Abstracts submitted to EURODINAME III

This proceedings volume presents the abstracts submitted for the EURODINAME conference. The topics are those proposed by the authors at the time of submission and do not predetermine the placement of the presentations during the conference.

Topic: Acoustics and vibroacoustics

Optical visualization and motion control of acoustically levitated particles

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This paper studies the controlled movement of acoustically levitated particles along a designated path by combining phase-based boundary control of actuators with mechanical tilting. The ultrasonic field is visualized using optical (Schlieren) imaging with stroboscopic modulation. The latter enables the separation of energy flux (traveling waves) from standing acoustic waves. Extensive simulations and experiments underscore the importance of incorporating impedance boundary conditions to model the pressure distribution accurately. The study challenges common modeling assumptions-especially the use of scalar Gor'kov potential formulations in standing wave analysis-and proposes an alternative approach that involves the acoustic intensity vector field. The local balance of standing and traveling waves is quantitatively evaluated through RMS calculations of this vector field and the real and imaginary parts of the acoustic pressure field. Boundary Element Method (BEM) simulations are extensively performed, validated, and refined using experimental data and Schlieren visualization. A modified Schlieren imaging technique, integrating an ABEL transformation designed to eliminate optically accumulated pressure artifacts, successfully reconstructs the true cross-section of the acoustic field.

Acoustics and vibroacoustics - Paper 10399

Reinforcement Learning Technics For Reaching Stable Control Of Electroacoustic Absorbers

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In recent years, active noise control approaches have gained growing interest in the market, being used in devices such as earbuds and headphones. One promising direction involves Electroacoustic Absorbers (EAs), systems that combine a loudspeaker diaphragm with collocated microphones. By monitoring the pressure inside a cavity and applying a control algorithm, the absorber adjusts the velocity at the resonator's surface to enforce a target acoustic impedance. This enables custom absorptions at specific frequency targets.This type of control differs from conventional active noise control by not employing the concept of anti-noise. Instead of creating a quiet zone, these devices modify the boundary conditions of a chamber, much like passive solutions such as porous materials or Helmholtz resonators.Although specific impedances can currently be targeted, these systems remain incapable of self-adapting their control algorithms to different conditions and are prone to instability depending on the target impedance. To overcome these limitations, this work explores the use of reinforcement learning (RL) to improve adaptability and robustness under changing environments.Reinforcement learning is a subset of machine learning algorithms in which an agent learns to identify an environment while taking actions to optimize its performance. It does so by receiving from the environment a reward function, which must be optimized to achieve its highest value over time. These techniques differ from traditional machine learning in that they do not require a pre-existing dataset to be trained. Thus, the agent can be deployed in an environment and learn its particularities from the data it collects, without relying on previously known information. By constantly updating the world model it constructs, the algorithm can track changes in the environment and adapt its policy accordingly.In this study, off-the-shelf reinforcement learning algorithms will be deployed to enhance the functioning of the current control strategy in order to reduce its instabilities while still making it capable of achieving the target absorption.

SPATIAL MODULATION OF ELECTROACOUSTIC ABSORBERS FOR PROGRAMMABLE WAVEFRONT CONTROL

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Controlling noise in built environments and transportation systems is of central importance in modern society, and recent developments in acoustic metasurfaces are opening new horizons for sound manipulation. Acoustic metasurfaces are composed of individual elements that can control the acoustic wavefield at a subwavelength scale and can be classified as passive or active. The concept of active acoustic metasurfaces, which can adapt their properties based on operational targets, has received significant attention in recent years. These metasurfaces can be built using diverse technological solutions, among them electroacoustic absorbers. These devices are composed of a loudspeaker and microphones, acting as local resonators that interact directly with the wavefield. By controlling the electrical current in the loudspeaker, it is possible to modify the acoustic impedance at the boundaries of the domain. The real-time adaptation and reconfigurability of electroacoustic absorbers make them a versatile framework for implementing noise control strategies. While previous work has focused on uniform control strategies, the effects of spatially varying the control laws of electroacoustic absorbers on the complete scattered field remain largely unexplored. This represents a significant gap, as spatial modulation of individual absorber properties could enable wavefield steering and anomalous reflection capabilities not achievable with uniform control. This work presents a theoretical framework for spatially modulating the control law parameters of electroacoustic absorbers and evaluates the impact of this modulation on the scattered acoustic field. A spatially varying resonant behavior is achieved by imposing a periodic spatial modulation on the active control law of the electroacoustic absorbers. To compute the scattered field under these conditions, an analytical Bloch-Floquet approach is developed specifically for spatial modulation of the control parameters. A numerical application is presented demonstrating control of the reflected field by spatially modulating the phase angle of the control law. This allows for an acoustic implementation of the Generalized Snell's Law, enabling beam steering and anomalous reflection without requiring mechanical reconfiguration. The proposed framework provides a foundation for designing spatially programmable acoustic metasurfaces with enhanced wave manipulation capabilities, serving as a cornerstone to futher developments into spatio-temporally modulated metasurfaces.

Wave Propagation Analysis in One-Dimensional Periodic Rod Structures with Defects-Induced

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This study investigates wave propagation in one-dimensional periodic structures containing damage modeled as local disruptions in periodicity. The systems are analyzed using the elementary rod theory, where axial wave motion is governed by longitudinal displacement fields. The introduction of a damage, represented as a discontinuity in stiffness or mass distribution, breaks the translational symmetry of the periodic medium, leading to the emergence of localized modes and modifications in the dispersion characteristics. The research aims to establish a correlation between the location of the defect and the resulting alterations in the wave transmission spectrum. The dispersion diagram and frequency response function (FRF) of intact periodic rods are first obtained through formulations based on Bloch-Floquet theory, and compared with those of defective configurations, evaluated via the spectral element method (SEM). The analytical results reveal that the damage introduces defect modes within the band gaps, acting as wave traps that localize energy near the damaged region. Furthermore, the attenuation and phase characteristics of transmitted waves are significantly affected by the degree of stiffness reduction at the discontinuity. These findings highlight the potential of wave-based techniques for identifying and characterizing fractures in rod-like periodic media, contributing to structural health monitoring and the design of vibration-tolerant engineering systems.

Acoustics and vibroacoustics - Paper 10502

Numerical analysis of natural fibers from the Legal Amazon of Maranhão as acoustic absorbers

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Common in both industry and domestic environments, noise caused by unwanted vibrations is a problem that can be addressed within the field of vibroacoustics. The use of natural materials to replace synthetic fibers in the design of acoustic absorbers is currently being extensively studied. Considered a low-cost raw material, these natural fibers are biodegradable, contributing to the environment through their reuse, often resulting from waste from other production cycles. Very abundant in the Legal Amazon of Maranhão, this type of raw material has been studied to produce sound-absorbing panels due to its high noise attenuation capacity. In this context, we intend to study the raw materials existing in the Maranhão flora that are viable for use in panels as sound-absorbing materials for noise reduction. These characteristics can be obtained through analytical, numerical, and experimental methods. This work aims to perform numerical simulations to calculate the sound transmission loss and acoustic pressure of natural fibers from the Legal Amazon of Maranhão.

Topic: Damage detection and structural health monitoring

Unsupervised Detection of Leak Onset in Multiphase Flows using Hidden Markov Models

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Leak detection in multiphase flow pipelines is a critical challenge in industrial safety. Conventional alternatives, such as fixed-threshold methods, often fail as the leak's dynamic characteristics vary with the flow pattern. Moreover, time series segmentation methods, while effective, can be computationally prohibitive for high-frequency signals. This work proposes an unsupervised, computationally efficient method to identify the transition instant between normal operation and the onset of a leak using vibration signals. The experimental apparatus consists of a pipeline with a two-phase flow of mineral oil and sulphur hexafluoride, where a set of pilot-operated valves simulates leaks in upward, downward, and lateral directions. Monitoring is performed by four accelerometers positioned along the line, and their signals are segmented into 15ms windows, from which features in both the time and frequency domains are extracted. To classify the sequence of features into two states (no-leak and leak) a Hidden Markov Model (HMM) is employed with a customized transition matrix that prohibits the transition back from the leak state to the no-leak state, reflecting the irreversible physical nature of the event. Unlike clustering algorithms such as K-Means or Gaussian Mixture Models, which disregard the chronological order of data, the HMM models temporal dependency, resulting in a much more precise demarcation of the transition boundary. Furthermore, compared to segmentation methods which become extremely slow on high-frequency raw data, the proposed methodology is significantly faster. This efficiency is achieved by extracting computationally low-cost features, which effectively reduce the problem's dimensionality and accelerate HMM execution. Finally, the fully unsupervised nature of the approach eliminates the need for labelled data and allows for adaptation to varying flow conditions.

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Integrated Approach for Failure Investigation and Prevention in Large-Scale Hydromechanical Systems

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This paper describes a failure in a 350 MW generating unit driven by a Francis turbine resulted in significant damage to the turbine headcover. The design features a baffle plate, which partially detached and caused damage to the rotor. The monitoring system did not issue any alerts. The event required the complete disassembly of the unit and the shipment of components for repair, leading to a prolonged loss of generating capacity. Given the severity of the incident and the potential for similar occurrences in other units of the power plant, the utility company adopted a structured and multidisciplinary approach to manage the crisis and prevent recurrence.Immediately after the event, a partnership was established with a university to support the root cause investigation. The work included reviewing technical documentation, reprocessing monitoring system signals, mathematical modeling, and numerical simulations of the unit's components, as well as inspections and dynamic testing on the remaining machines. Preliminary results indicated that pressure pulsations and self-excited vibrations, associated with operational conditions, were major contributing factors to the failure. Based on these findings, urgent corrective actions were implemented. Metallographic and structural tests performed by a specialized institution identified deficiencies in the quality of welds at critical joints, which were insufficient to withstand dynamic stresses under certain operating conditions. Borescope inspections in the remaining units revealed similar defects at early stages. Consequently, mechanical reinforcements were emergently implemented in the baffle plate attachment by installing tie rods in a complex process, carried out with the units still assembled. Operation was resumed with intensive monitoring and continuous supervision of the identified critical areas. In addition to emergency actions, the utility initiated the development of long-term solutions focused on preventive maintenance and intelligent monitoring. Data acquisition and real-time diagnostic systems are being evaluated using vibration analysis and structural integrity techniques, aiming at the early detection of anomalies. Maintenance protocols were revised to include new inspection routines and non-destructive testing procedures. The manufacturing process of the new turbine headcover was also modified, replacing welded joints with more reliable fabrication methods. Continuous collaboration with universities and research institutes has been essential for developing innovative solutions and improving operational efficiency. The integrated response of the utility demonstrated that synergy between academic and industrial sectors is crucial to enhancing the reliability and safety of large-scale hydromechanical systems.

Robotic In-Situ Detection of Magnetic Wedge Looseness in Hydropower Generators Using AI

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Magnetic wedges are widely employed in hydropower generators to secure armature windings within stator slots, ensuring electromagnetic efficiency and mechanical stability during operation. However, prolonged cyclic loading, thermal stresses, and electromagnetic vibrations can progressively loosen the wedges, a critical failure precursor linked to insulation degradation, abnormal vibration, catastrophic machine failures, and reduced generator efficiency. Conventional inspection methods, such as manual percussion tests or partial disassembly, require extended outages and pose safety risks to inspectors; they also introduce strong operator dependence and subjective interpretation. To overcome these limitations, this work presents the development of an autonomous robotic system capable of in-situ detection of wedge looseness without stator disassembly. The proposed solution is a compact magnetic climbing robot (10 mm height, 250 mm width, 350 mm length) designed to navigate the narrow air gap of large generators. A solenoid-actuated impact module with an instrumented hammer locally excites the wedges, while a microphone captures the acoustic response for subsequent analysis via artificial intelligence. All motion-control and data-acquisition subsystems are fully embedded in the robot architecture, enabling remote operation and automated inspection. Experimental bench tests achieved 99% correct classification of wedge fastening conditions, demonstrating the system's feasibility for reliable, minimally invasive condition assessment.

Variational Autoencoder-Based Monitoring for Fault Detection in Wind Turbines

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As global wind energy capacity grows, ensuring the operational reliability and economic viability of wind turbines remains a critical challenge due to their susceptibility to unexpected failures that can compromise structural integrity and safety. Unsupervised deep learning has shown great promise in structural health monitoring, enabling automated fault detection through data-driven approaches. This work presents an unsupervised approach for anomaly detection in wind turbines using vibration signals acquired by accelerometers strategically placed across the turbine. The methodology is a Variational Autoencoder (VAE) trained exclusively on healthy operational data. By learning a compact latent representation of normal turbine dynamics, the VAE captures complex temporal and spatial patterns in the vibration signals. Deviations from this representation are identified as anomalies, enabling the detection of faults without requiring labeled failure data. This allows the detection of rare or unexpected events, such as rotor icing. The results highlight the potential of Variational Autoencoders for continuous, real-time monitoring, enhancing operational safety, reducing maintenance costs, and increasing turbine availability. By combining unsupervised deep learning with multivariate vibration analysis, the proposed methodology offers an efficient and flexible solution for early fault detection in wind turbines.

