks for Traffic Forecasting*, 10.48550/arXiv.2305.05740, 2023.

[3] E.E. Kosasih, F. Margaroli, S. Gelli, A. Aziz, N. Wildgoose, A. Brintrup, *Towards knowledge graph reasoning for supply chain risk management using graph neural networks*, International Journal of Production Research, vol. 62/15, pp. 5596–5612, 2022.

AI-based maturity detection system for field-grown melons: towards automated harvesting decisions

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I INTRODUCTION

Determining the optimal harvest time for melons remains a significant challenge in agricultural practice. Traditional methods rely on subjective human judgment involving tactile and visual inspection, often leading to inconsistent results and crop loss. This research proposes an AI-assisted solution that eliminates human factors and supports objective, automated decision-making directly in the field.

II PROJECT OBJECTIVE

Our goal is to develop a field-deployable prototype based on deep learning and computer vision to detect the ripeness of watermelons. The system will utilize RGB imagery captured under controlled lighting conditions, processed by convolutional neural networks

III METHODOLOGY

The prototype follows a phased development plan:

Proof of Concept (PoC): model training and evaluation on test image datasets.

Field Integration: refinement of lighting setup and real-time image processing capability.

Deployment: multi-season field tests on selected melon cultivars to validate accuracy and robustness.

The AI model will be iteratively trained on thousands of annotated images collected under real outdoor conditions.

IV EXPECTED OUTCOMES

We expect to produce a working AI-based detection system capable of supporting harvest decisions without human expertise. The system will mark ripe fruit visually or digitally for manual harvesting. This work lays the foundation for future autonomous harvesting solutions and precision agriculture applications.

V LITERATURE REVIEW AS FOUNDATION

This abstract is based on a systematic literature review which serves as the starting point for our three-year R&D project. Our aim is to comprehensively map the current global state of the art in fruit maturity detection – specifically focused on watermelon. We investigate both mechanical and AI-based approaches that have been used in similar contexts.

From a mechanical perspective, we examine non-invasive sensing techniques such as near-infrared spectroscopy, acoustic resonance, and pressure sensing technologies. On the AI side, we explore image-based classification methods, deep learning algorithms (e.g., CNNs, YOLO), spectral image analysis, and decision-tree models trained on multi-modal datasets.

The insights gained from this review will guide our prototype development, including the selection of sensing hardware, the AI model architecture, and the training strategy. Our goal is to bridge existing knowledge gaps and contribute a novel, field-ready solution for maturity detection.

VI CONSLUSION

This three-year research initiative merges AI with practical agricultural needs. The proposed system enhances harvest reliability and opens new directions for non-invasive fruit monitoring under real-world conditions.

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EUROPEAN MECHANICS SOCIETY

2D truss optimization using FEM-PSO and Generative AI

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I INTRODUCTION

This paper presents the theoretical foundations and implementation of a web-based application for the Particle swarm optimization of 2D truss structures. The framework achieves its objective through the integration of three powerful computational tools: the **Finite Element Method (FEM)** for deterministic structural analysis, **Particle Swarm Optimization (PSO)** for heuristic, population-based design exploration, and **Large Language Model (LLM)**, Google's Gemini, for automated interpretation of results.

Mathematical foundation of the FEM, the bio-inspired algorithmic behavior of PSO [1], and the transformer-based architecture that enables the reasoning capabilities of LLMs [2] are shown. The result is a tool that not only solves engineering problem but also serves as a case study in the powerful emerging synthesis of classical numerical methods and advanced artificial intelligence.

II APPLICATION ARCHITECTURE AND WORKFLOW

The application's workflow, depicted in Fig. 2, is organized into three primary stages: Setup and Configuration, Particle Swarm Optimization (PSO), and Results with AI-Powered Analysis. The process begins in the Setup stage, where the user defines the structural problem. This involves loading a truss geometry from a JSON file or using a default sample structure.

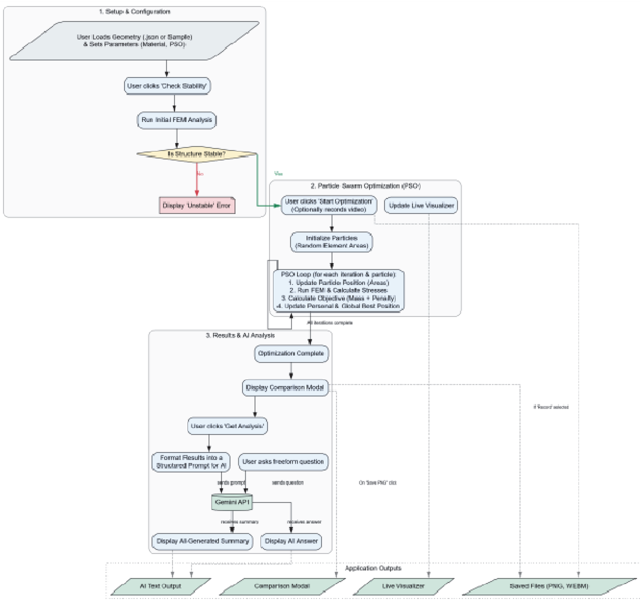

Fig. 2. The architectural flowchart of the web application

The user then specifies key material properties and sets the initial optimization parameters, including constraints like the maximum allowable stress.

The user can proceed to the Particle Swarm Optimization (PSO) stage. The system initializes a swarm of particles, where each particle represents a candidate design with a unique set of cross-sectional areas for the truss elements. The application performs the following sequence: updates the element areas based on the PSO velocity and position equations, executes a FEM analysis to calculate displacements and stresses, and evaluates an objective function that penalizes both high mass and stress violations.

When the optimization completes or is stopped by the user, a comparison is presented. The initial design, the stressed (but unoptimized) initial design, and the final optimized design, allowing for a clear assessment of the improvements in mass and stress distribution are displayed. To augment this quantitative data, the user can request an AI-powered analysis. The application formats the key results into a structured prompt and queries the Gemini large language model.

III CONCLUSION

This paper has shown the architecture of a web-based framework for 2D truss optimization, built on the foundations of the FEM and PSO. By understanding the theory of Large Language Models, applying methodical prompt engineering, and implementing these systems in a web application, we have successfully transformed a powerful LLM into an automated engineering analyst. This synergy where classical analysis provides the data, heuristic search finds the solution, and AI provides the insight demonstrates a new and compelling paradigm for the development of intelligent, intuitive, and accessible computer-aided engineering (CAE) tools.

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V REFERENCES

[1] R.S. Talbi, A.H. Boukhemis, *Hybrid particle swarm and genetic algorithm for efficient truss structure optimization under stress and displacement constraints*, Computers & Structures, vol. 235, 106458, 2020.
[2] S. Gupta, P. Johnson, K. Chen, *Large language models for the interpretation of finite element analysis results: A study in automated engineering report generation*, Advanced Engineering Informatics, vol. 55, 102145, 2023.

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Robust crack modeling with the quadrature-based Deep Energy Method (Q-DEM)

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I INTRODUCTION

The deep energy method (DEM) [1] is a highly versatile physics-informed neural network (PINN) approach which has proven to be very promising for nonlinear elastostatic problems [2, 3]. The integration of phasefield modeling for crack propagation straightforward due to the inherently energy-based nature of the problem [4]. However, to avoid divergence and overfitting behavior during training, the conventional DEM requires a very high number of collocation points which is further intensified in cases where the necessary NN expressivity is elevated to model discontinuities such as cracks. In combination with the computation of several load steps and a large number of epochs per load step, that results in high computational effort .

The current contribution resolves this drawback by applying a quadrature-based DEM (Q-DEM) combining the simplicity of energy-based modeling and significantly advanced numerical stability and efficiency.

II QUADRATURE-BASED DEEP ENERGY METHOD (Q-DEM) FOR PHASEFIELD CRACK MODELING

Similar to FEM based phasefield damage modeling, the DEM solves the equilibrium condition w.r.t. the displacement solution, coupled with the crack growth governed by Griffith's critical crack energy. Here, the material law is extended by a degradation term that is dependent on the damage variable.

Collocation points are distributed in the domain and displacements and damage field are approximated by an NN. The resulting potential energy is extended by the crack energy potential and then directly used as loss function during training, eliminating the requirement for a stiffness matrix. Dirichlet boundary conditions are enforced by a transformation of the NN output.

While the conventional DEM uses automatic differentiation by autograd and Newton-Cotes type integration, the Q-DEM employs a mesh-based discretization akin to the FEM with Gaussian quadrature, analogous to variational PINNs (V-PINNs) [5].

III CASE STUDY

The method is validated by a case study on a brittle plate made of Aluminium 7075-T6 subjected to traction loading leading to a mixed Mode I-II fracture. The resulting crack path is shown in Fig. 1.

The NN consists of 7 hidden layers with 40 neurons each with Tanh activation function, except for the last layer which applies ReLU. The simulation requires, dependent on the crack width parameter between 13 and 18 load steps, the first one trained with 10'000 epochs, all subsequent making use of transfer learning and requiring only 2000 epochs, all with the Adam optimizer algorithm. The mesh consists of first-order quadrilateral elements. Second-order elements have been tested as well but did not increase the accuracy or stability.

The validation is carried out by conventional FEM with phasefield crack modeling coupled in a staggered scheme. The standard approach has requires a significantly finer mesh and five times larger number of time steps.

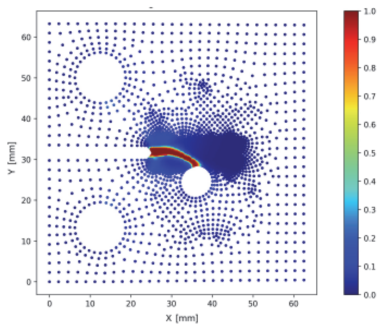

Fig. 1. Q-DEM results for mixed Mode I-II fracture.

IV CONCLUSION

The results of the Q-DEM for crack modeling are highly promising. The crack path is obtained with great robustness w.r.t. mesh size and time step width. The elastic energy and crack progress are comparable to the FEM solution, the computed elastic energies are in good agreement.

The energy-based modeling in the Q-DEM allows for the easy integration of multiple phenomena, which shall be exploited further in future work for coupled problems.

V ACKNOWLEDGEMENT

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VI REFERENCES

[1] V.M. Nguyen-Thanh, X. Zhuang, T. Rabczuk, *A deep energy method for finite deformation hyperelasticity*. European Journal of Mechanics - A/Solids, vol. 80, 103874, 2020.
[2] S. Hildebrand, S. Klinge, *Comparison of neural FEM and neural operator methods for applications in solid mechanics*. Neural Computing and Applications, vol. 36, pp. 16 657–16 682, 2024.
[3] S. Hildebrand, J.G. Friedrich, M. Mohammadkhah, S. Klinge, *Coupled CANN-DEM simulation in solid mechanics*, Machine Learning: Science and Technology, vol. 6/1, p. 015 038, 2025.
[4] S. Goswami, C. Anitescu, T. Rabczuk, *Adaptive fourth-order phase field analysis using deep energy minimization*, Theoretical and Applied Fracture Mechanics, vol. 107, 102527, 2020.
[5] S. Berrone, C. Canuto, M. Pintore, *Variational physics informed neural networks: The role of quadratures and test functions*, Journal of Scientific Computing, vol. 92, 100, 2022.

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A neural network framework for concrete damage plasticity modeling

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I INTRODUCTION

Accurately capturing complex material behavior like damage evolution and cyclic plasticity remains a central challenge in computational mechanics [1,2]. One of the most widely used constitutive models for nonlinear analysis of concrete is the Concrete Damage Plasticity (CDP) model, which combines plasticity theory with damage mechanics [3]. Traditional finite element approaches often suffer from mesh sensitivity, convergence issues, and high computational cost, especially when modeling damage and plasticity under varying loading conditions. The parameter identification of the conventional CDP model furthermore requires information about tensile behavior which usually is not provided by lab measurements and is commonly indirectly determined and iteratively manually adapted. A neural network (NN)-based framework that models concrete material behavior using a history-dependent NN is proposed to address these limitations.

II FRAMEWORK ARCHITECTURE

The modeling of cyclic plasticity with neural networks has proven to be accurate and promising for use in large scale [4] without dependence on the associativity of the flow rule. A similar stateless recurrent neural network architecture is designed for concrete and extended to include damage evolution. The model predicts the plastic strain and damage parameter increments based on the corresponding information from the previous timestep as well as on total strain from the previous and current timesteps as the input. Accordingly, it serves as material point damage model and can be implemented as a drop-in replacement to concrete damage plasticity models currently implemented in FE solvers.

III DATA GENERATION

Standard tests are typically performed as uniaxial compressive, flexural bending and split test. Tests involving stress–strain relationships under loading–unloading conditions or direct tensile tests are more challenging and less frequently conducted.

This contribution suggests to extend the conventional tests by Direct Image Correlation (DIC) and to perform flexural bending tests with sub-critical loads and a low number of load reversals.

Surrogate data generated with the Concrete Damaged Plasticity (CDP) model in Abaqus is applied to train and validate a first version of the NN model. This data covers tensile, compressive, and cyclic loading cases.

In future versions, a complete neural setup for inverse material characterization can be applied instead [6], as well as transfer learning based on previous training with surrogate data and experimental data from other, related concrete types.

IV RESULTS

The results demonstrate that the NN generalizes well across both training and testing load cases and offers a promising alternative to conventional material models. The network captures the nonlinear plastic strain and damage evolution with high accuracy and computational efficiency. Fig. 1 shows the results for a single material point. The results from the NN are in very good agreement with the results from the standard model.

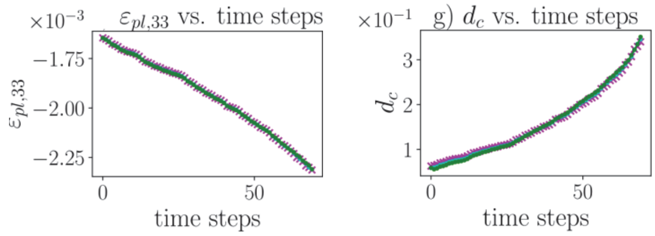

Fig. 1. Evolution of plastic strains and damage in compressive test along 33 direction

V CONCLUSION

The NN modeling of concrete plasticity and damage evolution is highly promising, as no iterative manual model adaptation is required for the material characterization. The current high requirements on the available training data will be relaxed in future work with new version of the neural network architecture.

VI REFERENCES

[1] T.K. Caughey, *Nonlinear theory of random vibrations*, Advances in Applied Mechanics, vol. 11, pp. 209–253, 1971.
[2] S. Aygün, T. Wiegold, S. Klinge, *Coupling of the phase field approach to the Armstrong-Frederick model for the simulation of ductile damage under cyclic load*, International Journal of Plasticity, 2021.
[3] D. Xenos, P. Grassl, *Modelling the failure of reinforced concrete with nonlocal and crack band approaches using the damage-plasticity model CDPM2*, Finite Elements in Analysis and Design, vol. 117-118, pp 11-20, 2016.
[4] S. Hildebrand, S. Klinge, *Hybrid data-driven and physics-informed regularized learning of cyclic plasticity with neural networks*, Machine Learning: Science and Technology, 2024.
[6] S. Hildebrand, J.G. Friedrich, S. Klinge, *Coupled CANN-DEM Simulation in Solid Mechanics*, Machine Learning: Science and Technology, 2025.

A quadrature-based Deep Energy Method (DEM) for heterogeneous solids

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I INTRODUCTION

Hydrogels gain increasing attention in biomedical and industrial applications for their highly adaptive properties and utility. However, this high adaptivity calls for application-specific parameter tuning, and therefore suitable mechanical simulation and optimization [1]. The simulation of the microstructure of calcified hydrogels is numerically challenging due to intense discontinuities and stress concentrations caused by substantial contrasts in stiffness between the hydrogel and the calcium inclusions, spanning over several orders of magnitude.

The deep energy method (DEM) [2] is a highly versatile physics-informed neural network (PINN) approach which has proven to be very promising for nonlinear elastostatic problems [3, 4]. However, existing suggestions for the resolution of stress concentrations tend to require high computational cost and exhibit a behavior similar to overfitting. No suggestions the simulation of composites, especially with materials of highly varying stiffness have been made so far.

The current contribution addresses this gap by a quadrature-based DEM (Q-DEM) combining the simplicity of energy-based modeling, a straight-forward modeling of composite microstructures and significantly advanced numerical stability and efficiency.

II THE QUADRATURE-BASED DEEP ENERGY METHOD

Similar to the finite element method (FEM), the DEM solves the equilibrium condition w.r.t. the displacement solution. In the DEM, collocation points are distributed in the domain and displacements are approximated by an NN. The resulting potential energy is directly minimized as the loss function during training, eliminating the requirement for a stiffness matrix. Dirichlet boundary conditions are enforced by a transformation of the NN output, whereas Neumann boundary conditions are directly included in the potential energy formulation via external work. The overall information flow during training is shown in Fig. 1.

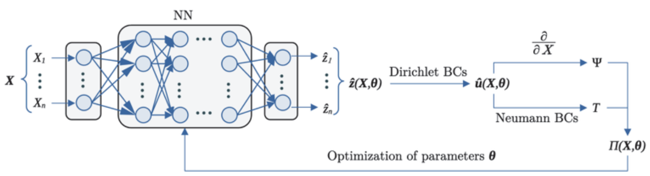

Fig. 1. Information flow in the DEM.

While the conventional DEM uses automatic differentiation by autograd and Newton-Cotes type integration, the Q-DEM employs a mesh-based discretization akin to the FEM with Gaussian quadrature, analogous to variational PINNs (V-PINNs) [5]. Thanks to this modification, the DEM can be applied to highly complex problems without requiring additional NN outputs or loss terms that could complicate the optimization process. The energy-based loss function setup is retained, so that e.g. hyperelastic constitutive models, phasefield damage models and approaches corresponding to other phenomena can be integrated with moderate effort.

III RESULTS AND CONCLUSIONS

The accuracy of the Q-DEM is investigated on coupons with hard inclusions of varying geometries using both linear and hyperelastic material laws (Fig. 2.). Hydrogels with calcium inclusions provide a test case for materials with high contrast in stiffness properties [6, 1].

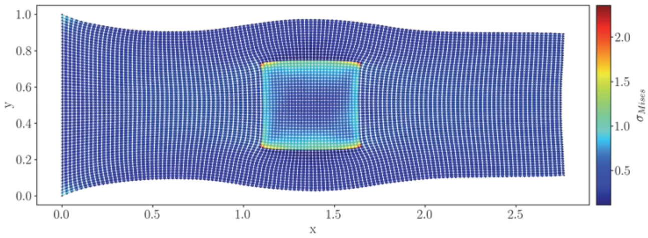

Fig. 2. V-DEM solution for a coupon with a hard inclusion under tensile loading (v. Mises stress).

While the conventional DEM exhibits poor convergence behavior for two-phase materials, the Q-DEM yields highly accurate results with precision comparable to the FEM. The training process is greatly accelerated and the solution quality robust over a wide range of material combinations and geometries, making the Q-DEM a compact yet powerful tool for solving complex heterogenous problems in solid mechanics.

IV REFERENCES

[1] M. Graham, S. Klinge, *Multiscale homogenisation of diffusion in enzymatically-calcified hydrogels*, Journal of the Mechanical Behavior of Biomedical Materials, vol. 149, 106244, 2024.
[2] V.M. Nguyen-Thanh, X. Zhuang, T. Rabczuk, *A deep energy method for finite deformation hyperelasticity*, European Journal of Mechanics - A/Solids, vol. 80, 103874, 2020.
[3] S. Hildebrand, S. Klinge, *Comparison of neural FEM and neural operator methods for applications in solid mechanics*, Neural Computing and Applications, vol. 36, pp. 16 657–16 682, 2024.
[4] S. Hildebrand, J.G. Friedrich, M. Mohammadkhah, S. Klinge, *Coupled CANN-DEM simulation in solid mechanics*, Machine Learning: Science and Technology, vol. 6/1, 015038, 2025.
[5] S. Berrone, C. Canuto, M. Pintore, *Variational physics informed neural networks: The role of quadratures and test functions*, Journal of Scientific Computing, vol. 92, 100, 2022.
[6] W. Du, W. Ji, Z. Jiao et al., *Injectable hydrogels exhibiting real-time in situ reinforcement under dynamic mechanical conditions*, ACS Applied Polymer Materials, vol. 7/ 9, pp. 5766–5779, 2025.

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Optimal trajectory tracking of robot manipulator using resonant controller

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I INTRODUCTION

Controlling robotic manipulators remains a challenging research area due to their complex, nonlinear, and coupled dynamics [1]. Numerous tracking control methods have been proposed, particularly for tasks requiring repeated execution of closed trajectories in three-dimensional (3D) space - common in industrial applications like welding and painting. While resonant controllers are widely used in electrical systems, their potential in robotics has been largely overlooked. These controllers offer a key advantage: a structural term aligned with the fundamental frequency of the target trajectory. This paper proposes integrating a resonant controller with a particle swarm optimization (PSO) algorithm to minimize tracking error. The main contribution is the novel combination of PSO and resonant control for improved motion accuracy.