Damage detection and structural health monitoring - Paper 10558

Fusing physics, data, knowledge and uncertainty for Structural Health Monitoring

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This talk will describe the fusion of physics, data, knowledge and uncertainty for addressing challenges in in real-world engineering applications of Structural Health Monitoring (SHM), especially when hybrid physics-data (i.e., Physics-Enhanced Machine Learning) models are developed. The engineering applications would span from laboratory setups to bridges, ferry quays and offshore wind turbines. Initially it will be assumed that the physics is well-known, and that there is uncertainty in the "data", in terms of obtaining measurements at critical locations of wind turbines and ferry quays. This challenge is addressed by developing PEML strategies that enable to combine Operational Modal Analysis with probabilistic machine learning strategies, to yield virtual measurements at critical locations. These virtual measurements have been validated with real-world measurements obtained in operating conditions, showcasing the flexibility of It will be then considered that in typical engineering applications a partially correct physics-based model (uncertainty in the physics) of the underlying structure (e.g., without damage) is typically available, and confounding factors (including environmental and operational inputs, damage conditions, and other factors) are normally hidden in the structural response measurements (observable data). Blindly applying Bayesian Model Updating in such cases, would lead to a wrong assessment of the posterior distribution of the latent parameters of interest. In turn, this will affect downstream tasks such as damage detection and reliability assessment, therefore hindering the value of SHM. An adversarial Disentanglement strategy based on Backpropagation with Physics-Informed Variational Autoencoder is going to be presented. This approach enables learning disentangled representations of the contributing factors in the measurements that are used to build an explainable, controllable and robust digital twin with enhanced generalisation performance. A bridge-like case study is going to be detailed. Finally, an approach for dealing with the uncertainty in the knowledge of the force function model to be used to described non-smooth nonlinearities is going to be presented, with particular focus to the identification of the friction and vibro-impacts functional form of a laboratory setup.

Topic: Dynamics of metastructures and metamaterials

Dynamics of metastructures and metamaterials - Paper 10385

Modal interactions of an essentially nonlinear chain metamaterials

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In line with the economical and ecological realities of the current day, industries -such as aerospace- turn towards increasingly lighter structures, whose integrity and overall performance must nevertheless be at least equivalent to that of previous designs. In this context, metamaterials offer a promising alternative, since they can be taylored in such a way as to achieve mechanical, acoustic and/or dynamical properties out of reach for conventional materials.In the field of vibrations, a current trend sees nonlinearity exploited to produce notable vibration reduction mechanisms, including in particular the mass-in-mass concept. Furthermore, recent advances in the field of hybrid control (i.e., combining passive and active components) has lead to the development of hybrid nonlinear absorbers. This motivates the idea of incorporating such mechanisms at the material level.The present work deals with the design of intelligent or adaptive structures, where nonlinear effects are understood as performance enhancers for advanced metamaterials rather than limitations. In particular, we conduct the study of a chain of lumped masses coupled to their neighbors through essentially nonlinear (cubic) springs, in order to understand its modal interaction mechanisms and their potential use within a functional chain-like metamaterial. To this end, a three-degree-of-freedom is generalized by leveraging periodicity boundary conditions. This modelling approach makes it possible to cast a light on atypical phenomena such as mode localization, forbidden bandwidths and bifurcations of different types.Our analysis incorporates both analytical and numerical methods. Nonlinear normal modes and frequency responses are computed to highlight the role of modal interaction as the driving mechanism behind efficient vibration absorption by a nonlinear chain. In this way, we pave the way for experimental validation of this metamaterial concept in the near future, and consider extensions such as the coupling with more traditional active or passive control strategies.

Dispersion tailoring by nonlocal acoustic liners

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Nonlocality is being exploited by so-called metamaterials or metasurfaces to achieve larger wave manipulation capabilities, for example by dispersion tailoring or reflection and transmission steering, both in solid mechanics and acoustics. The study of nonlocal interactions in acoustic metamaterials has larger impacts also in other fields of research, such as quantum mechanics and medicine, where the dimensions involved are excessively small. Indeed, nonlocality is often introduced in acoustic macroscopic analogues of condensed-matter systems, which are able to reproduce salient phenomena of quantum mechanics. In addition, nonlocality also characterizes the recent modelling of the cochlea of our ears, as an array of micromechanical resonators, in the attempt to explain the tinnitus. In this contribution, we investigate the potential of nonlocal interactions in acoustic liners to tailor the dispersion function, by extending the previous achievements from solid mechanics to acoustics. Acoustic liners are used to treat noise propagation in waveguides, and are applied to ducts' parietal walls. It is the so-called grazing-incidence problem. The industrial application of acoustic liners ranges from noise treatment of Heating and Ventilation Air Conditioning systems (HVAC) to reduction of noise radiation from turbofan engines. The general framework employed in this contribution might be exploited by either passive or active means.

Dynamics of metastructures and metamaterials - Paper 10396

Investigating Space-Time Periodic System Dynamics Using a Simple String-Mass Model

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This work investigates the dynamics of a mechanical system exhibiting space-time periodicity. The system consists of an ideal string periodically loaded with lumped masses. The string tension is modulated in time, introducing temporal periodicity in addition to the spatial modulation from the periodic lumped mass distribution. The analysis is conducted in the frequency-wavenumber ($\omega - k$) domain using the Plane Wave Expansion (PWE) method to derive the dispersion characteristics. The results highlight the influence of generalized space-time modulation and are compared with the specific case of traveling-wave modulation previously studied in the literature. The combination of lumped and distributed parameters in the proposed model provides an intuitive yet powerful framework for exploring the exceptional dynamics of space-time periodic media, such as nonreciprocal wave propagation and frequency conversion. Preliminary experimental results are also presented, validating theoretical predictions and illustrating the potential of space-time engineered mechanical systems.

Dynamics of metastructures and metamaterials - Paper 10405

Exploring the dynamics of magnetic resonators for vibration controlling metamaterials

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Metamaterials are engineered resonant structures that derive their unique mechanical and acoustic properties from the combination of their design and material. In recent years, they have gained significant attention as a promising solution for noise and vibration attenuation, offering tunable and lightweight alternatives to conventional materials, at least in dedicated frequency regions. Within this growing field, magnetic resonators stand out as a largely unexplored yet highly promising concept, offering the potential for a quick plug-and-play attenuation solution that can be implemented without the need for major redesigns of existing components. In contrast to traditional integrated or glued-on mechanical resonators, the connection of magnetic resonators is non-rigid, relying on magnetic forces to transfer the resonant interaction forces between host and resonator. While this magnetic coupling offers clear advantages in ease-of-installation and reversibility, it also introduces a risk of dynamic decoupling near resonance, potentially reducing the attenuation efficiency or, worse, introducing vibrations into the structure. This research aims to explore the feasibility of predicting the loosening range in terms of amplitude of frequency of magnetically connected resonators through a combined numerical-experimental approach. A finite element model is developed to simulate and characterize the magnetic interaction and dynamic behavior both at the unit-cell and component (plate) levels. Experimental testing is then used to validate numerical predictions and to study the actual response of the magnetic connection under dynamic loading conditions. This numerical and experimental approach provides valuable insight into the (nonlinear) stiffness, detachment, and the role of negative modal effective mass in shaping the overall vibration attenuation mechanisms of magnetic resonators. The results of this study confirm the capability of magnetic resonators to introduce localized bandgaps and achieve significant vibration reduction near their tuned frequencies. However, several practical challenges remain before they can be fully implemented as industrial solutions - including surface roughness and resulting air gaps. Despite these limitations, the study demonstrates that magnetic resonators hold great potential as a rapidly deployable vibration reducing technology.

Dynamics of metastructures and metamaterials - Paper 10410

Analytical Modeling of Dynamic Buckling and Nonlinear Mode Coupling in Rotatable 2D Mechanical Metamaterials

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Programmable mechanical metamaterials hold great promise for applications in vibration control and adaptive structures. However, their design is often constrained by the complexity of nonlinear dynamic behaviors. In this work, we investigate the dynamic buckling phenomena observed in coupled two-dimensional networks composed of rotatable nonlinear oscillators. Based on experimental prototypes, a finite element model is first developed using COMSOL to examine the static buckling behavior and identify mechanical parameters such as stiffness and mass. Subsequently, an analytical model of the 2D network is established to analyze the linearized pre-stressed modes. The comparison with finite element simulations confirms the validity of the analytical formulation. Finally, the analytical model is employed to reproduce the experimentally observed nonlinear dynamic responses and to analyze the nonlinear coupled modes. This study provides theoretical insights into the coupled nonlinear dynamics of programmable mechanical metamaterials, offering a foundation for the design of adaptive and reconfigurable metastructures.

Design methodology for synclastic sandwich composites at resonance

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This work proposes a methodology for the dimensioning and design of synclastic sandwich composites. For conventional materials, Poisson's ratio typically ranges between 0 and 0.5. In certain cases, however, cellular solids can be structured to exhibit a negative Poisson's ratio. Such structured materials referred to as auxetic involve two main types of geometrical configurations: inverted honeycomb cells and chiral structures (e.g., tetrachiral, hexachiral). The use of an engineered auxetic structure as the core layer of a sandwich composite can allow the overall structure to exhibit auxetic behavior. Such behavior can be useful in several applications such as piezoelectric energy harvesting [1]. The behavior of auxetic structures embedded in sandwich composites is well understood under axial loading, but less under bending. When dealing with structures with global negative Poisson ratio, the corresponding flexure is referred to as synclastic. Here, we propose a new dimensioning methodology for sandwich composites employing an auxetic structure as the core layer. The dimensioning approach combines finite element analysis with homogenization techniques. The auxetic core layer is modelled as a homogenized orthotropic material characterized by directional elastic moduli and Poisson's ratios. It appears that, to maximize the ability of the auxetic core layer to achieve overall synclastic behavior, its lateral stiffness should be maximized. Indeed, if the lateral Young modulus, E2, is weak compared to the stiffness of the outer skin layers, Achieving proper synclastic behavior may be challenging. However, using re-entrant honeycomb, parametric studies also show that the higher the lateral stiffness is, the higher the Poisson's ratio is (getting closer to 0, even turning positive), reducing therefore, the synclastic behavior. The analysis of these initial results, obtained using FEM Comsol simulations under static loading conditions and subsequently validated at resonance, will be presented at the conference. Preliminary experimental results with a prototype with re-entrant honeycombs, based on 3D vibrometry and curve fitting, confirm the trends. Experimental measurements are under progress on machining an aluminum core layer and bonding it with outer layers to validate the experimental Poisson's ratio behavior under resonance conditions of sandwich. [1] Ferguson, William JG, et al. Auxetic structure for increased power output of strain vibration energy harvester. Sensors and Actuators A: Physical 282 (2018): 90-96.

On the Wave Propagation in Hydroelastic Phononic Crystals: Theory and Experiments

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Periodic structures have been enabling vibration and noise reduction thanks to the so-called bandgaps, i.e., frequency ranges within which wave propagation is forbidden or strongly attenuated. By exploiting human-designed periodic patterns in one-, two-, or three-dimensional arrays, a single unit cell of a lattice can be engineered, thus enabling wave propagation manipulation within a given structure and thereby allowing for the design of safer, more efficient, and more reliable systems. Although extensive efforts have been devoted to periodic structure modeling and design in recent years, very little is known about the dynamic behavior of hydroelastic phononic crystals (HPCs) - lattices that combine both elastic (solid) and fluid media in their periodic structures. In such cases, complex wave phenomena arise due to the coupled dynamic behavior resulting from the underlying multiphysics interactions. To investigate this, HPCs composed of a baseline three-dimensional unit cell featuring an internal void that allows the confinement of fluid (water) within its cavity is considered in this work. To model such periodic, fluid-structure coupled systems, reduced-order unit cell models are first derived, taking into account i) the occurrence of (linear) fluid sloshing in partially filled unit cells, ii) strong coupling conditions between fluid and structure, and iii) the system's periodicity. These reduced-order unit cell models are then invoked in the Wave-based Finite Element Method (WFEM), ensuring time-efficient and accurate wave propagation analysis through the HPCs. Results from model-based simulations are compared with tested-based ones. The analyses indicate that the derived WFEM models can satisfactorily predict the dynamic behavior of the tested specimens, as the forced responses of both are in very good agreement. In addition, the forced responses obtained by the WFEM show perfect agreement with reference solutions obtained by the FEM, while the WFEM proves to be significantly faster than the traditional FEM. Moreover, numerical simulations and experiments reveal that HPCs can function as alternative strategies for wave manipulation in PC-based materials/structures, owing to the versatile nature of fluids, whose volume can be finely tuned and whose shapeless nature allows them to conform to any geometry. In particular, partially-filled HPCs can enhance the bandgap formation in periodic structures, as confirmed through dispersion analyses, forced response computations and experiments. This work therefore exploits a novel concept of PC-like material for advanced metastructure design. The results from this research open new avenues for wave manipulation, with applications ranging from tunable bandgaps to more advanced smart and adaptive devices.

Dynamics of metastructures and metamaterials - Paper 10431

Evaluating a metamaterial-based vibration mount for electric vehicle battery packs using additively manufactured polymer elements

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The increasing operational demands of battery packs in hybrid and electric vehicles present significant challenges for their structural integrity and long-term durability. A critical issue is the susceptibility of battery packs to road-induced vibrations. Dynamic excitations within specific frequency ranges can lead to internal component damage, such as electrolyte degradation, potentially causing micro-short circuits and significantly reducing battery longevity. This paper presents the design and numerical validation of an innovative support structure engineered to isolate the battery from the detrimental vibrations of the vehicle chassis. The proposed solution consists of a periodic vibration mount concept, made of highly damped 3D-printed Thermoplastic Polyurethane (TPU), designed to create targeted frequency band-gaps. These mounts combine band gaps and high damping to isolate vibrations in a large frequency band. A mock-up model, representing the vehicle chassis, the periodic vibration mounts, and the battery pack, was developed and analyzed using the COMSOL Multiphysics® software. The performance of the proposed periodic mounts is compared with conventional solutions, including a rigid connection and a traditional rubber mount, under realistic operational scenarios. Frequency Response Functions (FRFs) were generated to assess acceleration transmissibility from the chassis to the batteries under various dynamic load cases, including vertical, pitch, yaw, and roll excitations to simulate operating vehicle conditions. The results consistently demonstrate the superior performance of the periodic mounts, which provide broadband vibration attenuation across all tested conditions. The findings confirm that the 3D-printed periodic mounts offer a highly effective passive solution to enhance the safety and lifespan of electric vehicle batteries.