II MATHEMATICAL MODEL AND CONTROLLER DESIGN

Robotic segments are typically driven by electric actuators like DC motors, often coupled with transmission gears. When high gear ratios are used, the complex nonlinear robot dynamics can be approximated by a linear DC motor model [2]. In this study, a manipulator with three revolute joints is actuated by three identical Maxon motors. The transfer function of the DC motor can be derived as follows:

$$G_m(s) = \frac{K}{s(Ts+1)} \tag{1}$$

wherein $K = 22.515$ and $T = 0.0056409$. Now, the objective of this paper is to design a controller capable of accurately tracking a closed trajectory in 3D space. As already stated, an appropriate solution to this problem can be achieved using a resonant controller in the following form:

$$C(s) = \frac{(Ts+1)(a_3 s^3 + a_2 s^2 + a_1 s + 1)}{b_0 s(s^2+\omega_0^2)} \tag{2}$$

wherein $a_3 = T^2(T+3\lambda)$, $a_2 = T(3T + 3\lambda - T^2\lambda\omega_0^2)$, $a_1 = 3T + \lambda$, $b_0 = KT^3\lambda$. The controller is expressed in a nonproper transfer function form to allow direct use of angular velocity measurements as feedback. In this formulation $\omega_0 = 2\pi/T_0$, where T_0 is the period of one complete traversal of the desired closed trajectory by the end-effector. The tuning parameter λ enables the control designer to balance performance and robustness in the closed-loop system. A more detailed design procedure is provided in [3].

Given that the manipulator consists of three robotic links, independent control of each link is required. Accordingly, three separate resonant controllers $C_i(s)$, $i = 1,2,3$, are designed. The corresponding tuning parameters λ_i, $i = 1,2,3$, must be selected based on a well-defined design criterion to ensure desired performance [4]:

$$J(\lambda_1, \lambda_2, \lambda_3) = \frac{1}{T_0}\int_0^{T_0} \Delta(\lambda_1, \lambda_2, \lambda_3, t)dt \tag{3}$$

wherein $\Delta(\circ)$ represents positional (distance) error of the end-effector from the desired trajectory at time instant t. The performance criterion $J(\circ)$ represents the average positional error of the end-effector. The objective is to optimize the free parameters λ_i, $i = 1,2,3$ to minimize this error. Due to the highly nonlinear nature of $J(\circ)$ a particle swarm optimization algorithm is employed to effectively solve the resulting optimization problem.

III SIMULATION RESULTS

Graphical results are presented below. The figure illustrates the end-effector's trajectory at various path-tracking speeds. As expected, the deviation between the actual and desired trajectories increases with velocity V grows, indicating a performance trade-off at higher speeds.

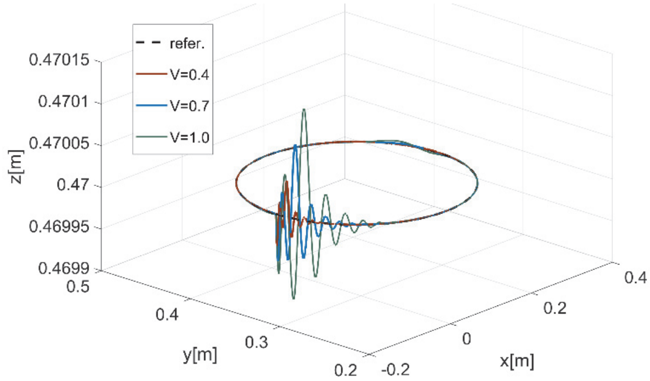

Fig. 1 End-effector's trajectory for different velocity values $V\left[\frac{m}{s}\right]$

IV ACKNOWLEDGEMENT

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V REFERENCES

[1] B. Siciliano, L. Sciavicco, L. Villani, G. Oriolo, *Robotics*, London: Springer-Verlag, 2009.

[2] P. Mandić, *Advanced modeling of complex robotic systems and mechanisms and applications of modern control theory*, PhD Dissertation, Faculty of Mechanical Engineering, Belgrade, 2019.

[3] P. Mandić, T. Šekara, M. Lazarević, *Analytical design of resonant controller applied for solving robot arm tracking problem*, 9th International Congress of Serbian Society of Mechanics, Vrnjačka Banja, Serbia, July 5-7, 2023.

[4] P. Mandić, M. Lazarević, T. Šekara, *PSO-based resonant controller for trajectory tracking of robot manipulator*, 10th International Congress of Serbian Society of Mechanics, Niš, Serbia, June 18-20, 2025.

EUROPEAN MECHANICS SOCIETY

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Development of a static test platform for determining the loads on an Unmanned Aerial Vehicle (UAV)

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I INTRODUCTION

The development of a static platform for determining loads on an unmanned aerial vehicle (UAV) represents a critical step in verifying the mechanical performance and structural reliability of the aircraft prior to its operational deployment. Such testing allows the simulation of real-world loading conditions experienced by the UAV during vertical take-off or during the initiation of the fifth cruise motor. This platform enables the measurement of forces and moments at six predefined points, as well as vibrations and impulsive loads.

Static testing is used to validate numerical models, identify critical stress points, and detect potential structural weaknesses. In this context, a finite element method (FEM) model is developed to simulate the structural behavior and serves as a validation reference for a complementary artificial neural network (ANN) model. The ANN model is designed to provide rapid estimations of forces in structural rods, enabling faster preliminary assessments and optimization during the design process. The ANN model was additionally applied to optimize the arrangement of sensors and positioning points of the rods, with the aim of maximizing the accuracy and representativeness of the measured data within the experimental setup.

The platform consists of a robust supporting frame, force sensors (load cells), and displacement measurement systems (LVDTs, optical sensors). Using a data acquisition system, structural responses to the applied loads can be accurately monitored. This type of experimental validation is increasingly used in UAV development, especially in industries where a high level of reliability is required, such as defense, surveillance, logistics, and precision agriculture. Compared to purely numerical simulations, experimental verification using a static test platform contributes to the development of more robust and optimized structures, while reducing the risk of unforeseen events during flight testing [1–3].

II METHODOLOGY

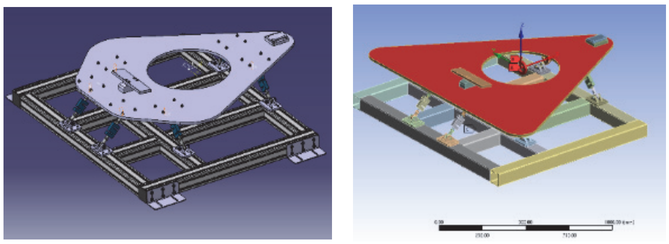
In the direct problem, the resultant force vector and the resultant moment with respect to a selected reference point T are known, and it is required to determine the forces in the force sensors.

The inverse problem consists of determining the resultant force vector and the resultant moment for known values of the forces measured by the force sensors.

The required equations are obtained from the condition that the resultant force vector and the resultant moment must be equal to zero.

$$\vec{F}_R = \vec{0}\,; \quad \vec{M}_T = \overline{TO} \times \vec{S}_R + \sum_i \vec{r}_i \times \vec{S}_i \qquad (1)$$

The numerical model was established by defining the platform's boundary constraints and applying predefined forces and moments that simulate the loads acting on the UAV during vertical take-off. The corresponding numerical setup is presented in Figure 1b.



a) *b)*

Fig. 1 a) 3D model of the developed static test platform. b) Numerical simulation model.

III CONCLUSION

An analytical and numerical approach was used in the development of this platform. The initial concept was established through analytical calculations, based on which the forces in the approximated rods (load cells) were determined. For the same load values, a finite element (FE) analysis was performed. A comparison of the results showed small relative differences in the forces within the rods. The platform enables accurate measurement of forces in the bar elements and other key parameters relevant to the specified testing procedure.

Table 1. Comparison between theory and numerical values.

Rod number	Numerical values of Force [N]	Theory values of Force [N]	Relative differences [%]
1	442.29	449.60	1.62
2	-452.33	-458.41	1.33
3	-470.51	-477.34	1.43
4	424.99	430.67	1.32
5	-1846.5	-1872.97	1.41
6	1846.5	1872.97	1.41

These platforms play a crucial role in the early stages of UAV design, as they allow for comprehensive testing of the structural load-bearing capacity of all components under operational loading conditions, as well as measurement of engine performance and evaluation of the power system.

IV REFERENCES

[1] A. Brezina, S. Thomas, *Measurement of Static and Dynamic Performance Characteristics of Electric Propulsion Systems*. 10.2514/6.2013-500, 2013.

[3] R.L. Rubin, D. Zhao, *New development of classical actuator disk model for propellers at incidence*, AIAA J., vol. *59*, pp. 1040–1054. 2021.

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EUROPEAN MECHANICS SOCIETY

Neural network based controller parameters learning for a mechanical system

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I INTRODUCTION

Control parameters learning is crucial for achieving optimal control performance and system efficiency. Traditional control methods often rely on fixed controller parameters, which can deliver satisfactory results under steady-state conditions or around a predefined operating point. However, when the system operates under varying conditions, these fixed parameters may lead to degraded performance or even failure of controller to achieve control task.

To overcome these limitations, control strategies that incorporate learning and adaptation of controller parameters offer a more robust and flexible solution. Instead of relying solely on expert knowledge and manual tuning, which can be both time-consuming and limited by prior assumptions, learning-based approaches adapt the parameters in response to changing system behavior.

In particular, artificial intelligence (AI) techniques can greatly enhance the process of control parameter optimization. AI can either support the intelligent selection of constant parameters for a given operating regime or enable an adaptive learning approach, where parameters are continuously updated in real time to match evolving conditions.

This work focuses on the design of a learning-based control system that uses radial basis function (RBF) neural networks to learn and optimize the parameters of a PID controller. Alongside parameter learning, the system estimates the equivalent gain of the plant, which helps update the internal model of the plant during the learning process. This joint learning of controller parameters and plant characteristics results in a control system with significantly improved tracking performance.

The effectiveness of this control parameter learning approach is validated through an implementation example of a mechanical system (inverted pendulum), designed for a swing-up and position control tasks.

II CONTROL PARAMETERS LEARNING BASED ON NEURAL NETWORKS

In the proposed control parameters learning scheme the underlying idea is based on using radial basis function (RBF) as an activation for the NN which learns the controller parameters on one hand and adapts the plant model required for the controller design on the other hand. Learning the controller parameters requires definition of the appropriate inputs and outputs to the layers of the NN, where the outputs of this primary NN should represent the controller parameters being learned. In a similar way the secondary NN predicts the model of the plant at every time-step, which in turn results in a more precise controller parameters learning. The update of the controller parameters is based on the minimization of the error e between of the desired (r) and the real measured system output y, expressed in terms of the minimization of the objective function J_c in equation (1).

$$J_c = e^2/2 = (r-y)^2/2 \tag{1}$$

Specifically for the design of the proportional integral derivative (PID) controller the error, its integral and derivative are required as inputs to the NN for the controller parameters learning. Learning evolves through the minimization of the objective function using stochastic gradient descent (SGD) learning algorithm for the NN and the PID controller parameters.

III IMPLEMENTATION

The proposed approach is implemented for solving the control problem of an inverted pendulum, which may be considered as a part of a manipulating system. Both the swing up and positioning of the pendulum cart with the pendulum in the upright position belong to those tasks.

The control scheme implemented on a real-time platform with dSPACE is shown in Fig. 1.

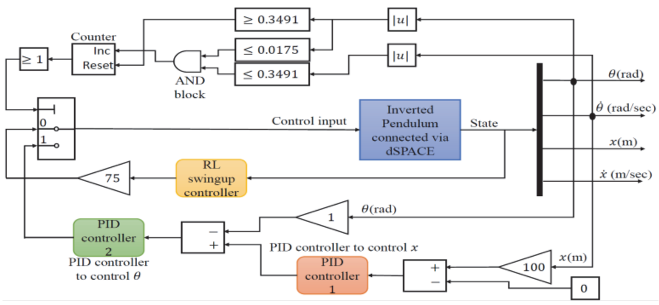

Fig.1 Adaptive NN based PID controller and reinforcement learning module for controller performance learning

Controller implementation tasks have shown good controller performance for the tracking and balancing problems.

IV REFERENCES

[1] A.K. Pal, T. Nestorović, *Artificial Intelligence Neural Network Approach to Self Tuning of a Discrete-Time PID Control System*, 9th International Conference on Systems and Control (ICSC), pp. 146-151, 2021.

[2] A.K. Pal, T. Nestorović, *Swing Up and Balance of an Inverted Pendulum Using Reinforcement Learning Approach Coupled With a Proportional-Integral-Derivative Controller*, ICECCME 2022, pp. 1-6, 2022.

[3] A.K. Pal, A. Oveisi, T. Nestorović, *The effect of model uncertainties in the reinforcement learning based regulation problem: An experimental case study with inverted pendulum.* PAMM e202300130, 2023.

Theoretical and numerical studies on the perfect one-way longitudinal wave absorption in rods

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I INTRODUCTION

One of the main challenges in modern engineering is controlling elastic or acoustic waves or vibrations in structures. A potential way to address this is using artificially designed structural patterns, e. g. metamaterials. With precisely tailored position, mass, stiffness and damping properties they can create local frequency bandgaps and – as a result – waves with frequencies that fall within these bands cannot travel through the modified part of the structure [1]. These phenomena have great practical applicability for solving variety of issues, it is necessary, however, to understand them.

In this study we present the possibility of using a combination of point scatterers attached to a rod for obtaining non-symmetric wave propagation. This effect can lead to perfect one-way longitudinal wave absorption or other types of reflection asymmetries [2]. Our studies are based on analytical solutions, in particular the dispersion relation and the Green's function for a rod, and are validated via numerical models. In this current work, we focus on investigating the transient nature of wave scattering – an effect that has not been widely studied. Moving beyond the classical harmonics analysis assumptions, we find that reaching the equilibrium state may require numerous wave reflections, which, in physical structures may be decisive for an efficient application.

II METHODS

Numerical models were implemented with the Finite Element Method (FEM) and included 1-D rod (2-node) elements with point resonators attached to selected nodes. The resonators were modeled as separate lumped mechanical systems with mass, stiffness and damping elements precisely tuned to achieve the desired wave response. It is noteworthy that the properties of the resonators were frequency dependent so for each case their properties were selected individually. Tukey window was utilized for 10% of the excitation signal length to reduce spectral leakage. The domain size was adjusted based on the wavelength. Numerical results were later compared to analytical solutions obtained from the dispersion relation and the Green's function for a rod system.

III CONCLUSION

The results shown very good agreement between numerical and analytical studies, in particular in terms of the reflection (R), and transmission (T) coefficients of resonators' clusters. Owing to the numerical model, the transient nature of wave scattering phenomena was addressed. Example of this behavior is shown in Figs. 1 and 2. In the former case, the cluster of resonators response settles almost immediately and achieves the expected reflection coefficient, i.e. R = const. In the latter example, the transient effect of building up the harmonic response is clearly visible resulting in a time-dependent reflection coefficient R(t). In that case, the system requires a long excitation signal and – therefore – time, for reaching its designed performance. This effect can substantially impact the system characteristics and the potential device performance.

IV ACKNOWLEDGEMENT

This research was supported by the DYNAMO project (101046489), funded by the European Union.

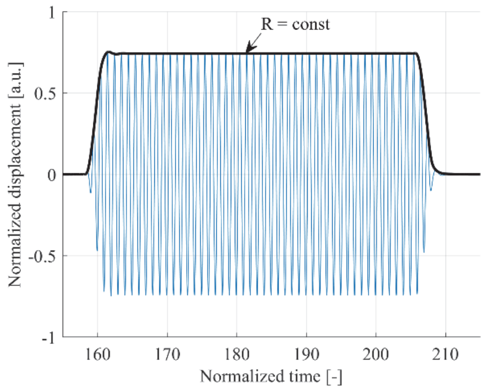

Fig. 1. Example of fast stabilizing resonator cluster.

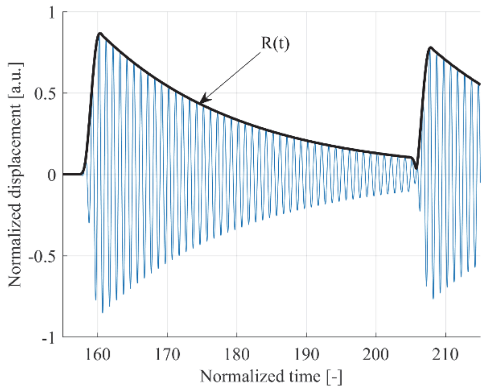

Fig. 2. Example of slowly stabilizing resonator cluster.

V REFERENCES

[1] J. Jung, J.S. Jensen, C. Jeong, S. Wang, *Optimizing a distribution of resonators on a thin plate for the desired sound radiation*, Journal of Sound and Vibration, vol. 496, 115926, 2021.

[2] A.N. Norris, P. Packo, *Non-symmetric flexural wave scattering and one-way extreme absorption*, The Journal of the Acoustical Society of America, vol. 146/1, pp. 873–883, 2019.

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Design of metamaterials for ultrafast imaging

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I INTRODUCTION

Imaging is of high importance for various disciplines of science and industry. The imaging process is based on detecting and analyzing the wavefield scattered from an object and is subject to various limitations – one of the most prominent being the diffraction limit.

A number of methods have been proposed to improve imaging accuracy and quality. Among other, approaches based on the analysis of evanescent waves have gained popularity. This work explores an application of active and passive metamaterials for improving and enhancing the imaging process.

II THE IMAGING PROCESS

The imaging process consists in detecting and analyzing a wavefield after its interaction with an object. In order to overcome challenges related to the imaging process, various strategies and devices have been developed over the last decades. In this work we elaborate on an approach based on a modulation device, e.g. an active screen or mirror, that encodes spatial patterns and – along with the incident excitation signal, allows for enhancing the imaging process.

Assuming a 2-D object to be analyzed, represented by $A_0(\mathbf{r})$, the wavefield transmitted by the system, ψ_T, is given by [1]

$$\psi_T(\boldsymbol{r},t) = \sum_n e^{-i\Omega_n t} \iint A_0(\boldsymbol{r}')T_n(\boldsymbol{r},\boldsymbol{r}')d^2\boldsymbol{r}' \qquad (1)$$

where $\boldsymbol{r}$ is the 2-D position vector, Ω_n is the (modulated) wave frequency and t denotes the time. In Eq. (1), T_n has the form [1]

$$T_n(\boldsymbol{r},\boldsymbol{r}') = \iint T_n(k,\omega_0)e^{i\boldsymbol{k}(\boldsymbol{r}-\boldsymbol{r}')}d^2\boldsymbol{k} \qquad (2)$$

with $\boldsymbol{k}$ denoting the wavevector (of magnitude k) and ω_0 being the circular frequency of the incident wavefield.

The image of an object is to be recovered by measuring $\psi_T(\boldsymbol{r},t)$ knowing the incident wavefield and the modulation pattern.

III IMAGE RECOVERY AND METAMATERIAL DESIGN

We first demonstrate how the modulation of the screen can be used to enhance the imaging process. For this purpose, an image of a letter – with the resolution of 1024 × 1024 pixels – is investigated. We first represent the image in the Fourier space with the spectral resolution of (128 + 1) × (128 + 1) coefficients. Next, we use a harmonic incident wavefield of frequency ω_0 along with various screen modulation sequences. The example results, shown in Fig. 1, demonstrate that the imaging process can be substantially improved with the proposed approach.

As a second step, we introduce and analyze an imaging setup composed a metamaterial structure that acts as a modulating mirror. This metastructure is designed to facilitate the imaging process. In particular, we are interested in specific dynamic properties that display high density of modes in an assumed frequency range.

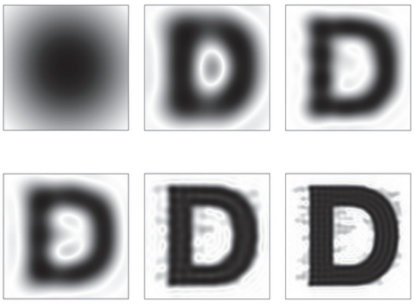

Fig. 1. Imaging process demonstration of the letter D. The top row shows an image for the letter (physical) size of $\lambda \times \lambda$, while the bottom for $4\lambda \times 4\lambda$. The subsequent columns list results for no modulation and two nonzero modulation frequencies of ¼ and ½ the incident wave frequency.

In the analysis we consider two types of metastructures, namely half-spaces decorated with pillars or holes, of specific sizes and distribution. The design is carried out through both analytical and numerical studies, while the latter include topology optimization with deterministic and stochastic methods. Prior to the actual design through optimization, we perform sensitivity studies to select critical structural parameters.

IV CONCLUSION

This work reports on results of a metamaterial design for ultrafast imaging. We demonstrate that the concept of ultrafast imaging with modulated metamaterials can bring substantial benefits in terms of image quality and the imaging speed. Besides that, we outline the structural design process that can lead to metamaterial mirrors to be applied in practice.

V ACKNOWLEDGEMENT

This research was supported by the DYNAMO project (101046489), funded by the European Union.

VI REFERENCES

[1] P. Packo, D. Torrent, *Far-field perfect imaging with time-modulated gratings*, Physical Review Applied, vol. 17, 064040, 2022.