Phononic crystal beam with embedded acoustic black holes as local resonators

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Phononic crystals have gained considerable ground in the field of mechanics. These structures are commonly composed of a unitary cell periodically spaced, creating a unique characteristic of band gaps, for passive wave propagation control. Recently, some studies have addressed the idea of embedded local resonators for wave attenuation in these crystals. In this work, we apply a phononic crystal beam with embedded acoustic black holes to work as local resonators. This effect is achieved by incorporating a local modification in the thickness of the beam, producing a significant reduction in the wave propagation speed and an increase in attenuation properties. A numerical approach is established using the Spectral Element Method (SEM) and verified by the Finite Element Method (FEM). Examples are performed, and the results are compared between the methods and with those found in the literature.

Dynamics of metastructures and metamaterials - Paper 10465

Structural and Acoustic Wave Propagation Patterns in Hyperbolic Lattices

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The need for high-performance structures has led to the development of metastructures, namely, structured materials designed to have properties not found in conventional materials such as metals and polymers. Metamaterials exhibit many interesting wave manipulation properties in structural vibration and acoustic applications, as their wave pass bands and band gaps offer significant benefits in wave control, filtering, or isolation at specific frequencies. Metamaterials based on hyperbolic geometry are a recent and promising branch of metamaterial studies, exhibiting wave localization phenomena, super-resolution imaging, and robustness to defects, in addition to effects inherited from traditional metamaterials. In a brief outline, these hyperbolic metamaterials are constructed according to rules from hyperbolic geometry, enabling negative-curvature spaces that offer infinite possibilities of regular tessellations impossible at the usual Euclidean one. These tessellations allow for positioning any polygonal arrangement without spacing gaps, opening possibilities of periodic cell-placing configurations that cannot be assessed in traditional, Euclidean-based metamaterials. This work explores this topic by investigating how mechanical and acoustic waves propagate in hyperbolic lattices. To achieve this, we assess hyperbolic lattices for mechanical structures and sonic crystals through numerical simulations, validating expected localized energy phenomena in particular frequency bands. These results allow insights into the potential applications of hyperbolic metamaterials for noise and vibration control.

Piezoelectric metamaterials for sound and vibration control

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Dynamic metamaterials are engineered structures capable of controlling wave propagation through band gaps, i.e., frequency ranges in which waves are suppressed. Tunable or programmable functionality is typically achieved via mechanical reconfiguration or multifield coupling. Among the available coupling mechanisms, piezoelectric materials are a particularly attractive choice, as wave behavior can be adjusted by modifying external passive shunt circuits or employing active control strategies. This talk explores tunable piezoelectric metamaterials for sound and vibration control. The presented cases focus on a reconfigurable piezoelectric metamaterial plate designed for both acoustic and vibration attenuation, as well as sound directivity control. In the first configuration, numerical and experimental results demonstrate that, by selectively adjusting the spatial distribution of tuned unit cells, vibrations can be confined to specific regions of the plate, producing distinct far-field radiation patterns at a target frequency. In a second case, an experimentally validated mode-shaping technique is introduced, enabling the induction of a specific mode at different target frequencies via an electromechanical coupling mechanism. The results highlight the metamaterial's ability for on-demand wave manipulation and adaptive sound field shaping, exhibiting similar directivity patterns across different operating frequencies. Overall, these findings underscore the potential of reconfigurable piezoelectric metamaterials as a versatile platform for adaptive noise and vibration control in engineering applications.

Wave Cancellation Mechanisms in Periodic Herschel-Quincke-Inspired Frame Structures

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Mechanical metamaterials have emerged as a promising research field focused on controlling and manipulating the propagation of elastic and acoustic waves, providing innovative alternatives to conventional noise and vibration mitigation techniques. Among the various configurations explored, structures inspired by the Herschel-Quincke (HQ) acoustic tube have attracted attention due to their capability to induce wave interference and cancellation through phase manipulation. In this study, a periodic HQ-inspired frame structure is proposed and analyzed to investigate the mechanisms of wave cancellation in such structural systems. Spectral formulations based on the Timoshenko-Ehrenfest beam theory are employed to model the wave propagation, while a finite element (FE) model is developed for validation through forced response analyses. The dispersion diagram of the periodic unit cell reveals the presence of wide wave band gaps in which wave propagation is effectively suppressed. These results identify the frequencies of maximum attenuation. Furthermore, the analysis of transmission and reflection coefficients demonstrates that flexural waves propagating through the multiple branches of the HQ-inspired frame experience phase shifts that result in destructive interference and strong vibration attenuation within the identified band gaps. The findings provide new insights into the dynamic behavior of periodic HQ-inspired beam structures and highlight their potential as efficient and robust passive solutions for vibration isolation.

Dynamics of metastructures and metamaterials - Paper 10476

Wave and vibration attenuation from railway traffic in tracks with Winkler foundation and local resonators

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Vibrations induced by railway traffic are transmitted to the ground and can affect nearby residential and industrial areas, potentially causing damage to infrastructure and rail vehicles. The conventional methods for mitigating this phenomenon include the use of dampers on tracks and sleepers, improved train suspensions, and ground barriers. However, the scientific community has been exploring metastructures (i.e., artificially engineered structures that exhibit mechanical properties not found in conventional materials) as an innovative solution for vibration control. Despite notable advances, a significant gap remains in the literature regarding the application of metastructures in the railway sector. This study aimed to design a railway track based on the concept of metastructures, incorporating local resonators to attenuate low-frequency vibrations using the Euler-Bernoulli beam model on a Winkler foundation. The finite element method (FEM) was employed to compute the band structure and the frequency response function (FRF). The proposed metastructure was able to attenuate vibrations in the 1-500 Hz range, according to the resonator properties. The band structure revealed the formation of a band gap associated with the damping of the rail on the Winkler foundation. The introduction of local resonators generated localized modes that split this band gap into two distinct gaps. The FRF of the finite structures corroborated these findings, showing an attenuation zone coinciding with the band gap region. Results also showed that, in the presence of the Winkler foundation, local resonators operating within the band gap frequency range concentrate energy within a significantly narrower interval. Conversely, in the model without the foundation, the resonators exhibit the opposite behavior, producing a broader attenuation effect over a wider frequency range. This design proved effective in preventing wave propagation and mitigating ground vibrations within specific frequency bands, demonstrating its feasibility for practical application and its potential for optimization to extend the attenuation range.

Computing Nonlinear Dispersion Relations via Harmonic Balancing

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We introduce a general framework for computing nonlinear dispersion relations in homogeneous and periodic media exhibiting smooth nonlinearities. The method relies on a multi-harmonic expansion of nonlinear Floquet-Bloch waves, resulting in a nonlinear system of equations that can be efficiently approximated using the Harmonic Balance Method. As an illustrative example, the approach is first applied to a geometrically nonlinear Euler-Bernoulli beam, from which we derive amplitude-dependent dispersion relations and corresponding waveforms. We then extend the methodology to arbitrary finite element (FE) models, thereby generalizing the Wave Finite Element Method to nonlinear regimes, before applying it to a geometrically nonlinear locally resonant metamaterial. Although computationally intensive for full FE models, the proposed framework provides a powerful tool for designing complex nonlinear metamaterials.

Dynamics of metastructures and metamaterials - Paper 10479

Vibration control induced by railway traffic using piezoelectric metamaterial in Euler-Bernoulli beams

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Railways consume less energy and generate less pollution than road transport, reducing operational costs and promoting sustainability. However, railway traffic induces mechanical vibrations that propagate through the ground, affecting residential and industrial areas and potentially causing discomfort and structural damage. Conventional methods, such as tracks and sleeper dampers, improvements in train suspensions, and ground barriers, are widely used to mitigate these vibrations. As an innovative alternative, the scientific community has explored piezoelectric devices, i.e., materials capable of converting mechanical energy into electrical energy and vice versa. When coupled with periodic or resonant structures, these devices form metamaterials with effective properties uncommon in nature, enabling control over the propagation of mechanical waves. Additionally, they can function as actuators, generating opposing forces to attenuate unwanted vibrations. These systems stand out due to the formation of band gaps, which block wave propagation in specific frequency ranges. Despite advancements in this field, a significant gap remains in the literature regarding the application of piezoelectric metamaterials in the railway sector. This study proposes the design of railway tracks incorporating piezoelectric devices strategically positioned between the rail and the sleeper. In this way, the Euler-Bernoulli beam model on a Winkler foundation was adopted to investigate the bending vibrations. The proposed configuration consists of piezoelectric patches periodically arranged along this interface, forming a metamaterial capable of attenuating vibrations in low-frequency ranges. To this end, the finite element method (FEM) was employed to generate the band structure and the frequency response functions (FRF). The results show that the designed metamaterial attenuated vibrations in the 10-500 Hz range through the formation of band gaps. The formation of band gaps evidenced good agreement between the band structure and the FRF. The position and distribution of the piezoelectric devices significantly influenced the width and frequency range of these gaps. In addition to mitigating ground vibrations at specific frequencies, the metamaterial demonstrated feasibility for application and optimization potential to enhance attenuation in the railway sector, with the possibility of energy harvesting.

In-Plane Band Gaps in 2D Metamaterials using SBFEM

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In this paper, a theoretical investigation of the in-plane vibration characteristics in 2D metamaterials is presented. The metamaterials are composed of a periodic arrangement of unit cells with local resonators. The initial modeling is performed using the Scaled Boundary Finite Element Method (SBFEM) for the two-dimensional state. The governing equations for in-plane vibration are derived and solved semi-analytically, and the obtained results are compared with those derived through the Finite Element Method (FEM) using the commercial software COMSOL. Additionally, a parametric study is conducted to investigate the effects of the geometric and material properties of the unit cells on the resulting band gaps. These effects are analyzed through the elastic band diagrams and the forced response for the metamaterials.

Attenuation of mechanical vibrations in railways soil using seismic metamaterials

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This work focuses on the attenuation of mechanical vibrations from the railway system in the ground, which create environmental and structural challenges due to their low frequency operation. Conventional barriers have limited applicability; therefore, seismic metamaterials (SM) emerge as an innovative solution to overcome these limitations. The study is justified by the need to develop more efficient and compact technologies for vibration control, in alignment with UN SDG 9, with a specific focus on the development of materials simulation and emphasizing innovative and sustainable approaches to improve the dynamic behavior of structures. The objective is to design and analyze, via numerical simulation, a SM composed of conventional engineering materials, aiming to attenuate low frequency vibrations in the ground by creating band gaps. The methodology uses the Finite Element Method (FEM) in COMSOL Multiphysics software, applying Floquet-Bloch theory to analyze 2D unit cells and generate band diagrams and Frequency Response Functions (FRF). Preliminary numerical simulations, validated by Floquet-Bloch theory, demonstrated the effectiveness of SM. The results indicate that materials with greater stiffness and density, such as steel, are more effective than concrete in forming higher and lower frequency bands. Currently, the research is developing and experimentally validating a prototype, employing cylindrical concrete inclusions in a soil matrix, seeking to correlate the numerical results with the experimental ones. Future work will involve optimizing geometric configurations and exploring materials to understand, expand, and evaluate dynamic behavior aimed at opening band gaps at low frequencies.

Vibration Attenuation in a Nonlinear Crankshaft Using Identical and Rainbow Resonators

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Rotary machinery is inherently prone to torsional vibrations, which, if not adequately addressed, can lead to increased maintenance costs and even mechanical failures. Therefore, effective vibration control is a crucial aspect of project design, ensuring proper operation and extending the lifespan of these machines. This work studies the performance of two distinct types of metastructures in mitigating torsional vibrations within a single-cylinder crankshaft system subjected to concentrated harmonic excitation. The proposed model assumes the shaft as a continuous and nonlinear system, where the motion of the crank-slider mechanism is represented as a concentrated equivalent inertia that changes with the shaft's rotation. First, the system's response without the metastructures is analyzed, followed by an examination of the crankshaft's response with the addition of identical resonators and rainbow metamaterials. The behavior of the crankshaft displays rich nonlinear dynamic phenomena, including multistability, where multiple attractors coexist, and transient chaos. However, when both types of metastructures are introduced to the shaft, the dynamics simplify to a stable period-1 motion with low amplitude, even under conditions that typically induce transient chaos. Both the identical resonators and rainbow attachments exhibit similar effectiveness in attenuating vibrations within a frequency range characterized by strong nonlinearities. For well-defined resonance peak, both metastructures effectively reduce vibration amplitudes, resulting in a characteristic bandgap. Notably, the rainbow metamaterials outperform the identical resonators, achieving a bandgap that is 63% wider while maintaining the same additional inertia.

Dynamics of metastructures and metamaterials - Paper 10496

Bandgap Enhancement and Mode Localization in Finite metastructures with Non-Periodic Configurations

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This study explores the dynamic behavior of finite metastructures arranged in periodic, quasi-periodic, and aperiodic configurations, establishing a basis for comparison with the performance of infinite periodic counterparts composed of an unlimited number of resonators. The primary objective is to determine whether finite arrangements can yield broader bandgaps than those observed in infinite periodic systems. A secondary aim is to assess the beneficial and adverse effects of mode localization induced by quasi-periodic and aperiodic patterns in finite metastructures. Analytical expressions for estimating the bandgap suppression range are derived from the poles and zeros of the finite structure. Mode localization is investigated through the eigenvalue problem associated with the discrete dynamic model of the metastructure. The evolution of poles and zeros and consequently the bandgap characteristics is examined as a function of both the number of unit cells and perturbations in the resonators' stiffness parameters. To identify optimal configurations, genetic algorithms and gradient descent methods are employed, guided by an objective function formulated from the system's eigenvalue structure. These optimization techniques enable efficient estimation of aperiodic configurations in systems with numerous stiffness and mass parameters. The metastructure consists of nonlinear magnetoelastic resonators mounted on a host structure, with both bistable and monostable configurations analyzed. Variations in stiffness coefficients are achieved by adjusting the spacing between magnets, and dimensional stiffness values are obtained via polynomial regression based on the resonators' potential energy functions. The host structure is modeled as an elastic cantilever beam subjected to harmonic base excitation, with its dynamic response measured along its length. It is discretized into unit cells, each containing a centrally attached resonator. Additionally, each cell includes a movable mass whose position relative to the resonator alters the magnetic force, allowing for tunable stiffness. The quasi-linear regime near stability points is examined to facilitate the use of conventional transfer functions for frequency response analysis and state-space formulations for time-domain simulations.

Dynamics of metastructures and metamaterials - Paper 10497

Analysis of the trade-off between absolute filtering properties and mechanical strength of elongated sandwich structures with lattice material core

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Lattice structures offer very interesting properties for vibration control due to their lightness and the possibility of adjusting their stiffness by choosing the geometry of the lattice. This presentation explores how these lattice materials can be used to create slender structures that act as absolute vibration filters capable of preventing any elastic wave from propagating, regardless of its polarization, within a selected frequency band. This work involves an analysis of wave dispersion similar to the classification of Lamb waves. It is possible to obtain an absolute filter, but this leads to structures that can be particularly flexible. To overcome this practical difficulty for mechanical engineering application, the introduction of skins is proposed, defining sandwich beams with a lattice core, which are stiffer but reduce filtering bandwidth. An analysis of the trade-off between these two properties is then developed. This work is based on numerical modeling using the spectral element method and experiments on demonstrators produced using 3D additive manufacturing.

Vibration mitigation in railway systems using piezoelectric metamaterials with Shunt circuits

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This work investigates strategies for vibration reduction in railway systems, focusing on the application of piezoelectric metamaterials and periodic structures capable of attenuating undesirable mechanical waves. Excessive vibrations, mainly generated by the wheel-rail interaction, compromise infrastructure integrity, cause environmental impacts, and reduce the energy efficiency of rail transport. To mitigate these effects, this study proposes the use of local resonators and piezoelectric materials coupled to shunt circuits, which convert mechanical energy into electrical energy and enable the passive control of vibrations. The research analyzes the propagation of waves in one-dimensional (1D) periodic Euler-Bernoulli beams, representing sections of railway tracks. Different structural configurations are considered: homogeneous beams, beams with discontinuities, and beams with piezoelectric (PZT) layers. The Finite Element Method (FEM), implemented in COMSOL Multiphysics, and the Floquet-Bloch Theorem are employed to model the dynamic behavior of the structures and to identify forbidden frequency bands (band gaps), i.e., frequency ranges where wave propagation is inhibited. Numerical results indicate that the homogeneous beam does not present band gaps, while the introduction of structural discontinuities generates attenuation regions in the ranges of 2.8 to 3.7 kHz and 12.9 to 13.4 kHz. The inclusion of PZT elements shifts these bands to lower frequencies (2.5 to 2.9 kHz and 10.5 to 11.7 kHz) due to local resonance and energy dissipation induced by the shunt circuit, enhancing the system's vibration isolation capability. This combination demonstrates that the integration of piezoelectric metamaterials and structural resonators allows the development of smart infrastructures capable of absorbing vibrational energy and reducing impacts on the soil and surrounding flora. The study demonstrates that applying phononic crystal and mechanical metamaterial concepts to railway systems is a promising approach for enhancing the sustainability and energy efficiency of transportation. It enables the selective blocking of unwanted frequencies and the optimization of the structural response of the rails. The results provide a foundation for designing adaptive railway tracks, contributing to the advancement of engineering solutions aimed at vibration mitigation and environmental impact reduction in the railway sector.

Dynamics of metastructures and metamaterials - Paper 10501

Parametric analyze of a thermal wave crystal using Cattaneo-Vernotte (CV) Model from of Wave Finite Element Method

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This work presents a parametric analysis of a thermal wave crystal using the Wave Finite Element Method (WFEM) under the Cattaneo-Vernotte (CV) non-Fourier heat conduction model. Replacing the classical Fourier's law, the CV model introduces a finite thermal wave speed via a relaxation time, resulting in a hyperbolic heat equation that supports wave-like thermal propagation. The WFEM is applied to a unit cell discretized by the Finite Element Method (FEM), enabling the efficient computation of complex dispersion relations in the infinite periodic structure. The core of this parametric study involves systematically investigating the influence of key geometric and material parameters on the emergence and characteristics of thermal band gaps in frequency ranges where wave propagation is forbidden. The findings provide direct insights for the targeted design of thermal wave crystals, with potential applications in thermal management systems known to exhibit pronounced non-Fourier conduction at low temperatures.

Engineering analysis of spin excitation and wave directivity in topological metamaterials

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In recent years, some concepts originating from quantum mechanics, such as edge and bulk states and spin phenomena, have been investigated in the context of structural dynamics. Although considerable advances have been made in the study of wave attenuation, localization, and directivity, most of these works still lack an engineering-oriented approach. For example, it has been shown that chiral excitation can induce polarization of the spin angular momentum (SAM) in elastic media, enabling controllable energy steering with potential engineering applications. While this topic is well known in quantum and condensed-matter physics, an engineering perspective remains limited. In this work, the wave steering produced by chiral excitation is interpreted from an engineering viewpoint, based on the combined action of internal forces and continuity of displacements. Furthermore, a closed-form expression for the external loads that optimize wave directivity in beamsis derived and validated through spectral analysis, time-domain simulations, and experiments. Finally, simulations and experiments show that the propagation direction remains unchanged in a topological phononic crystal, showing evidence that the topological effect prevails over the spin effect.

Dynamics of metastructures and metamaterials - Paper 10524

Periodic structures for wave and vibration control: progress and perspective on Bragg scattering, local resonance, and coupling mechanisms

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Over the past few decades, periodic structures and metamaterials have revolutionised the way elastic and acoustic waves can be controlled, enabling vibration attenuation, noise reduction, and energy localisation from microstructured materials to large-scale engineering systems. Their fundamental mechanism, known as Bragg scattering, relies on periodic impedance changes that cause destructive interference and create frequency band gaps where vibrations and waves are attenuated even without material damping. This mechanism, first recognised in early studies of periodic strings and later formalised by Brillouin through wave dispersion theory in periodic media, provides the understanding of elastic and acoustic wave blocking in periodic waveguides. Although Bragg-type stop bands provide broadband attenuation, they depend on the lattice spacing (period), which limits their effectiveness at low frequencies. The introduction of locally resonant metamaterials, by embedding periodic subwavelength resonators within a host medium, has overcome this limitation. The hybridisation between resonator and host modes produces negative effective parameters and subwavelength stop bands, enabling significant low-frequency isolation. Analytical models and experiments - from the classical mass-in-mass chain to continuous resonant beams and plates - have shown how band gaps can be tuned by adjusting resonance frequency, mass ratio, and coupling stiffness. However, local resonance results in narrow attenuation zones, prompting strategies that widen or merge band gaps through hierarchical resonances, inertial amplification, or aperiodic arrangements. Beyond periodicity and resonance, a third, increasingly acknowledged pathway for controlling elastic and acoustic waves emerges from interactions induced by wave coupling. When waves from different families, such as axial, flexural, or torsional modes, interact, their dispersion branches may exhibit codirectional veering or contradirectional locking. These phenomena, initially classified within dispersion theory, are now employed to create complete band gaps without the need for external resonators. Geometry-induced coupling in folded, wavy, or corrugated structures exemplifies this mechanism: the locking of counter-propagating wave modes results in complex-conjugate wavenumber pairs and the formation of absolute band gaps. By combining periodicity, local resonance, and contradirectional coupling within a unified design framework, exceptionally broad and tunable band gaps can be achieved. This presentation aims to trace this development - from Bragg scattering to local resonance and coupling-driven mechanisms - and to explore how these mechanisms can be synergistically combined through optimisation and inverse-design strategies for broadband, adaptive wave and vibration control.

Topic: Human Vibration, Bioengineering

Human Vibration, Bioengineering - Paper 10468

Whole-Body Vibration in Wheelchair Users: Methodological Problems in Measurement and Analysis of Data Collected in Real-World Settings

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It is well known that the number of wheelchair users is growing worldwide, not only due to an increase in chronic health conditions but also due to the aging of the population. In 2023, it was estimated that 1% of the population falls into such a group, representing 80 million people in such a situation, according to the World Health Organization (WHO, 2023). The research which result is presented here was conducted irrespective of gender, type of disease, type of wheelchair (propulsion or manual), and type of route, to understand the levels of Whole-Body Vibration (WBV) a wheelchair experiences during his/her daily routine, for a period of 24h. Understanding how to obtain such data and how to analyze it is important before considering the measured levels in public solutions. Therefore, the main objective of the article is to present the methodology of analysis of one volunteer, showing how the data was obtained and the main problems observed during the measurement and analysis of that. For measuring the levels of WBV of the wheelchair user for such a long period, a low-cost sensor was developed in-house (GOEKING, LIMA II, et al., 2024) since the commercial ones, apart from being very expensive, do not allow for a long period of measurement. However, for daily use, it proved to need some adjustments, what is being performed currently. A software was also developed in-house to read the data and to process it according to the levels set by the European Union (DIRECTIVE 2002/44/EC, 2002) and the (ISO2631-1, 2010), which is more restrictive than the first. These standards mention that the levels must be assessed based on two parameters. The weighted acceleration (aw) and vibration dose value (VDV). What was found is that the levels of the weighted acceleration in general did not exceed the ELV (Exposure Limit Value). However, the VDV extrapolated a lot. Understanding that may be important for governments to deliver more appropriate routes and means of transport for such populations.

Topic: Inverse problems and parameter estimation

Inverse problems and parameter estimation - Paper 10383

Physics-Informed Neural Networks for the Identification of Spatially Varying Elastic and Damping Properties in Beams

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This study presents a Physics-Informed Neural Network (PINN) approach for identifying spatially varying elastic and damping properties in beams subjected to bending. Conventional identification techniques often face difficulties in capturing local variations in mechanical parameters, especially when data are sparse or when prior assumptions are required. The proposed framework leverages the ability of PINNs to integrate the governing equations of structural dynamics directly into the learning process.The beam's equation of motion, describing flexural vibrations and incorporating both stiffness and damping effects, is embedded into the loss function of the neural network. This allows the model to simultaneously fit measured displacement fields and satisfy the underlying physics, resulting in more accurate and physically consistent parameter estimation. The method enables the reconstruction of the spatial distribution of Young's modulus and damping coefficients without relying on explicit meshing or additional regularization terms.The approach is validated through both simulated and experimental test cases involving non-uniform beams under steady-state bending excitation. Results demonstrate that the PINN framework can successfully recover complex spatial variations of material properties, even when the available measurements are limited or affected by noise. The study also evaluates the robustness and generalization capability of the method with respect to different boundary conditions, excitation frequencies, and measurement sparsity.Overall, the proposed PINN-based identification strategy offers a flexible and data-efficient alternative to conventional inverse methods for beam characterization, providing new perspectives for the analysis and monitoring of non-homogeneous or degraded structural components.

AN APPROACH TO CIRCUMVENT UNRELIABLE AIRSPEED CONDITION

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The accurate measurement of air data - such as airspeed, angle of attack, and angle of sideslip- is a fundamental pillar for aircraft safety and efficiency. However, the reliance on physical sensors exposes aircraft to critical vulnerabilities that can lead to catastrophic failures. This work addresses this challenge by developing and validating a Synthetic Air Data System (SADS) based on a hybrid methodology: Physics-Informed Neural Networks (PINNs).The proposed approach is distinguished by formulating the task as a dual estimation problem, aiming not only to estimate the unmeasured air data states but also to simultaneously identify the aircraft's aerodynamic coefficients. To this end, the 6-Degrees-of-Freedom (6-DOF) equations of motion are integrated into the neural network's loss function, compelling the model to learn solutions that are both consistent with trusted sensor data (IMU and GPS) and compliant with the laws of flight mechanics.The results, obtained from a F-16 simulation dataset, are promising. The PINN model demonstrated satisfactory performance in estimating the air data states, achieving a Root Mean Squared Error (RMSE) of 1.15 degrees for the angle of attack and 10 kts for the airspeed. The identification of aerodynamic coefficients proved to be a more complex task, with the model identifying the most dominant stability and damping derivatives, while other coefficients showed some deviations, highlighting the challenges of system identifiability.This work validates the PINN framework as an adaptive approach for SADS, establishing a foundation for future research, which includes the implementation of uncertainty quantification, and the enhancement of the aerodynamic model's adaptability.