Pyro-starter procedure in expendable turbojets and elements of artificial intelligence

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I INTRODUCTION

Expendable turbojets are used in various missiles where fast and reliable start is one of the primary requirements. In most of the cases the pyro-starter hot gases are acting on turbine rotor although there is solution like in turbojet engine Teledyne J-402 where hot gases are acting on radial compressor. This work presents procedure chosen for start of the engine in 40daN thrust class with incorporation of artificial intelligence in control system.

II ARANGEMENT AND PROCEDURE

The proposed starting and ignition system is based on pyro-starter, a block of solid propellant and pyro-igniter, also piece of solid propellant. They differ in composition because starter gases are acting directly on turbine blades so their temperature is around 1450K while igniter gases have the temperature of 2200K. Duration of pyro-starter is 3 seconds and it is important that proper procedure, i.e. when to activate fuel flow and ignition, is chosen. More than this because the fuel system has some time delay (fuel pump delay, fuel valve delay), typically the order of one second, it is important to proper schedule these actions.

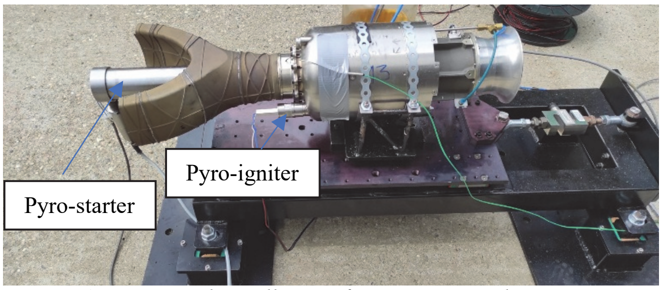

Fig. 1. Engine and installation of pyro-starter and pyro-igniter

The complete procedure is presented at Fig.2. At initial moment-To the Electronic control unit (ECU) of the engine activates the pyro-starter. Step 1-when engine rotation per minute (rpm) reaches 5000, approximately 0.1 second, ECU activates the pyro-igniter. Step 2-when engine rpm reaches 30000, approximately 1 second, ECU activates fuel pump and fuel valve. Step 3-when engine reaches 50000 rpm, approximately 1.5 second, ECU starts to apply given fuel function i.e. to add the fuel according to time dependent function to reach given rpm, in this case 70000. After 3 seconds pyro-starter is finished while pyro-igniter is continuing to work 3 seconds more. Step 3 incorporates a human like behavior because the fuel function depends of engine rpm response and exhaust temperature: if engine rpm acceleration and temperature are not in desired range the control unit will try to decrease the fuel flow and repeat step 3 to maintain the proper start.

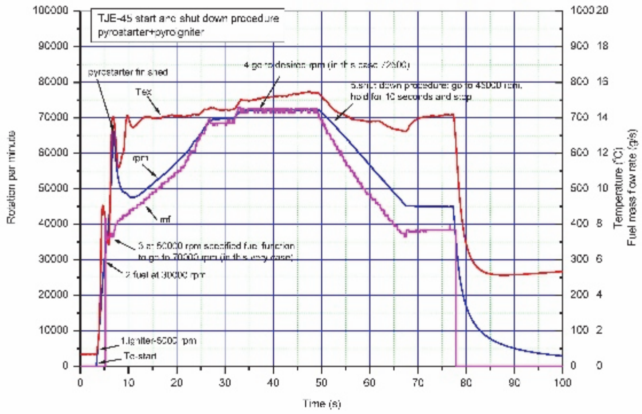

Fig. 2. Engine starting sequence shown at complete run diagram

It can be seen that after pyro-starter ends the rpm of the engine starts to decelerate. It is because the fuel flow in that moment corresponds to lower rpm than it was with pyro-starter on. Actually, the main limitations are, for given size and energy of pyro-starter, the engine compressor stability. That's why certain fuel flow value for the ignition and fuel function for acceleration are chosen.

III CONCLUSION

Procedure for starting the expendable turbojet engine with pyro-starter is described with artificial elements in the control unit. We must underline that it is not the only solution, the optimum could be different: the minimum time, the minimum fuel spent, the minimum temperature or compromise between these requirements. However, it shows typical sequences and challenges for engineers dealing with similar engines.

IV ACKNOWLEDGEMENT

The authors want to thank to EDePro company for their support because the material shown belongs to their turbojet engine TJE-45.The research results presented in this work were supported by the Ministry of Science, Technological Development, and Innovation of the Republic of Serbia under contract 451-03-137/2025-03/200105 and 451-03-136/2025-03/ 200213 from 04.02.2025.

V REFERENCES

[1] D.E. Barbeau, *A Family of Small, Low Cost Turbojet Engines for Short Life Applications*, ASME 81-GT-205, 1981.

Alternative ways to test components of turbojet engines and innovative, artificial intelligence approach for operation

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I INTRODUCTION

Compressor, combustor and turbine are propulsion elements which are forming so called gas-generator and are usually tested during engine development phase. Testing of compressor requires power element to generate the power and also that element must deliver required power at compressor angular speed. Standard solution is to use electric motor and multiplicator-gear box but that choice could be substituted with alternative solutions. Testing of combustors requires source of air and heater in order to simulate conditions at turbine entrance. Testing of turbine traditionally consists of dynamometer and reducing gear box. The alternative ways of testing could be beneficial from standpoint of price and envelope of the operation and also an innovative artificial intelligence type approach is applied for automatic operation.

II ARANGEMENT OF TESTING FACILITY

The proposed presented facility is shown at the figure 1.

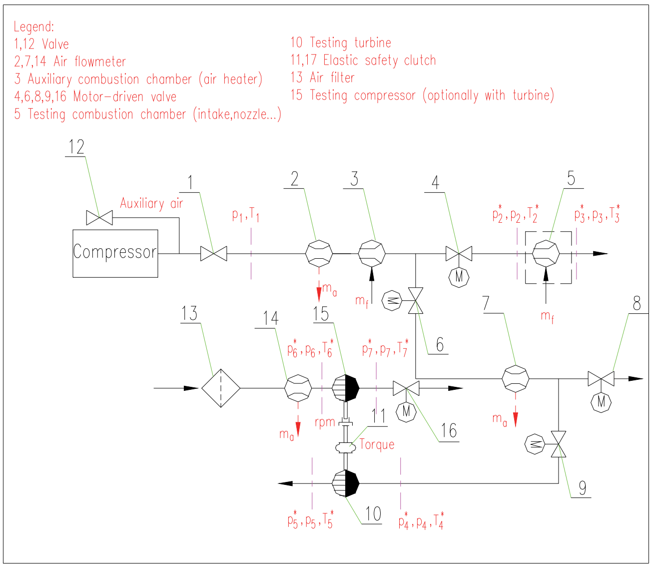

Fig. 1. Layout of laboratory for testing turbojet engine components

It consists of air compressor, which serves to supply the air to facility. The air passes through flow measurement orifice and then could be preheated at preheater (3) which is actually modified combustor from turbojet. Now, if want to test combustor (5) the preheated air will be directed through valve (4). If we want to test turbine, preheated air is supplied through valves (6) and (9) to the testing turbine (10) while the modified compressor from turbojet engine will serve as power absorber (15). If we are testing compressor (15) everything is the same except the turbine (10) is now modified for that purpose.

Practically, except of air supply compressor which is commercial item, we could test main turbojet components (compressors, combustors and turbines) using modified or designed for that purpose compressors, combustors and turbines. The point is that we could increase range of testing and decrease the cost of the facility by using similar elements and knowledge how to design and use these elements. On the other hand these elements are not industrial standard elements and their life generally would be lower. In order to allow regular functionality of the facility control system with elements of artificial intelligence is introduced. Control system is generally allowing automatic function of the facility but incorporates functions which are related to vibration monitoring of compressors (15) and turbines (10) and associated bearings temperatures. More than this it is capable to substitute the operator for typical testing i.e. performing all procedures to get compressor and turbine map as well as combustor stability loop.

III CONCLUSION

The proposed concept of turbojet engine concept testing facility shows innovative solutions of testing engine components. It is capable to test very wide range of elements, practically the only limiter is capacity of air supply compressor or optionally battery of them. It allows to engineers to combine propulsion elements and extract required data from testing while using innovative solutions in energetic components and control units.

IV ACKNOWLEDGEMENT

The authors want to thank to EDePro company for their support because the material shown was used in their laboratories. The research results presented in this work were supported by the Ministry of Science, Technological Development, and Innovation of the Republic of Serbia under contract 451-03-137/2025-03/200105 and 451-03-136/2025-03/ 200213 from 04.02.2025.

V REFERENCES

[1] J. Erhard, *Design, construction and commissioning of a transonic test-turbine facility*, PhD thesis, Institute of thermal turbomachinery and machine dynamics, Technical University of Graz, Austria, 2000.

Challenges in spill out lubrication systems in expendable turbojets and elements of artificial intelligence

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I INTRODUCTION

Expendable turbojet engines are used in applications with limited life. Therefore, their design is supposed to be simple and low cost. Consequently, their subsystems, such as lubrication system have to be simple and reliable which are somehow opposite requirements which are imposing challenges is such systems. Elements of artificial intelligence are applied in order to control and improve reliability.

II REVIEW OF TYPICAL SOLUTIONS

The method of applying the oil or fuel in spill out systems depends on engine architecture and designer choice. Expendable turbojet engines are covering the range of thrust from 40 to 400 daN and that dictates their size and design. Typical configurations are listed below.

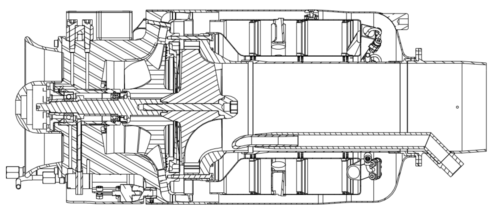

Fig. 1. Configuration 1: radial compressor + radial turbine, back to back

In the configuration number 1 with radial compressor and turbine positioned back to back oil or fuel for lubrication is supplied in front of first bearing or in front of both, first and second bearing. Air is entering through holes generator cover in the front of the engine, then passing through both bearings, transferring the fuel and oil, cooling the bearings and then entering in the main flow in front of the compressor due to low static pressure at compressor entrance. Air is at atmospheric pressure and temperature which causes the perfect conditions for the bearings.

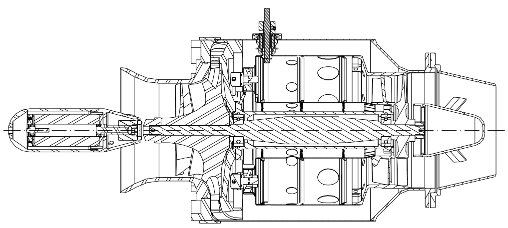

Fig. 2. Configuration 2: radial compressor + axial turbine

In the configuration number 2, the air is taken after compressor rotor and supplied through first and second bearing and then exiting in front of the turbine rotor due to pressure difference. The oil or fuel is supplied in front of first only or in front of first and second bearing. The air temperature is as after the compressor so the bearings used should be selected for higher temperatures.