Characterization of frequency-dependent mechanical properties of highly damped Thermoplastic Polyurethane (TPU) for vibration isolation using periodic structures

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Characterizing frequency-dependent mechanical properties of highly damped polymers 3D-printed with various infill patterns and densities using conventional dynamic testing methods based on measured natural frequencies presents significant challenges due to overdamped responses. This work explores the dynamic characterization of such materials by curve-fitting frequency response functions (FRFs) of periodic arrangements of the material intercalated with metal elements. This introduces features in the measured FRFs due to frequency band-gaps that increase the information for parameter identification via curve fitting. This study considers frequency-dependent functions for the Young's modulus, the shear modulus, and the loss factors. These functions are systematically identified by applying a non-linear least-squares curve-fitting algorithm to experimentally obtained FRFs. This enhanced approach allows for a more accurate and comprehensive characterization of additively manufactured polymers, which are essential for predictive modeling and engineering design. Furthermore, this paper proposes a novel periodic vibration mount optimized for low-frequency vibration attenuation. The design, composed of alternating 3D-printed TPU and metal elements, is engineered to generate wide band gaps in the low frequency range. Its performance is rigorously evaluated through numerical simulations conducted in COMSOL Multiphysics, where force and acceleration transmissibility analyses are performed to predict its vibration isolation capabilities. The experimental validation of a physical prototype is currently being performed. This research aims to provide a comprehensive framework for both characterizing overdamped polymers and investigating their application as passive vibration isolators by associating wave band gaps and damping.

Inverse problems and parameter estimation - Paper 10487

Data-driven stochastic model updating: How GenAI can advance?

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Model updating improves the fidelity of physics-based models by aligning simulations with observations. Classical sensitivity-based optimisation and Bayesian sampling often struggle in high dimensional spaces and with multi modal posteriors. This work proposes a generative AI framework for uncertainty aware model updating using conditional normalising flows and conditional diffusion models. Both approaches are trained on paired datasets of system parameters and structural responses, learning mappings from observations to posterior distributions. The conditional normalising flow learns an invertible, observation conditioned transform between latent and parameter spaces, enabling fast posterior sampling and stable convergence. The conditional diffusion model learns a stochastic denoising process conditioned on observations, which captures complex non-Gaussian and multi modal posteriors. We demonstrate the framework on two case studies. First, the NASA UQ Challenge 2025 serves as a public benchmark to assess accuracy and scalability. Second, we use a practical benchmark testcase built for stochastic model updating, based on a family of nominally identical scaled aircraft models with controlled geometric variability. This design embeds multiple sources of uncertainty arising not only from the experimental process but also from the structure itself, for example manufacturing tolerances and assembly errors. Across both studies, the methods accurately approximate the posterior of uncertain input parameters and reproduce observed system responses after updating. Normalising flows are computationally efficient but can struggle with strongly multimodal or discontinuous posteriors due to invertibility constraints, whereas diffusion models are more flexible at the cost of higher training and sampling effort. Overall, the proposed framework offers a unified, data driven route to scalable model updating that complements classical Bayesian and optimisation based techniques for nonlinear, high dimensional inverse problems.

Topic: Multibody control of mechanical systems

Multibody control of mechanical systems - Paper 10427

From Data to Debrief: A Framework for Analyzing Pilot Performance

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This paper presents the development of a framework for the quantitative analysis of pilot performance using flight simulation systems. The proposed methodology is based on analyzing the aircraft's state vector, including flight path and parameters, alongside pilot control inputs. This data is benchmarked against pre-defined standardized flight profiles to provide an objective basis for evaluation. Statistical metrics are employed to process the dynamic flight data, enabling a precise and repeatable assessment of pilot proficiency. This approach applies established concepts from systems dynamics and statistical analysis to the domain of aeronautics science and human factors. The core contribution of this work is the development of a model that translates complex flight data into a clear and actionable performance report for pilots. By focusing on the practical application of these analytical techniques, the framework offers a robust method for creating personalized training evaluations and providing insightful, data-driven feedback, ultimately enhancing pilot skill and safety.

Learning-based Control of a Single-DOF Aero System

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This paper presents a learning-based control that integrates feedback linearization and reinforcement learning (RL) for adaptive control of nonlinear mechatronic systems. The control law is derived through Lyapunov stability analysis, ensuring closed-loop stability and convergence.Feedback linearization is employed as the main control framework, while a reinforcement learning component estimates and adapts to modeling uncertainties, unmodeled dynamics, and external disturbances. The RL module is based on the REINFORCE-with-baseline algorithm, which improves learning efficiency by reducing the variance of policy gradient estimates. This enables faster and more stable policy updates during online adaptation.The reward function is designed to balance trajectory tracking accuracy and control effort, promoting precise reference following while avoiding excessive actuation. Through this formulation, the controller autonomously refines its policy to minimize both the tracking error and the energy consumed in control actions.The proposed controller is experimentally validated on a one-degree-of-freedom (1-DOF) Quanser Aero system representing the pitch dynamics of an aerial platform. Results demonstrate accurate tracking performance, rapid convergence, and strong robustness against parameter uncertainties and disturbances.Overall, the proposed framework combines the analytical guarantees of Lyapunov-based control with the adaptability of reinforcement learning, providing an effective approach for intelligent and energy-efficient control of nonlinear mechatronic systems.

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Multibody control of mechanical systems - Paper 10457

Precision Control of a Synchrotron X-ray Phase Retarder

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The analysis of the magnetic properties of materials is a critical field of study in material science, directly impacting several areas of science and engineering. These properties are characterized through precise experiments that utilize high-energy X-rays produced by a synchrotron particle accelerator. The success of these experiments depends on achieving high precision in the positioning of the X-ray phase retarder system, a challenging task due to environmental factors and system flexibility. The X-ray beam generated by the synchrotron crosses a frame with a set of crystals that spins around its center of rotation. The frame alternates between two fixed angles, holding each position for a specified period of time. To achieve the required positioning precision, an accurate angular position control system for the rotating frame is essential. A reduced-order computational model is developed to represent the mechanical system dynamics. The basic system consists of two frames, each equipped with a mounted set of diamond crystals. Attached to each frame is a plate-like structure with a vertical hinge that allows it to rotate. In the neutral position, these two plates are aligned, with their free ends adjacent. A single actuator is positioned at the center point where these two free plate ends meet. When activated, the actuator pushes the plate ends outward, causing each plate to rotate around its hinge and, consequently, the frames to rotate. In the model, the input is a reference signal of the square-wave type, and the output is the position of the frame corners. The difference between the output signals provides the angular rotation of the frame containing the crystal. It is shown that the reduced-order computational model adequately reproduces experimental results. This reduced-order model is used for control design and performance analysis. A control system is designed to ensure that the rotation of the crystal frames robustly follows the desired reference signal with adequate settling time and minimal overshoot, while rejecting measurement noise and external vibration disturbances, despite uncertainties arising from nonlinearities and unmodeled dynamics. The controller design is based on robust H2 optimal control, which is a well-known technique for achieving optimal performance while rejecting noise and disturbances. The optimal controller is obtained from the solution of two Riccati equations. The angular position control system is expected to provide the required accuracy under parameter variations, noise and disturbances. Numerical simulations validate the design.

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Multibody control of mechanical systems - Paper 10473

Performance Analysis of RBF Neural Networks with Different Activation Functions in Intelligent Robot Control

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This paper presents an intelligent control framework that integrates feedback linearization and artificial neural networks (ANNs) for trajectory tracking of robotic manipulators. The proposed method combines model-based control with learning capabilities, enabling adaptation to complex and uncertain environments. The control structure is derived through a rigorous Lyapunov stability analysis, ensuring closed-loop stability and guaranteeing the convergence of tracking errors.In this approach, Radial Basis Function (RBF) neural networks are employed to estimate and compensate for system uncertainties, nonlinearities, and unmodeled dynamics that commonly degrade the performance of conventional feedback linearization controllers. The RBF networks provide online adaptation and learning, allowing the controller to adjust in real time to changes in the robot's dynamics or external disturbances. A key focus of this work is the investigation of different activation (basis) functions within the RBF structure-such as Gaussian, multiquadric, and inverse multiquadric functions-to evaluate their influence on estimation accuracy and control performance.The proposed control scheme is applied to a two-degree-of-freedom (2-DOF) robotic manipulator, serving as a benchmark for assessing the controller's performance under various reference trajectories and operating conditions. Simulation experiments are conducted to analyze the effects of different activation functions on convergence speed, steady-state error, and robustness to modeling errors and disturbances.Results demonstrate that the integration of feedback linearization with adaptive RBF neural networks significantly enhances tracking precision and robustness compared to traditional linear or fixed-parameter controllers. Moreover, the comparative study of activation functions reveals that the choice of basis functions critically affects the controller's learning capability and overall performance.The findings provide valuable insights for the design of intelligent, learning-based controllers for robotic systems operating in uncertain and dynamic environments, highlighting the potential of neural-network-assisted feedback linearization as a reliable and adaptable control strategy.

ANALYSIS OF ROLLERS' INFLUENCE ON THE CARGO VELOCITY DURING A GRAVITY AIRDROP OPERATION

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The floor of cargo aircraft is equipped with rollers that facilitate the loading and airdrop of palletized cargo during resupply missions. Since different aircraft use rollers of varying diameters and geometries, understanding if and how these parameters can influence the cargo drop time and its exit velocity from an aircraft is essential for improving drop accuracy and operational efficiency. To study this, in this work, the cargo airdrop is modeled as a rigid-body dynamic system, accounting for normal and tangential contact forces between the cargo and rollers. The tangential component of the contact forces is modeled such that static, dynamic, and transitional friction regimes are taken into account. The rollers are represented as cylindrical bodies of finite length, including their inertia and resistive damping moments that simulate bearing friction. Simulations were performed using a MATLAB code validated against MATLAB's Simscape platform. The results show that the damping coefficient associated with the rollers' resistance to rotation is the parameter with the greatest influence on the cargo dynamics, while variations in roller diameter and contact friction coefficients have lesser effects. The developed simulation framework provides a useful basis for enhancing the modeling and design of cargo airdrop systems and can support future studies aimed at improving drop accuracy and overall system performance.

Topic: Nonlinear dynamics

Nonlinear dynamics - Paper 10350

Hybrid Modeling of Nonlinear Dynamics through Sparse and Interpretable Discrepancy Learning

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Physics-based models remain essential tools for understanding structural dynamics, yet they often diverge from experimental observations due to unmodeled nonlinearities or incomplete physical knowledge. Rather than discarding these imperfect models, their discrepancies with experimental data can be leveraged to reveal the missing physics. In this presentation, I introduce an interpretable framework for discrepancy modeling that combines sparse system identification and nonlinear autoregressive modeling, referred to as the B-SINARX approach. Starting from a known physical model, an interpretable library of candidate nonlinear terms is constructed and refined through Bayesian regression, enabling both model sparsification and uncertainty quantification. The framework is applied to two cases: a numerical Bouc-Wen system, where the hysteretic nonlinearity is unknown, and an experimental bolted-joint structure exhibiting nonlinear contact effects. The results show that the B-SINARX framework effectively captures the missing nonlinear dynamics and highlights the potential of hybrid modeling strategies that integrate physical insight with data-driven learning.

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Nonlinear dynamics - Paper 10373

On the use of a co-rotational finite element method to investigate flapping wing UAVs

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Flapping wing air vehicles have attracted the interest of many researchers due to their flight efficiency, maneuverability and reduced noise generation. The silent and inconspicuous flying animal-like appearance reveals an interesting potential which can be used for military applications, ecological research and others. In nature, birds or insects use flexible wings and muscles to generate aerodynamic forces. Therefore, understanding the influence of flexibility on flapping wings can be useful to design unmanned aerial vehicles (UAVs). Despite the most recent research, it is still a challenge to develop this kind of aircraft, in part due to the nonlinear dynamics and unsteady flow, combined with the quantity of parameters that characterize the problem, for example, wing kinematics, geometry and structural properties. This work uses the co-rotational finite element model for three dimensional problems to evaluate the dynamic responses of a wing with spanwise flexibility. The co-rotational finite element analysis is a method applied to flexible multi-body systems with large displacements and rotations. An inertial system is used to define nodal coordinates, velocities, accelerations, displacements, and rotations. The equations of motion are defined with respect to the inertial system, while stresses are measured in the co-rotational coordinate system of the element. This element coordinates system rotates and translates along with each element but does not deform with it. This formulation is one of the approaches applicable to geometrically nonlinear problems, and its main advantage is that it leads to an artificial separation between material and geometrical nonlinearity. Moreover, Lagrange multipliers are used to impose the flapping motion, the structure's first node is constrained to follow a pre-determined sinusoidal motion. The structural flexibility is evaluated by considering different levels of stiffness, mainly focused on determining the influence of the nonlinear stiffness on the system responses. The wing behavior is also analyzed considering different flapping frequencies and amplitudes. The results demonstrate that it is an interesting approach to investigate flapping wing systems focused on designing bio-inspired aerial vehicles.

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Nonlinear dynamics - Paper 10391

Characterizing the complex dynamics of a resonant linear oscillator coupled to a BNES and a piezoelectric element through fast-slow analysis

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In the context of the ecological transition, renewable energy sources such as wind turbines have become essential. However, these structures can experience harmful structural vibrations. A scientific, economic, and industrial challenge thus lies in designing devices capable of mitigating these vibrations. Among passive solutions, nonlinear energy sinks (NES) can be implemented. NES devices absorb vibrational energy over a wide range of frequencies through a phenomenon known as targeted energy transfer. Specifically, compared to classical NES, bistable NES (BNES) demonstrate enhanced ability to attenuate low-amplitude vibrations. Furthermore, the vibrational energy harvested by the NES can be converted into useful electrical energy using a piezoelectric element. This electrical energy could be used to power sensors, enabling wireless monitoring of wind turbines. The dynamic behavior of a mechanical oscillating system coupled with a BNES and a piezoelectric element is highly rich and complex, exhibiting multiple time scales. Therefore, to deploy such absorbers in complex systems like wind turbine blades, it is crucial to understand and identify the underlying dynamic mechanisms in simpler systems. To this end, this study examines an academic model: a damped harmonic oscillator forced by sinusoidal excitation, coupled with a BNES and a piezoelectric element connected to an electrical circuit with a simple resistor. Numerical simulations first reveal the wide diversity of observed vibrational regimes - periodic, quasi-periodic, or chaotic - and show the voltage obtained across the resistor. In a novel approach, the Multiple Scale/Harmonic Balance Method (MSHBM) is then adapted to account for the specific characteristics of the BNES compared to classical NES. This results in a reduced model, known as the modulation flow, which can capture the main diverse responses of the original system. Finally, a slow-fast analysis of the modulation flow is conducted, providing insight into (i) the emergence of these regimes and (ii) the effect of the piezoelectric element. This understanding paves the way for identifying optimal configurations of the NES and piezoelectric element to maximize both energy harvesting and vibration attenuation.