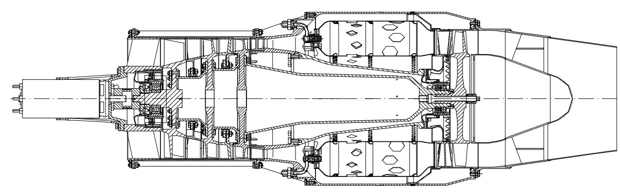

Fig. 3. Configuration 3: axial compressor + axial turbine

In the configuration number 3, the air for the front bearing is entering through generator cover in the front of the engine and then passing through the bearing and exiting at compressor entrance, practically the same as in configuration 1. The oil or fuel should be supplied in front of the bearing. The air for the rear bearing is taken after the third stage of the compressor, passing through the bearing and exiting at turbine rotor inlet due to pressure differences between these two points, practically the same as in configuration number 2. The oil or fuel is supplied in front of the bearing.

Common for all three mechanical configurations is incorporation of criteria for reliability. Control system is monitoring vibration level, temperature of the bearings and oil or fuel flow used for lubrication and cooling. If temperature or vibration level exceeds certain level the control system will react as a human: it will try to reduce rpm while increasing lubrication flow.

III CONCLUSION

Typical solutions for spill out lubrication systems used in expendable turbojets are described. Although they depend on engine architecture it was shown that practically the same solutions were used. Artificial intelligence was incorporated in control system in order to improve the reliability of the system.

IV ACKNOWLEDGEMENT

The shown layouts of configurations are from the real motors from EDePro company. The research results presented in this work were supported by the Ministry of Science, Technological Development, and Innovation of the Republic of Serbia under contract 451-03-137/2025-03/200105 and 451-03-136/2025-03/ 200213 from 04.02.2025.

V REFERENCES

[1] J.F. Rideau, G. Guyader, A. Cloarec, *Microturbo Families of Turbojet Engine for Missiles and Uav's From the TR60 to the New Bypass Turbojet Engine Generation*, In 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exibition, Hartford, CT,21-23 July 2008., paper no: AIAA 2008-4590, 2008.

EUROPEAN MECHANICS SOCIETY

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Combining solar production with pumped hydropower for settlement-scale decarbonization and grid balancing

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I INTRODUCTION

The energy system is a significant contributor to atmospheric carbon dioxide emissions, and thus directly influencing climate change [1]. To mitigate these effects, the transition to sustainable, renewable energies has a globally high priority [2]. Over the last decade, the number of operating solar systems has boosted, which facilitates the decarbonization efforts. However, the highly fluctuating and the varying, partially asynchronous nature of electricity supply and demand pose new and unsolved challenges for system stability, both locally and across the high-voltage transmission networks [3]. During peak solar irradiation hours, photovoltaic overproduction can overload the grid, while during the mornings and afternoons, the rapid changes in solar radiation require dynamic counteractions and regulation by the system operators [4].

II METHOD

This study examines an energy management and conversion strategy to overcome these production fluctuations in a hilly settlement. The proposed near-carbon-neutral and sustainable energy concept consists of three core elements as shown in Fig. 1.:

(1) the storage of surplus solar energy during peak production hours;

(2) the subsequent utilization of the stored energy when there is no solar production; and

(3) the combination of hydropower reservoirs and stormwater management.

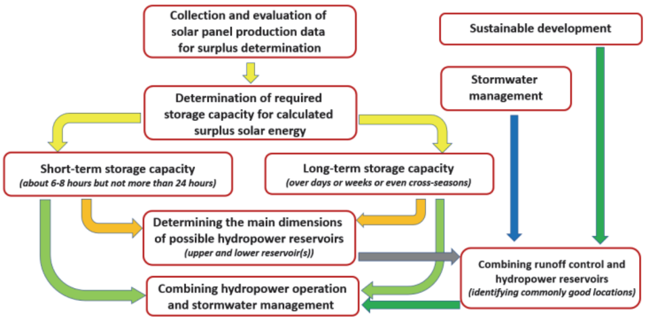

Fig. 1. Flow chart of research activity

A pumped hydro storage system is designed and optimized to complement the existing systems and the planned solar developments. The storage capacity of hydropower reservoirs is determined based on multiple optimization criteria – technical, environmental, social, and economic – and the effect of several solar expansion scenarios are analyzed to consider their impacts on production and storage needs.

III CONCLUSION

The results show that integrating pumped hydro storage (Fig. 2.) can significantly increase the energy independence of the settlement, support a sustainable, low-carbon electricity supply, and improve water management possibilities.

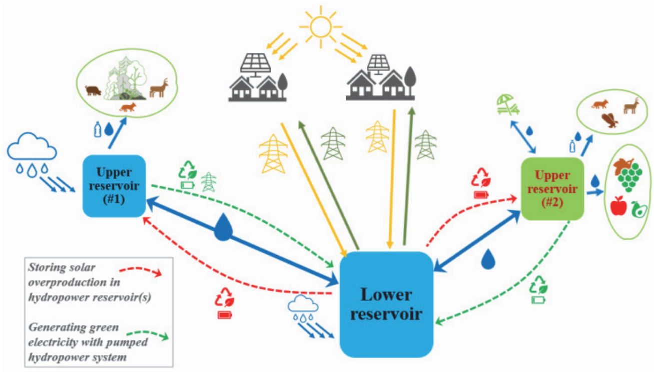

Fig. 2. System layout of combined solar and pumped hydropower electricity production and system balancing

Life-cycle-based optimizations result in relatively fast returns on investment in both single- and multi-criteria assessments, with most scenarios achieving positive returns as early as the first quarter of their lifespans.

IV ACKNOWLEDGEMENT

The research presented in this article was carried out within the framework of the Széchenyi Plan Plus program with the support of the RRF 2.3.1 21 2022 00008 project.

V REFERENCES

[1] International Energy Agency, https://www.iea.org/energy-system/renewables

[2] Q. Hassan et al., *The renewable energy role in the global energy Transformations*, Renewable Energy Focus, vol. 48, 100545, 2024.

[3] G. Yang, D. Yang, B. Liu, H. Zhang, *The role of short- and long-duration energy storage in reducing the cost of firm photovoltaic generation*, Applied Energy, vol. 374, 123914, 2024.

[4] S. Impram, S.V. Nese, B. Oral, *Challenges of renewable energy penetration on power system flexibility: A survey*, Energy Strategy Reviews, vol. 31, 100539, 2020.

Experimental and numerical analysis of the fatigue fracture behavior of the Ti-6Al-4V alloy

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I INTRODUCTION

This paper presents the results of an experimental and numerical analysis of the fatigue fracture behavior of the selected Ti-6Al-4V alloy, which was chosen because of its frequent use in industrial applications [1-3].

Brittle fracture typically occurs due to the presence of cracks, notched [1,2] or stress concentrators [3], whereas the stresses in these regions represent the crucial factor in determining if the crack will propagate under the acting load. Brittle fracture is preceded by small strain. Unstable crack growth occurs when crack driving force reaches its critical value, given by the equation (1) below.

$$\sigma_c = \sqrt{\frac{E}{\pi}\frac{G_{IC}}{a}} \qquad (1)$$

Hence, fracture criteria is determined by crack growth which corresponds to critical stress values, which is related to critical crack driving force.

II EXPERIMENTAL AND NUMERICAL INVESTIGATION

Experimental investigations of specimens taken out of Ti-6Al-4V titanium alloy plates were performed to determine the critical stress intensity factor, K_{Ic}. in order to evaluate the fatigue behavior of this material, in the presence of a crack-type defect. For testing, compact tension specimens C(T) were used, the geometry of which is defined by the standard, as a tension-loaded plate with a notch on only one side and a fatigue crack. Tests were performed on modified test specimens of small thickness where, after determining the experimental values of K_Q, the parameters $CTOD_c$ or J_c were determined, according to the ASTM E1820 standard.

During the experimental tests to monitor the material's behavior in relation to the crack-type error, a test system based on the optical measurement methodology was applied. The GOM optical system and Aramis software were used for three-dimensional experimental optical analysis of selected titanium alloy. Based on the experimental research, the results related to the fracture behavior and fracture mechanics parameters of the selected material were obtained. As part of further research, numerical models of the tension test specimens C(T) were made based on the dimensions of the modified test specimens that were used in the experimental analysis. Simulation and analysis of fatigue crack growth was performed on the numerical models defined in this way, and the number of cycles leading to failure was determined. The variations of the K_I parameter along the crack front were numerically calculated.

III RESULTS AND DISCUSSION

To overcome the limitations of classical finite element methods (FEM) in simulating crack growth, which require creating a new mesh after each growth step, this research employs the SMART crack growth feature of ANSYS software. This option significantly enhances the numerical modeling of crack growth, and the results show that this approach enables accurate modeling of crack behavior. The results of test specimens with a crack show the local behavior of the material around the crack tip and assume that the material of the test specimens is homogeneous enough, which means that the results of the local behavior can be treated globally, that is, they can be directly transferred to the appropriate construction.

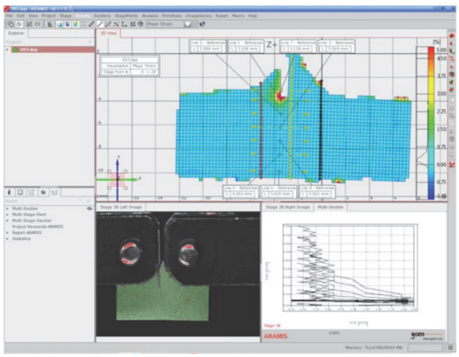

Fig. 1. Strain field in the biomaterial during crack growth

IV CONCLUSION

The results of this research show the field of main deformations under tensile load acting on the test specimen during the crack tip opening, its growth and fracture. It can be concluded that the influence of the heterogeneity of the structure and mechanical properties of biomaterials on exploitation is primarily reflected in the position of the tip of the fatigue crack and the characteristics of the area through which the fracture develops.

V ACKNOWLEDGEMENT

This study was funded and supported by the Ministry of Science, Technological Development and Innovation of the RS (Contr. 451-03-136/2025-03/200213), Slovenian Research Agency ARIS for the research program P2-0137 Numerical and Experimental Analysis of Nonlinear Mechanical Systems and Serbian–Hungarian joint research project no. 9 (2024–26) – Structural optimization of additively manufactured cellular titanium implant using artificial intelligence

VI REFERENCES

[1] A. Sedmak et al., *Fatigue crack growth in locking compression plates*, Int. Journal of Fatigue, 157, 106727, 2022.
[2] K. Čolić et al., *Structural Integrity and Life Assessment of Ti-6Al-4V Orthopaedic Implants*, Metals, Vol. 15/ 3: 333, 2025.
[3] K. Čolić et al., *Numerical analysis of static stresses in partial hip implant*, Structural Integrity and Life, Vol. 24/1, pp. 17-20, 2024.