A Novel Nonlinear Metastructure for Broadband Vibration Energy Harvesting

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This work proposes a nonlinear metastructure architecture for vibration energy harvesting and sensing applications, enabling operation across both low- and high-frequency ranges. The system is modeled as an array of lumped-parameter piezoelectric Duffing oscillators, where the nonlinearity arises from geometric effects and the coupling between oscillators is magnetically induced. This configuration allows the exploitation of nonlinear resonance, multi-frequency synchronization, and inter-oscillator interactions to enhance power output and extend the operational bandwidth beyond that achievable by linear counterparts or by the simple superposition of individual units. Each unit cell consists of a nonlinear beam whose geometry and axial stress distribution are parametrically controlled, allowing tunability through straightforward adjustments in a 3D-printed design. Such flexibility simplifies the metastructure adaptation to vibration spectra typically encountered in industrial and commercial environments. In addition to frequency tuning, magnetic coupling between neighboring cells enables spatial management of mechanical energy within the array, promoting localization phenomena such as stationary solitons and enabling both passive and active modulation of vibrational energy transfer, leading to an increase in harvested power and usable frequency range. The proposed 3D-printed manufacturing strategy further provides a cost-effective and easily reconfigurable platform for fast geometry optimization. The main contribution of this study is the demonstration of a metastructure for vibration-related domains, that bridges nonlinear dynamics theory with practical engineering applications. To illustrate the approach, two theoretical configurations of particular interest are analyzed: a quasi-periodic array (periodic with impurities), where nonlinear energy localization is demonstrated with emphasis on sensing applications, and an aperiodic array, considered here as an industrial case study for energy harvesting.

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Evaluation of thermal effects in a bit-rock interaction model and its impact on a simplified drill-string dynamicsmodel

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In this paper we evaluate the thermal effects of a new thermal-assisted drilling technology in the rock stress field and how it can favor the cutting process. Then we propose to use this information to change the parameters of a bit-rock interaction model. Finally,the impact of the proposed model is applied to a simplified nonlinear axial-torsional drill-string dynamic model. Results show the positive impact of the new technology in the stability of the system.

Nonlinear dynamics - Paper 10414

Nonlinear dynamics of a post-buckled elastica

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In contrast to rigid bodies linked by connectors, flexible elements can undergo large strains when subjected to external time-dependent forces, which result in nonlinear stress-strain relationships. Such compliant mechanisms, in architectured materials, permit to engineer and to program build-in properties at the microscale in order to control the macroscale behaviours. This has led to the fabrication of structures/materials showing extraordinary responses such as energy trapping and shock absorption. This study focuses on the nonlinear postbuckling responses of an elastica under external harmonic excitation. Such system can be supposed as a single element of an overall architectured material. We consider the model of a forced and prestressed elastica, with clamped-guided boundary conditions. It is supposed that the external loading is applied gradually until reaching a desired buckling configuration. Then, a harmonic excitation is added to the buckling load. The system is treated analytically around one of its arbitrary equilibria and around its vibration modes. This study provides necessary insight for tuning physical and mechanical properties of the element for having engineered responses. It is spotted that, around different postbuckled configurations and vibritary modeshapes, the variation of corresponding nonlinear frequency can present different types of behaviours, namely softening and hardening ones. These analytical and numerical predictions will be compared with results obtained from the prototype experimental system.

Nonlinear dynamics - Paper 10416

On the role of translation-to-rotation coupling in omnidirectional vibro-impact nonlinear energy sink for vibrations mitigation of structures

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Our numerical study addresses a nonlinear device for the passive vibration control based on the mechanical energy dissipation achieved from impacts between solids in arbitrary directions.The device under consideration is an omnidirectional vibro-impact nonlinear energy sink (OVINES), consisting of a small rigid disk moving and bouncing inside a larger disk-shaped container. Such apparatus is attached to a primary structure with two degrees of freedom (one radial translation and one axial rotation), both systems lying in the same plane.The theoretical formulation describes the trajectories and rebound velocities of the disks after collisions. The normal and tangential components of the post-impact velocities are evaluated from the change in both linear and angular momentum due to the impacts. The formulation takes into account for normal and tangential coefficients of restitution; the later depends on the coefficient of friction between the colliding surfaces and the angle of incidence. Our study evaluates the influence of some of the OVINES parameters and of the main structure on the overall nonlinear dynamics of the system. In particular, we take into account — or not — the angular degree of freedom to reveal the effect of rotation on the mechanical response of the OVINES. For this, time responses and bifurcation diagrams will be presented and analyzed. The device's ability to mitigate structural vibrations in free and forced regimes, as well as energy dissipation and rejections mechanisms, will be discussed.In particular, we alternatively take into account or discard the angular degree of freedom to reveal the effect of rotation on the mechanical response of the OVINES. The latter is determined by computing time responses and bifurcation diagrams, which are correlated to the device's ability to mitigate structural vibrations in free and forced regimes thanks to energy dissipation and rejections.

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Nonlinear dynamics - Paper 10423

Numerical Study of Non-linear Dynamic Behaviour of Bellows for Aircraft Bleed Air

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Hot air bleed systems used for aircraft anti-icing and air conditioning are subjected to extreme loads like pressure (5 to 30 bars), high temperature (400 to 700°C), and severe vibrations inherent to engine environment. Until the 1990s, the modelling of these ducting lines relied on simplified representations using rigid beam elements, which limited consideration of thermos-mechanical interactions and assessment of their effect. The progressive introduction of flexible and damping devices such as ball joints into bleed air architectures led to a new system design approach. This evolution enabled thermo-mechanical decoupling of stresses, increased system flexibility, and damping of loads within pneumatic ducts. Previous studies have highlighted the nonlinear dynamic behaviour of ball joints, a characteristic that depends on both excitation amplitude and the direction of the frequency sweep. Literature suggests that the bellows are responsible for the joint's flexibility and plays a key role in this phenomenon. These bellows are subjected to geometric and contact nonlinearities (due to their multilayer geometry) that influence the ball joint's overall dynamic response. The primary objective of this paper is to develop a numerical model capable of accurately capturing the nonlinear (material, large displacements, contact-friction) behaviour of the bellows. This local model is then integrated into the global joint assembly to reproduce the structure's overall dynamic response. This integrated approach aims to bridge the gap between experimental observations and predictive modelling, providing a clearer understanding of the mechanisms driving the nonlinearities observed under operational conditions. Multiple numerical modelling strategies were developed and applied to various bellows configurations to investigate their static and dynamic behaviour. These models were then compared and validated against experimental results to identify key parameters governing the observed nonlinearities. Once validated, the bellow modelling was integrated into a numerical model of the complete ball joint assembly. This enabled direct comparison of the predicted and measured nonlinear responses. This multiscale modelling approach provides valuable insights into the mechanisms governing the ball joint's nonlinear dynamic behaviour and contributes to enhancing predictive accuracy of vibrations simulations. The findings of this study confirm the significant influence of geometric and contact nonlinearities on the dynamic behaviour of ball joints used in hot air bleed systems. Furthermore, the developed modelling approach enables a more accurate prediction of the system's response under operational conditions. This work advances the understanding of the mechanisms governing the nonlinear behaviour of ball joints and provides a robust foundation for future design optimization.

Experimental assessment of a novel vibro-impact magnetic energy sink

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In contrast to linear vibration absorbers, nonlinear energy sinks (NES) are known to be effective over a wide frequency range. This is achieved through the targeted energy transfer mechanism, which results in passive, irreversible energy pumping from a primary structure to the NES when the vibration amplitude of the former exceeds an activation threshold. Many practical realizations of the NES have been proposed, among which the vibro-impact (VI) variant is particularly interesting due to the small amount of added mass required for an ef-ficient performance. In this contribution, we introduce a new concept for a VI magnetic energy sink (VI-MES) which is based on an energy harvesting device recently developed by the authors. The electromagnetic architecture consists in a variable reluctance generator which incorporates a moving permanent magnet that switches between two magnetic circuits upon the action of an external force; this process results in a conver-sion from mechanical to potential (magnetic) energy, which is then extracted by induction on two coils. The elec-tromechanical characterization of this device has shown excellent performances for energy harvesting while also presenting the advantages of easy scalability, modularity, and compactness. Therefore, our goal is to evaluate the potential of this technology as a VI-MES through an experimental campaign. To this end, a test bench has been designed in which a primary structure, mounted on a shaker table, has a VI-MES module fixed to its frame. Frequency and amplitude response tests were conducted to characterize the absorber per-formance. The determination of activation threshold as a function of magnetic circuit parameters and additional mass obtained by the design of structural components was given special attention, as this naturally leads to the prospect of a VI-MES whose properties may be adjusted in real time by an active controller to guarantee an optimal performance through simple manipulation of its electric component.

Numerical and experimental nonlinear dynamics of the MUSE tribometer

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In the industrial context of pressurized water reactors (PWR) within the French nuclear power plant fleet, some of the vessel internals are subject to wear, which requires the implementation of costly maintenance strategies. Faced with these challenges, EDF and CEA aim to enhance the understanding and prediction of wear phenomena. This work focuses on deepening the nonlinear dynamics modeling of wear testing machines, such as the MUSE tribometer, to better understand and predict vibratory regimes associated with impact and friction during testing. These advancements significantly contribute to optimizing experimental setups and ensuring the accuracy and repeatability of wear studies.The MUSE tribometer, which serves as the experimental support for this study, features newly patented electromagnetic actuators that drive a projectile along two perpendicular directions, enabling it to impact or slide on a fixed target with micrometer precision. Actuator motion is achieved by generating a Laplace force through electric currents in coils, powered by permanent magnets. A dedicated control software manages signal type, voltage, frequency, and phase shift to precisely adjust actuator displacement. In order to best control the contact conditions in the tribometer, particular attention is paid to understanding the conditions and parameters that need to be set up to obtain periodic vibration regimes.In this context, to reproduce and analyze these complex behaviors numerically, a continuation algorithm based on the Harmonic Balance Method (HBM) is used to compute the system's nonlinear frequency response. Stability analyses based on Floquet theory are then conducted on the obtained periodic solutions. Furthermore, the recently developed Koopman-Hill method is implemented on the MUSE 1D system to assess its suitability for highly stiff nonlinear dynamics. All developments are carried out within the DYN2 numerical library, which focuses on reduced-order nonlinear vibration modeling. Written mainly in Python with integrated compiled C routines, DYN2 is designed to evolve into an open-source platform for the scientific and industrial community.This combined numerical-experimental approach allows for a comprehensive understanding of the system's vibratory regimes, including the identification of bifurcations and transitions induced by the vibro-impacting nature of the system. Extended experimental tests have been conducted on the MUSE tribometer to validate the models. Initial results involving 1D normal contact without friction modeling show very good agreement with the experimental measurements. Future work will focus on extending the modeling to 2D configurations including friction.

Nonlinear dynamics - Paper 10448

Machine Learning-Based Dynamic Feedback Linearization Control of Quadrotor Drones under Unmodeled Dynamics

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The control of agile quadrotors in dynamic and uncertain environments remains an open area of investigation to this day, particularly when the complete system dynamics are partially or highly nonlinear. This work presents a novel machine learning-based dynamic feedback-linearization (DFL) control framework that employs a Hybrid Hyperbolic Tangent-Gaussian Radial Basis Function (HTG-RBF) neural network to model and compensate for unmodeled dynamics in real time. The proposed controller leverages the universal approximation capability of RBF networks to estimate nonlinear uncertainties. An online parameter adaptation of the RBF's neural network without prior specification of network architecture or training is employed. The control law stability is derived using the Lyapunov stability theory, hereby guaranteeing closed-loop stability and theoretical guarantee of asymptotic convergence of a trajectory tracking task. Simulation experiments are conducted on a quadrotor subject to unmodeled friction, actuator dynamics, and external disturbance. Despite incomplete knowledge of prior dynamics and presence of injected external disturbance such as drift in state estimation and unmodeled friction, the proposed achieves precise trajectory tracking with rapid convergence. In simulation, the robot is tasked with following trajectories such as circles, figure-eight paths under injected disturbances. Real-world tests are carried out on a physical quadrotor drone platform equipped with standard odometry and onboard sensing. Performance is evaluated using trajectory tracking error, convergence time, and robustness against disturbances. Results show that the proposed controller achieves rapid convergence to the desired trajectory, with significantly reduced tracking error compared to baseline PID and adaptive model-based controllers. Classical model-based controllers often require accurate system identification, and their performance degrades significantly under modeling errors, unmodeled dynamics, or external disturbances. By integrating data-driven function approximation with traditional control theory, this research establishes a generalizable framework for intelligent flight control, advancing the development of adaptive and autonomous aerial robotic systems capable of reliable operation in unstructured environments. Future extensions will incorporate the use of reinforcement learning-based parameter tuning and adaptation, extension of the framework to multi-robot coordination, and integration of obstacle-aware navigation.