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through
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Guided waves and artificial neural networks in classification of discontinuity location on the steel plate surface.

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I INTRODUCTION

Early diagnosis of problems resulting from surface defects on flat components of technical objects is a challenge in many engineering fields. Early detection and localization of discontinuity, such as corrosion spots, dents, or the deposition of foreign materials like sediment or dirt, can help avoid serious consequences, such as failure or serious, irreversible damage to the structure or machinery.

This paper presents the diagnostic results for a flat element in the form of a steel plate with disturbances in the form of a concentrated mass located at various locations. The goal of the algorithm was to classify the location of the additional mass into one of the defined classes. The study utilized the elastic wave propagation method and artificial neural networks (ANN) as an inference tool.

II LABORATORY MEASUREMENTS

Laboratory measurements were conducted on a 2000x1000x1 mm steel sheet, to which a set of PZT transducers was attached using flexible thermal adhesive. The transducer configuration had a rosette shape with a diameter of 360 mm, with each piezoelement serving as an exciter and elastic wave sensor. In a single measurement cycle, one of the piezo elements acted as a wave exciter, while the others served as sensors. Further analysis considered only the wave propagation paths located between the opposing rosette transducers (Fig. 1a). Measurements were performed for 129 disturbance locations in the form of an additional mass, which were divided into 25 classes. Examples of discontinuity location classes are shown in Fig. 1b.

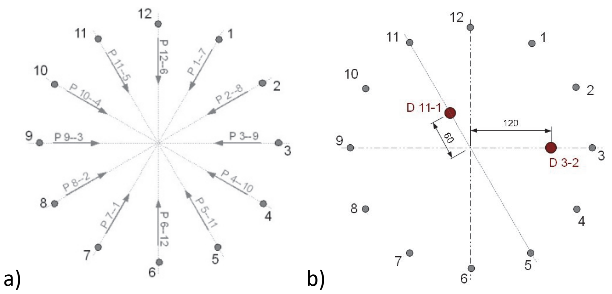

Fig. 1.Sensor grid (a) and sample discontinuity location (b).

It was assumed that the occurrence of a disturbance in the wave's path results in changes in the recorded time course. At the same time, the time courses of waves traveling sufficiently far from the introduced disturbance are not modified. Analysis

of the magnitude of the changes, taking into account the paths along which these changes occur, can lead to determining the location of the disturbance. Example time signal, along with the path on which they were recorded, is presented in Fig. 2. The parameter characterizing a single wave course was assumed to be the ratio R of the amplitude of the first wave packet (passing directly through the area inside the rosette) to the amplitude of the second wave packet (reflected from the edge of the model).

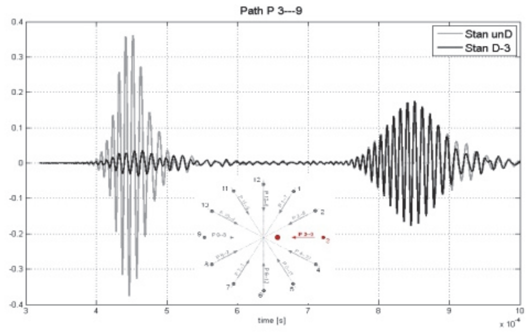

Fig. 2. Example time signal for a path passing near a discontinuity

III CLASSIFICATION TASK

A unidirectional ANN network with backpropagation of errors, nonlinear (sigmoidal) activation functions, and the Levenberg-Marquardt learning algorithm were used to classify the disturbance location. The input vector consisted of 12 elements representing the R parameters for paths showed on Fig. 1a. The output vector consisted of the class indices of the disturbance location, and depending on the classification stage. The results in the form of a confusion matrix for an example classification are presented in Fig. 3.

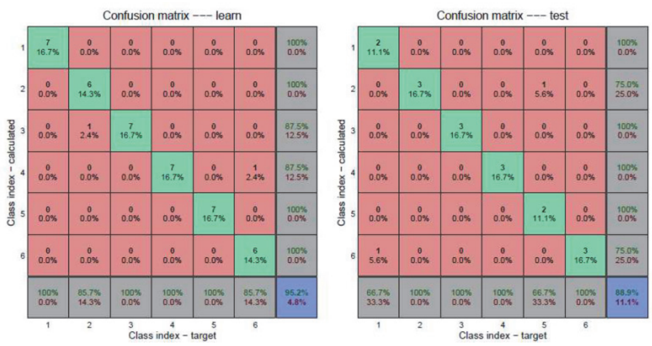

Fig.3. Confusion matrix for an example classification

IV CONCLUSION

The use of a hybrid approach, measuring a physical phenomenon such as an elastic wave and inferring it using soft computing as an ANN, allowed to obtain an efficient diagnostic tool for a simple laboratory case. It is possible to extend the method to make it effective for real structures.

EUROPEAN MECHANICS SOCIETY

The Euromech Colloquium 650 – Addressing Challenges in Applied Mechanics through Artificial Intelligence Applications, August 27– 29, 2025, Belgrade, Serbia

Heart failure modeling

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I INTRODUCTION

Transport across biological barriers such as vessel walls and cell or organelle membranes depends on their hydraulic and diffusion coefficients and the size of the surfaces separating different tissue compartments. In electrophysiology, the focus is on characterizing the properties of various body areas and how signals propagate. The SILICOFCM project (2018–2023) modeled familial cardiomyopathy by integrating patient-specific genetic, biological, pharmacological, and imaging data into a coupled multiscale model that simulates sarcomeric function, genetic profiles, electrophysiology, muscle fiber orientation, and fluid interactions within the heart. Initial results demonstrated that deformation in the left ventricle influences mitral valve movement and blood flow, while the model also examined drug distribution and effects, providing insights for treatment strategies. Accurate risk stratification and early diagnosis of heart failure (HF), which are essential for effective prevention and management, remain challenging due to non-specific early symptoms and limitations in existing clinical models.

II MATERIALS AND METHODS

The movement of fluid in the left ventricle can be considered as a laminar flow of the incompressible fluid, which is described using the continuity equation and Navier-Stokes equations:

$$-\mu\nabla^2 v_l + \rho\left(v_l \cdot \nabla\right) v_l + \nabla p_l = 0\,, \qquad (1)$$

$$\nabla v_l = 0\,, \qquad (2)$$

where v_l is the blood flow velocity, p_l is the pressure, μ is the coefficient of dynamic viscosity of blood, and ρ is the density of blood. These equations can be transformed into the balance equations of a FE by using the Galerkin method. The incremental-iterative balance equation of a FE for a time step 'n' and equilibrium iteration 'i' has the form

$$\begin{bmatrix} \frac{1}{\Delta t}\mathbf{M} + {}^{n+1}\tilde{\mathbf{K}}_{vv}^{(i-1)} & \mathbf{K}_{vp} \\ \mathbf{K}_{vp}^{T} & \mathbf{0} \end{bmatrix} \begin{Bmatrix} \Delta\mathbf{V}^{(i)} \\ \Delta\mathbf{P}^{(i)} \end{Bmatrix}_{blood} =$$

$$\begin{Bmatrix} {}^{n+1}\mathbf{F}_{ext}^{(i-1)} \\ 0 \end{Bmatrix} - \begin{bmatrix} \frac{1}{\Delta t}\mathbf{M} + {}^{n+1}\mathbf{K}^{(i-1)} & \mathbf{K}_{vp} \\ \mathbf{K}_{vp}^{T} & 0 \end{bmatrix} \begin{Bmatrix} {}^{n+1}\mathbf{V}^{(i-1)} \\ {}^{n+1}\mathbf{P}^{(i-1)} \end{Bmatrix} + \begin{Bmatrix} \frac{1}{\Delta t}\mathbf{M}\,{}^{n}\mathbf{V} \\ 0 \end{Bmatrix}, \qquad (3)$$

where ${}^{n+1}\mathbf{V}^{(i-1)}$ and ${}^{n+1}\mathbf{P}^{(i-1)}$ are the nodal vectors of blood velocity and pressure, with the increments in time step $\Delta\mathbf{V}^{(i)}$ and $\Delta\mathbf{P}^{(i)}$; Δt is the time step size and the left upper indices 'n' and 'n+1' denote start and end of the time step.

Although the solutions are obtained with different FE solvers, the parameters from one solution which affect the solution for the other medium are transferred successively (Kojić et al. 2008, Filipović et al. 2022a, 2022b).

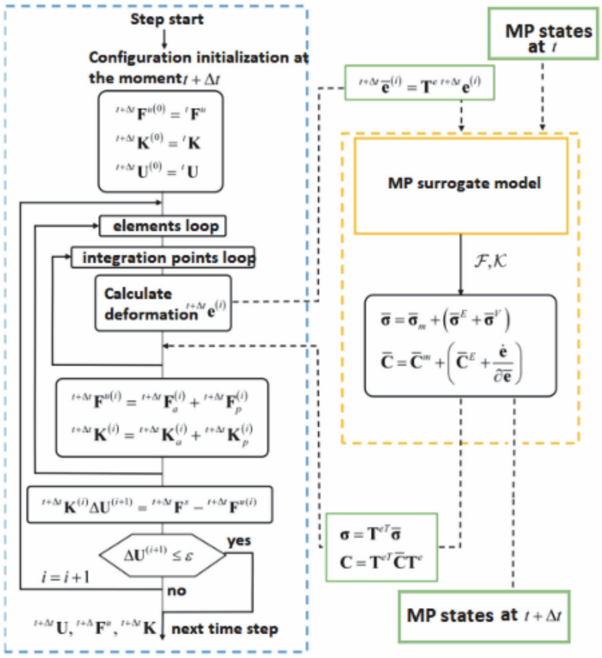

Fig. 1. Algorithm: FE analysis and MP surrogate model (Milicevic et al 2023, Filipovic et al 2022a, 2022b)

III RESULTS

The pressure-volume diagram, velocity distribution in the diastolic and systolic phase for the case after Entresto treatment is presented in Fig. 1 (Milićević et al. 2023, Filipović et al. 2022a, 2022b).

After Entresto treatment (Fig. 2), we can observe a lower systolic pressure as well as an increasing difference between the end of diastolic and the end of systolic volume. It directly leads to the increase in the ejection fraction.