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Nonlinear dynamics - Paper 10453

Rate-induced tipping in a dry-friction oscillator under parameter drift

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Self-excited oscillations due to dry friction often occur in mechanical systems where the friction force depends nonlinearly on the relative velocity between contacting bodies. Such systems can also display multistable behavior, with several coexisting stable solutions (attractors) for a given set of control parameters.Classical bifurcation analysis, which assumes constant parameters, captures the multistable behavior discussed above by analyzing the solutions and their stability. For some minimal models, the basins of attraction of the stable solutions can be computed to determine which stable solution is actually reached, again for a given set of constant parameters. During transient regimes, however, parameters may vary in time, giving rise to phenomena that lie beyond the predictive scope of classical bifurcation analysis and the conventional definition of basins of attraction. In particular, a multistable system with time-varying parameters can undergo rate-induced tipping, that is, an abrupt regime shift induced by the rate of change of a parameter rather than by its value. This phenomenon, mainly studied in climate science, is rarely documented in mechanical engineering, even though it is crucial for understanding regime selection in systems exhibiting multistability under realistic operating conditions.This study theoretically and numerically investigates tipping phenomena in a well-known dry-friction oscillator, modeled as a mass-spring-damper resting on a conveyor belt whose velocity acts as the control parameter. This minimal model exhibits bistability between stick-slip (oscillatory) and steady-sliding (non-oscillatory) motions. The proposed methodology allows us to determine, as a function of both the initial conditions and the rate of change of the belt velocity, whether oscillations are produced following a transient that ends in the bistable region.

Nonlinear dynamics - Paper 10454

Variable-Order Fractional Rheology for Predicting Time-Dependent Deformation in Polymeric Structures

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Polymeric materials exhibit complex time-dependent deformation governed by molecular rearrangements and evolving viscoelastic properties. This study employs a variable-order (VO) fractional rheological framework to model such behavior with enhanced physical fidelity. The approach generalizes the classical springpot element by allowing the fractional derivative order to vary smoothly with time, capturing continuous transitions between glassy, transition, and rubbery regimes. A cross-entropy-based optimization procedure is employed to identify model parameters from experimental creep data, providing robust and interpretable estimates of evolving viscoelasticity. The VO formulation reproduces the entire temporal response with superior accuracy compared to constant-order fractional and classical viscoelastic models. The results reveal a physically consistent evolution of the fractional order associated with internal structural relaxation and stiffness reduction. This framework offers a powerful, computationally efficient tool for predicting long-term mechanical response and reliability of polymeric components in structural and dynamic applications.

Topic: Railway engineering

EURODINAME III
8-11 Jun 2026 - Giens (FR)

Railway engineering - Paper 10387

Analysis and correlation of railway measurement data using Global Navigation Satellite System based curvature estimations

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This paper addresses the problem of accurately allocating measured railway operational data, obtained from different trips of an instrumented railcar. Precise geographic allocation of dynamical measurements obtained in different train trips is important to build a reliable database of the track's operational condition. The methodology involves transforming two or more Global Navigation Satellite System (GNSS) data into a consistent linear distance versus curvature information format. Both datasets are filtered and then resampled at regular, equal intervals to facilitate direct comparison. A correlation map image from curvature data is subsequently generated to identify the linear distance correspondence between the datasets, as well as to quantify and correct any linear scale discrepancies that may exist between them. The proposed correlation technique is applied to a couple of GNSS data collected from an actual railway instrumented vehicle, passing the same track position on different dates. A shorter distance length data record is compared to a longer track distance recording. This shows the ability of the technique to exactly position of the shorter distance measurements in the context of the longer distance track record. The quality of data correlation (possible linear scale discrepancies) is also accessed in the analysis.

Topic: Rotor dynamics

Rotor dynamics - Paper 10394

Unbalance Identification in Rotating Machinery Using Cokriging Metamodeling

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Along with misalignment, the leading cause of mechanical issues in rotating machinery is unbalance of the rotating assembly. Among the various balancing techniques available, the influence coefficient method is widely used. However, this technique demands test runs with trial masses, which is often inefficient, resulting in the need for new balancing attempts and prolonging service execution time.In the Oil and Gas industry, minimizing intervention time is paramount, directly translating to increased productivity and reduced lost profit, the financial loss due to the non-processing of oil derivatives. Specifically for refineries (downstream), where redundant (spare) machinery is often unavailable, any unscheduled intervention can lead to a complete unit shutdown. Therefore, exploring novel possibilities for unbalance detection without the need for trial mass runs is essential to significantly reduce the time required for these procedures. This work addresses this context by implementing an unbalance identification methodology using a Cokriging Metamodel. This approach leverages two distinct data sources: Experimental Data: Time-domain vibration signals collected directly from the machine (high-fidelity or expensive data). Numerical Data: Vibration signals generated from a numerical model (low-fidelity or cheap data).To validate the proposed methodology, two validation phases were conducted: a purely numerical validation followed by an experimental validation.

For the numerical validation, vibration signals generated from a numerical model were utilized as high-fidelity samples and Monte Carlo uncertainty was added to stiffness and damping of the bearings and rotor modulus of elasticity in order to create the low-fidelity samples. For the experimental validation, tests were performed using a test rig (a rotor kit with two disks between bearings). Unbalance sets were applied in two planes (two disks) and vibration measurements in time domain were taken. Subsequently, this vibration data was divided into training and validation datasets and a cross-validation was performed.The experimental validation is a crucial factor in establishing the methodology, for instance, defining the optimal quantity of high-fidelity and low-fidelity samples to be included in the metamodel to maximize its performance. Ultimately, this research aims to develop a robust Factory Acceptance Test (FAT) procedure that can generate a minimum required dataset, thereby enabling the implementation of this methodology during the machine's operational campaign. Keywords: Rotating Machinery, Unbalance, Cokriging Metamodeling, Multi-Fidelity Data.

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Rotor dynamics - Paper 10407

In-Situ Balancing of Overhung Rotors Using Video Motion Magnification

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Rotor unbalance is one of the primary causes of vibration, fatigue, and reliability problems in rotating machinery. Traditional in-situ balancing procedures, including the influence-coefficient method, are reliable but limited by their point-wise sensing, the need for physical sensor mounting, such as accelerometers, and lengthy setup times. Conversely, optical and vision-based techniques have recently emerged as promising alternatives, capable of providing full-field vibration data without contact sensors. This study investigates the use of Video Motion Magnification (VMM) to support the balancing of overhung rotors under operating conditions. The VMM technique, based on Eulerian and phase-based video processing, treats each pixel as a virtual displacement sensor, allowing the visualisation and measurement of small, otherwise invisible motions. Controlled experiments were carried out on an overhung rigid rotor operating at a constant speed under various unbalance conditions, including static, couple, and dynamic cases. Synchronised high-speed video and accelerometer data were collected and analysed for comparison. Optical data were filtered at the 1× rotational frequency and converted into velocity fields, while accelerometer signals were examined using classical spectral and phase estimation methods. The correction masses and their angular positions were determined using the traditional influence-coefficient approach, where response amplitudes and phases were used to construct the system's influence matrix. The balancing solutions derived from video and accelerometer measurements were then compared to assess the accuracy and consistency of the optical technique. Results showed very good agreement between VMM-derived and accelerometer-based measurements, resulting in similar correction weights and angular positions. VMM demonstrated potential practical benefits, such as shorter setup times, no contact sensors, and an improved ability to observe overall system dynamics, including movements of supports and connections that are often overlooked by traditional instrumentation. The experiments also confirmed that factors like surface texture, lighting, and camera placement significantly affect measurement quality, though these can be effectively managed through standardised setup procedures. The findings indicated that Video Motion Magnification is a promising contactless method for rotor balancing and could effectively complement traditional sensor-based techniques. Further work is ongoing to expand the experimental dataset and improve the measurement and processing framework for wider application and enhanced robustness.

Rotor dynamics - Paper 10446

Neural Networks Applied to Unbalance Analysis: A Literature Review

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Vibrations in machines present a significant challenge for engineers, particularly in components involved in rotational movements, such as rotors. Consequently, understanding rotor imbalance is crucial to ensuring safety and reliability in the design of machines and other mechanical structures that incorporate rotating elements. To comprehend the dynamic behavior and the impact of excessive forces on mechanical parts or machines caused by unbalanced masses, designers must study and select the optimal mass distribution in the parts. This allows them, in the early stages of the design process, to employ preventative measures or address potential issues by balancing rotating mechanical components. This approach protects these components from excessive vibrations originating from unbalanced masses, thereby mitigating the risk of catastrophic failures, primarily due to component fatigue. Commonly practiced methods involve balancing in one or two planes. Therefore, the primary focus of this study is to provide vibration control through mass distribution in components with irregular cross-sections. This review paper focuses on the application and performance of Artificial Neural Networks (ANNs) in identifying and quantifying unbalance in rotating systems. It explores how these methodologies can be employed to overcome challenges in fault diagnosis, presenting models of rotating systems used for data generation, along with neural network architectures, training algorithms, and the activation and objective functions used. A computational approach based on ANNs is presented to extract behavioral tendencies from dynamic systems of unbalanced rotors, assisting in the detection of unbalance. The results highlight the effective functionality and the validity of the ANNs' application, enabling their implementation in balancing mechanical parts such as rotors, within the standards and requirements defined by the industry.

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Rotor dynamics - Paper 10452

From Classical Rotordynamics to Smart Rotors

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Since the first paper on rotordynamics by W. J. M. Rankine in 1869, titled On the centrifugal force on rotating shafts, this research topic has gained increasing attention from scientists and engineers over the world. It is possible to say that most of the tools used in the study of rotating systems have been developed throughout the last century, particularly after 1950. In general terms, most of the work developed so far can be classified as classical rotordynamics, encompassing numerical methods dedicated to the determination of Campbell diagram, unbalance responses, orbits, and modal analysis, and experimental testing both in university laboratories and industry facilities. It is worth mentioning that the impressive development of digital computers together with enhanced numerical methods (such as those for direct and inverse problems and uncertainty analysis), control techniques, signal analysis, new sensors and actuators, and material science have made possible new achievements on rotordynamics, permitting an evolution from the so-called Classical Rotordynamics to Smart Rotors whose definition is still under construction. As a suggestion, a smart rotor is the rotating system that besides allowing classical rotordynamics analysis and optimization, can offer automatic diagnosis of faults together with the ability to apply control forces to optimize the dynamics of machine behavior aiming at quiet, ecological, robust and efficient machines. At the same time industry has increased the demand for high efficiency, thus requiring even higher rotation speeds requiring more flexible rotors and new types of bearings and couplings. The present contribution is dedicated to exploring some examples of successful research on the dynamic behavior of smart rotors.

An Integrated Compressible Bulk-Flow Model and Kriging Metamodel Approach for Non-Linear Rotordynamic Analysis

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Accurately predicting the vibration response to unbalance of rotating machinery is a persistent challenge in rotordynamics, fundamental for ensuring operational stability and mitigating the risk of component failure. In these systems, mechanical seals are components designed to prevent fluid leakage. However, they also introduce significant lift forces, which are conventionally linearized and represented as stiffness and damping coefficients. A primary limitation of traditional rotordynamic analysis is the assumption that these coefficients are constant, typically calculated only at the concentric rotor position. This work proposes a methodology for simulating the non-linear unbalance response of rotating machinery through a compressible bulk-flow model (BFM) for plain seals. Departing from common simplifications, this BFM incorporates the hypothesis of a compressible fluid and eliminates the constraint of a concentric rotor, allowing for the calculation of dynamic coefficients at any specified eccentric position. This comprehensive model is based on the governing continuity equation, together with axial and circumferential momentum conservation, and energy conservation equations. These are solved numerically by using the Finite Volume Method (FVM) with a density-based simultaneous solution approach, which ensures strong coupling between thermodynamic and flow variables, providing enhanced numerical stability. The central innovation of this contribution lies in the integration of this BFM model into the Rotordynamic Open-Source Software (ROSS) Python library. Recognizing that executing the computationally expensive BFM at every integration step is not viable, a surrogate modeling strategy is employed. First, the BFM is used to generate a comprehensive database of the seal's dynamic coefficients across a wide range of rotor center positions. Next, Kriging metamodels, selected for their efficient interpolation, are trained on this dataset. These computationally efficient Kriging models are then integrated directly with ROSS. During the transient dynamic simulation of unbalance responses, the numerical integrator determines the rotor center position at each time step. This position is fed to the Kriging metamodels, which instantly predict accurate position-dependent stiffness and damping coefficients. These updated coefficients are used to calculate the non-linear seal reaction forces for that specific instant, before proceeding to the next time step. This approach captures the non-linear dynamics of the seal, enabling a significantly more precise prediction of the unbalance response. The underlying BFM's validity was confirmed through comparisons with literature data, thus ensuring the physical fidelity of the entire simulation methodology.

Operating-Condition Effects on Rotating Machinery Unbalance and the Applicability of the Influence Coefficient Method

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Unbalance is a primary source of excessive vibration in industrial rotating machinery, degrading reliability, increasing dynamic loads, and shortening the service life of bearings, couplings, and shafts. Conventional field balancing typically relies on the trial-weight method: a test mass is applied at predefined correction planes, followed by iterative runs until vibration amplitudes are acceptably reduced. Despite its widespread use, this approach entails extended downtime, multiple iterative tests, and safety risks associated with accessing rotating components; for large machines, a single test-mass round rarely achieves the desired balance grade. To reduce outage duration, a practical alternative keeps the tachometer at a fixed position and reuses influence coefficients from a prior balancing campaign to predict the magnitudes and locations of correction masses, thereby eliminating trial-mass runs. Although often effective, we have observed cases with increased vibration amplitudes after implementation. Using a digital twin of a 9-ton machine, we systematically assessed how geometric and operational conditions affect the accuracy of the influence-coefficient method. The parameters investigated included load variations, shaft misalignment, bearing temperature, lubricant-film pressure, spurious noise, rigidity in hydrodynamic bearings, initial unbalance level, amplitude/phase errors in both test and correction masses, and proximity of harmonic and subharmonic excitations to natural frequencies. Results indicate that initial unbalance level, phase/position errors of test masses, spurious noise, and near-resonant operation are the dominant drivers of balancing inaccuracy.