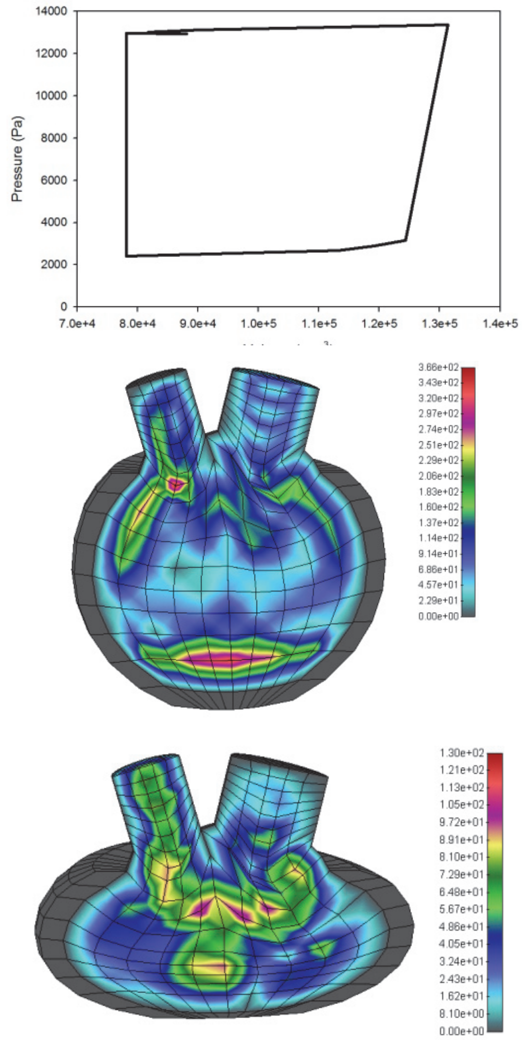

Fig. 2 PV diagram, velocity distribution in the diastolic phase, velocity distribution in the systolic phase for the case after Entresto treatment.

IV CONCLUSION

The study faced limitations including insufficient detail on the heart's physical and biological characteristics and difficulties in accurately estimating subject-specific parameters from limited, noisy, non-invasive data, which can prolong computations since large-scale finite element analyses may take several hours. Despite these challenges, computational platforms such as SILICOFCM (2018) and STRATIFYHF (2023) serve as innovative tools for evaluating familial cardiomyopathy and heart failure risks in individual patients, thereby advancing the potential for future in silico clinical trials.

V ACKNOWLEDGEMENT

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VI REFERENCES

[1] N. Filipović, I. Saveljić, T. Šušteršič, M. Milošević, B. Milićević, V. Simić, M Ivanović, M Kojić, *In Silico Clinical Trials for Cardiovascular Disease*, J Vis Exp, 183, 2022a.

[2] N. Filipović, T. Šušteršič, M. Milošević, B. Milićević, V. Simić, M. Prodanović, S. Mijailović, M Kojić, *SILICOFCM platform, multiscale modeling of left ventricle from echocardiographic images and drug influence for cardiomyopathy disease*. Comput. Methods Programs Biomed, vol. 227, 107194, 2022b.

[3] M. Kojić, N. Filipović, B. Stojanović, N. Kojić, *Computer modeling in bioengineering: Theoretical Background, Examples and Software*. Chichester, England: John Wiley and Sons, 2008.

[4] M. Kojić, N. Filipović, M. Živković, R. Slavković, N. Grujović, *PAK-FS Finite Element Program for Fluid-Structure interaction*. Kragujevac, Serbia, 2008.

[5] B. Milićević, M. Milošević, V. Simić, D. Trifunović, G. Stanković, N. Filipović, M. Kojić, *Cardiac hypertrophy simulations using parametric and echocardiography-based left ventricle model with shell finite elements*, Comput. Biol. Medicine, vol. 157, 106742, 2023.

[6] SILICOFCM project (2018-2023), *In Silico trials for drug tracing the effects of sarcomeric protein mutations leading to familial cardiomyopathym*, EU Horizon 2020, No 777204, www.silicofcm.eu

[7] STRATIFYHF project (2023-2028), *Artificial intelligence-based decision support system for risk stratification and early detection of heart failure in primary and secondary care*, European Union's Horizon Europe research and innovation programme under grant agreement No 101080905, https://stratifyhf.eu/

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The Serbian Society of Mechanics (SSM) is a professional organization focused on the field of mechanics, encompassing both theoretical and applied aspects. It aims to foster research, education, and collaboration within the mechanics community in Serbia and internationally. The society covers a broad range of mechanics, including classical, solid and fluid mechanics, computational mechanics, biomechanics, applied mathematics/physics, structural mechanics, and engineering.

Activities: International Congresses: The SSM organizes international congresses to bring together researchers and practitioners to discuss the latest advancements in mechanics. The society publishes the Journal of the Serbian Society for Computational Mechanics, which focuses on original research in computational mechanics and related methods.

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TIM-INVEST Ltd. is a company for engineering, production and services founded in 2000. The headquarters of the company is in Belgrade. Our business orientation and main activities are foreign and domestic trade, engineering and consulting in the field of energy, mining and metallurgy in the territory of Serbia and the territory of the former republics of SFRY.

Given the fact that our biggest customers are public companies in the field of mining and energy, we also specialize in business in the field of public procurement.

Through long-term representation and successful cooperation with renowned European ironworks, forges and foundries, the company has proven itself as the most important distributor of pre-processed and final-processed steel forgings and castings of various weight classes, from 100 kg to 37,000 kg, with an emphasis on the production of high-quality and dimensionally specific machine parts of a wide range of materials and demanding technical specifications according to the client's documentation.

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Our vision is to be strong global company for our clients, partners and employees recognisable by its values:

- Excellence is what makes us the best.
- We change the world with our innovativity.
- Integrity is the essence of our business.
- We always strive to greatest accomplishments.
- Human care is the foundation of our success.
- Our business philosophy is based on integrity, honesty and respect we have earned with our expertise and dedication to achieve best solutions for our clients.

GIR Ltd.

GIR was created from a small family business, driven by the passion and desire to create. In over 25 years it has become what it is today – a modern company that has a complete system of production of the best quality wood furniture, distribution worldwide, multi-brand shop, and from recently its own furniture collection.

GIR furniture factory was founded in Kraljevo over two decades ago as a small family company with lots of enthusiasm and work drive. Today, GIR employs almost 600 people, and their furniture decorates homes all around the world and the wheels of production are in full throttle.

GIR Store is a multi-brand shop, located in Belgrade, which gathering in one place all sorts of home products – from furniture, through lighting, up to art objects and accessories. It brings together producers and designers with a view to exchanging and implementing ideas in a space which enables a contextualization and understanding of the design.

Uncompromising dedication to quality and staunch commitment to design, identified in clear and modern form, have naturally allowed for another evolutionary step of GIR company, this time in the form of an author collection. New series of GIR products is marked by a modern character, but also the spirit of the heritage of the Balkans, along with a strong emphasis on technology and design, a trait that made our company renowned throughout Europe.

Radijator Inženjering Ltd.

In business terms, Radijator Inženjering Ltd. is a legal successor of a craftsman shop Radijator founded in 1991 whose main service has been the installation and maintenance of central heating up to this day. We made the first hot water boiler on solid fuel in 1985.

The company, as it is today, has existed since 2002 and has been taking huge steps as the years went by always tending to be the first in the use of new technologies, product quality, and conquering new - European markets. As we have been expanding and improving production, we have reached the point of making boilers by using the latest technologies. From the domain of sheet metal cutting, the following processes stand out: laser cutting, CNC plasma cutting process, and CNC punching. The process of welding is done by the machine (robot) as well as automatically. The greatest indicator of product and service quality is the fact that production increases annually.

Today, Radijator Inženjering employs over 350 employees including 40 Bachelors with honours in Mechanical Engineering who constantly work on improving product quality.

Assured constancy of product quality as well as of the company's business practices was confirmed by the acquisition of system quality certificate ISO 9001:2008.

Aqua crystal Ltd.

AQUA CRYSTAL is reliable partner in the development, design, construction and maintenance of swimming pools, drinking water and wastewater treatment plants, cooling and technological water in production facilities. Aqua crystal Ltd. is a spinoff company founded in 2009.

The main mission of the company is to commercialize the latest results of scientific research work in the field of water treatment. Aqua crystal Ltd. offers its clients water quality analysis services (drinking, waste, technological). Based on the obtained results, we provide the best technical and commercial solutions in order to solve the problem of water purification. We design the appropriate equipment, carry out the works, put the finished equipment into operation and train the personnel. We also offer reconstruction services for existing water treatment plants, equipment maintenance, on-site parameter checks, as well as remote monitoring and management via Ethernet. We monitor the operation of the installed equipment and, if necessary, correct the operation in order to obtain water of the specified quality. In agreement with the investor, we periodically monitor the operation of the water purification plant.

About the city of Belgrade

(source: https://www.beograd.rs)

Belgrade is one of the oldest cities in Europe. Besides Athens, it is the largest urban area in the Balkans. Located at the confluence of the Sava and the Danube, our city bears many millennia old symbols. The oldest traces of human settlements in the area of today's Belgrade date back to the Paleolithic Age. Members of the Celtic tribe founded Singidunum in the 3rd century B.C. while Belgrade was first mentioned in 878 A.D. During its long and turbulent history, Belgrade was conquered by 40 armies and has been raised from the ashes 38 times.

The City of Belgrade is the capital city of the Republic of Serbia and its biggest urban, economic and educational centre. Around 1.6 million people live in Belgrade. Belgrade has first-class traffic importance as a significant road and railway centre, as well as an international river port and airport and a telecommunication centre. It covers an area of 3.6% of the territory of Serbia. 15.8% of the Serbian population lives in Belgrade and 31.2% of all employees in Serbia work in Belgrade.

Significant economic and agricultural capacities have been developed in Belgrade, especially the metal industry, the metal-processing and electronic industry, as well as trade and banking. In the wider area of Belgrade, Smederevo and Pančevo, on the banks of the Danube, there is 2,000 m² free trade zone. 30% of the national products of Serbia are developed in Belgrade.

Belgrade is the capital city of the Serbian culture, education and science. It has the highest number of institutions in the field of science and art of national importance. The Serbian Academy of Science and Art founded in 1886 as the Serbian Royal Academy, the National Library of Serbia founded in 1832, the National Museum founded in 1841 and the National Theatre founded in 1869 are located in Belgrade. The University of Belgrade founded in 1808 as the Great School, as well as the University of Art are located in Belgrade.

Belgrade has the status of a separate territorial unit in Serbia with its autonomous city administration. Its territory is divided into 17 municipalities that have their own local authorities.

Belgrade – beginning of Knez Mihailova street: 1930 and 2022 [1]

[1] Source: Wikimedia Commons –
„Old phtograph of the Belgrade, the capital of Serbia“, Public Domain;
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