Integrated Multiphysics Framework for the Dynamic Analysis of Wind Turbine Rotors

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The technological evolution of large-scale wind turbines introduces new challenges to computational modeling, demanding approaches capable of accurately and efficiently representing the main physical phenomena involved in rotor operation. This work proposes the development of an integrated multiphysics framework for the global dynamic analysis of a wind turbine, combining a nonlinear and unsteady aerodynamic model based on the Vortex Lattice Method (NL-VLM), a generator electromagnetic force module, and a rotor structural model formulated using the Finite Element Method (FEM) with emphasis on vibrational response and the identification of dynamic patterns under different operating conditions. The first stage involves the implementation of the unsteady NL-VLM core, incorporating a dynamic stall model, a time-marching free-wake vortex formulation, and coupling with a decambering approach that uses 2D aerodynamic polars obtained via XFOIL. This combination allows the inclusion of viscous and flow-separation effects typically observed at high angles of attack. In parallel, the modeling of unbalanced electromagnetic forces generated by the alternator is developed, introducing periodic excitations into the system-particularly relevant under off-design operating conditions. These loads are integrated into the rotor dynamic model, which consists of a flexible shaft modeled by using the FEM, a gear meshing model representing the gearbox, and rigid disks accounting for the inertia of other drivetrain components. In the following stage, the aerodynamic model, including nonlinear and unsteady corrections, will be coupled to the rotor structural model, forming an integrated simulation environment capable of estimating the vibrational response of the system as a function of wind and rotational conditions. The developed framework enables the coupled analysis of the rotor's aeroelastic behavior, assessing its capability to properly represent the underlying dynamic phenomena. The integration of different physical domains into a single computational environment strengthens the potential of the methodology for future application to digital shadow systems for wind turbines, supporting the enhancement of monitoring and operational optimization strategies.

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Rotor dynamics - Paper 10494

Development and Calibration of a High-Fidelity Digital Shadow for Dynamic Analysis of Hydroelectric Generating Units

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The monitoring of faults in rotating machinery has proven to be a subject of significant interest across industrial sectors, as it is essential for maintenance processes and for ensuring operational efficiency and safety. One of the major challenges in this monitoring is the early detection and diagnosis of mechanical faults in such equipment. Several approaches for damage diagnosis can be found in the literature. Among these, a prominent methodology is the use of a mathematical model of the machine, also known as digital shadow, from which an inverse problem is constructed and subsequently solved using the Differential Evolution algorithm. In this process, modeled faults are added iteratively, with their parameters treated as design variables within the optimization. This vibration-based approach accurately estimates fault parameters. However, the technique's effectiveness depends directly on how well the mathematical model represents the rotating system's dynamic behavior. In this context, the present work proposes a new approach to the creation and calibration of a high-fidelity digital shadow, focusing on one of the generating units at the Foz do Chapecó Hydroelectric Power Plant, located in Brazil. This unit consists of a vertical machine supported by three hydrodynamic bearings, measuring 15451 mm in length and having a nominal power of 225 MVA. The calibration methodology for this digital shadow is based on the same heuristic optimization and inverse problem-solving process used for diagnostics. The objective is to adjust the parameters of the multiphysics model, which represents components such as the generator, turbine, hydrodynamic bearings, and shaft, until its simulated vibration response converges with the actual operating data collected by proximeters installed on the machine. Preliminary results, adjusting only the residual unbalance parameters in the generator and the turbine, have already demonstrated good agreement, showing deviations of 14% in the vibration amplitude at the machine's rotational frequency. However, this work advances by incorporating misalignment parameters at the shaft couplings as additional design variables in the calibration process. It is expected that by considering not only unbalance but also the intrinsic assembly misalignments, the resulting digital shadow will achieve a higher level of dynamic representativeness, which is fundamental for increasing the reliability and precision of future diagnostics.

Topic: Smart and advanced structures

Smart and advanced structures - Paper 10471

Piezoelectric-Based Detuning Monitoring System for Viscoelastic Vibration Neutralizers

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Dynamic vibration neutralizers employing viscoelastic materials as dissipative elements are widely used in industry to reduce excessive vibration amplitudes in mechanical structures such as rotating and non-rotating machinery, oil and gas pipelines, and civil or mechanical engineering systems in general. However, viscoelastic materials-particularly those based on vulcanized polymers-exhibit a strong dependence on temperature and frequency, as well as accelerated aging due to fatigue and environmental degradation. These conditions lead to undesired effects on the absorber's performance, reducing its control capability as a result of the shift in its natural frequency (detuning). To address this issue, it becomes essential to develop mechanisms capable of monitoring the neutralizer's detuning throughout its service life, in order to assess its performance and support predictive maintenance of such control devices. In this work, a diagnostic device based on a resonant piezoelectric element is proposed, acting as a detuning sensor. The piezoelectric element, attached to the dynamic neutralizer, exhibits both electrical and mechanical responses that are sensitive to variations in the dynamic properties of the system. Based on this concept, a mathematical model is developed to describe the coupled dynamics of the primary structure, the dynamic neutralizer, and the resonant piezoelectric device, hereafter referred to as the harvester. A sensitivity analysis of the harvester's response to induced changes in the neutralizer is performed. Furthermore, the analytical study will be extended to numerical simulations using finite element models, allowing for the inclusion of more complex geometries and boundary conditions representative of real systems. Finally, the numerical results provided by these models will be experimentally validated in the laboratory through the fabrication and implementation of the viscoelastic dynamic neutralizer and the piezoelectric harvester on a real primary system (e.g., a vibrating duct or machine).

A thermally driven smart sandwich structure with a shape memory polymer core for semi-passive vibration control

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Constrained layer damping (CLD) treatment is a passive technique used to reduce vibration levels by incorporating viscoelastic materials into multilayered structures to increase structural damping. As a passive vibration control technique, it does not require external energy input to operate. In particular, the damping layer contributes to vibration reduction when the structure is subjected to high-frequency excitations. However, the efficient design of such a solution often requires an appropriate strategy for allocating the viscoelastic layer, since the strain energy distribution varies with load frequency and boundary conditions. Moreover, improving the robustness of traditional CLD solutions leads to an increase in structural mass, and the resulting multilayered structures still lack adaptability once fabricated. The development of advanced materials such as shape memory polymers (SMPs) enables the design of structures with enhanced adaptability. By controlling the temperature-dependent mechanical properties - storage modulus and loss factor - of these viscoelastic materials, a multilayered structure can exhibit various dynamic behaviors. In this work, a thermally driven sandwich structure is developed by integrating embedded thermocouples and in-core heaters to achieve active thermal control. The structure is divided into independently controllable patches, allowing it to be programmed with distinct thermal configurations. This capability enables local adjustments of stiffness and damping through temperature control at each patch, thereby enhancing the overall adaptability of the structure. An equivalent modeling approach for the sandwich structure is adopted to construct a Pareto front that evaluates the damping and static stiffness levels of various thermal configurations. Based on different damping-stiffness trade-offs, the dynamic responses of selected configurations are experimentally characterized. The results demonstrate that the proposed structure exhibits improved adaptability and achieves significant vibration reduction under different imposed thermal configurations.

Smart and advanced structures - Paper 10480

Theoretical Development and Proof-of-Concept of Adaptive Mechanical Systems for Structural Monitoring

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Natural systems, such as flocks of birds, schools of fish, and swarms of insects, exhibit remarkable self-organization and adaptability, resulting from simple, decentralized interactions among immediate neighbors. Small local interactions give rise to complex global patterns, in which the collective behavior emerges spontaneously from the system dynamics, a phenomenon known as emergent behavior. These systems are self-regulated and responsive to changes, offering new perspectives for the development of adaptive structures. Inspired by these principles, this work proposes a self-adaptive structure divided into interconnected cells, capable of locally adjusting their viscoelastic properties in response to its environment. These properties vary according to the temperature and excitation frequency to which the cells are subjected. Adaptation is implemented through a physical multi-agent model, in which each cell acts as a dynamic agent governed by local interaction laws describing energy exchanges and couplings with neighboring cells. Each agent possesses its own states and physical rules, so that the global behavior emerges from local interactions without the need for centralized control. This decentralized approach allows each cell to autonomously adjust, generating emergent behaviors that maintain system stability under external disturbances. Unlike similar structural applications that combine centralized control with centralized thermal mapping, in this case, the mapping is used only to calibrate the initial parameters of the local dynamic laws. In this way, the proposed strategy provides a promising alternative for the development of intelligent, adaptive, and resilient structures in complex environments.

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Smart and advanced structures - Paper 10585

Hybrid Vibration Control Strategies for Large Wind Turbine Blades: A Reduced-Order Modeling Approach

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The continuous upscaling of wind turbine blades has greatly improved energy capture efficiency but has also introduced complex structural-dynamics challenges, including large-amplitude vibrations, fatigue damage, and aeroelastic instabilities. These issues motivate the development of reliable vibration-mitigation strategies capable of maintaining structural integrity while minimizing maintenance costs. This study presents a unified computational framework that combines passive and piezoelectric-based active control concepts for vibration attenuation in rotating wind-turbine blades, using reduced-order models (ROMs) to achieve computational efficiency without compromising dynamic fidelity. In the initial stage, a simplified yet accurate ROM was established to capture the essential flexural and torsional behavior of a representative large-scale turbine blade subjected to stochastic wind loading. Passive damping solutions-such as tuned mass dampers and viscoelastic layers-were integrated and numerically evaluated under variable wind profiles. The simulations demonstrated significant vibration-amplitude reductions and provided valuable insight into how such energy-independent devices can enhance overall structural stability. These results established the baseline for advancing toward active and hybrid control approaches. Building on this foundation, piezoelectric actuators were incorporated into the reduced-order framework to model electromechanical coupling in rotating conditions. Proportional feedback and gain-tuned control laws were implemented to examine their effectiveness in suppressing critical vibration modes. Parametric analyses revealed that actuator placement and gain optimization play decisive roles in improving attenuation performance. The numerical results confirmed that piezoelectric actuation can achieve additional reductions in vibration amplitude beyond passive damping alone, validating its feasibility for distributed, adaptive control in rotor-blade systems. The study highlights the synergistic potential of hybrid control configurations that merge passive energy-dissipating mechanisms with active piezoelectric feedback. Future research will extend the methodology to include nonlinear structural effects, aerodynamic coupling, and real-time implementation of hybrid strategies. The final objective is to formulate a scalable control framework that ensures robustness, energy efficiency, and adaptability for next-generation wind turbines. By integrating passive and active vibration-control paradigms into a single reduced-order modeling environment, this research advances the understanding of smart structural control for large, flexible rotating blades. The proposed approach offers a pathway toward more durable, efficient, and reliable wind-energy systems, contributing directly to enhanced sustainability and reduced operational costs in modern renewable-energy infrastructure.

Topic: Stochastic systems

Stochastic systems - Paper 10488

Application of Probabilistic Neural Network for Uncertainty Propagation in Rotordynamic: parametric and non-parametric approaches

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Uncertainty propagation methods are widely studied and applied in works aiming to understand and assess variations within a system, as well as to analyze how and to what extent such variations impact the system's response. Uncertainty propagation through stochastic modeling can generally be divided into two main approaches. The first one, parametric, considers a probability distribution for the parameters (material properties, dimensions, etc.). The second approach, nonparametric, considers uncertainty directly in the matrices (operators) of the reduced-order system (modal reduction). In this case, Random Matrix theory is applied, and each matrix has a probability distribution. While parametric propagation focuses on evaluating the influence of one or a few system parameters, matrix-based propagation considers the system as a whole. Uncertainty propagation can be done with Monte Carlo simulations, for example. As Monte Carlo relies on numerous calls to the solver, surrogate models can be employed to replace the solver by a mathematical approximation cheap to evaluate. Once those approximations are constructed, uncertainty propagation can be performed at low cost. The present work proposes a framework for comparing the results obtained from parametric and matrix-based uncertainty propagation, where surrogate models are exploited to speed up the computation. The developments are done on the Finite Element Model of an industrial rotor, where bearing properties are random. From both approaches (parametric and non-parametric), surrogate models are built. Two approaches are compared, namely Neural Networks (NN) and Probabilistic Neural Networks (PNN). The comparison is done in terms of numerical efficiency, but also in terms of interpretability for dynamics applications. The nuances between the different approaches are examined.

Topic: Structural dynamics and vibration

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Structural dynamics and vibration - Paper 10078

REDUCING VIBRATIONS ENHANCES THE AERODYNAMIC PERFORMANCE OF A FLAPPING WING VEHICLE

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Nature evolved the ability to fly using a reciprocating motion of the wings to generate the lift and thrust forces required to sustain flight.On the other hand, conventional rotary or fixed-wing aircraft configurations generate these forces using rotating propellers.The flapping wing vehicle is a configuration inspired on natural fliers attracting attention from the research community that replicates the motion from flying animals to obtain better stealth, safety and maneuver characteristics in comparison with conventional designs. However, the flapping motion generate vibrations that propagates to the vehicle body and affecting the velocity on the aerodynamic surfaces.The objective of this work is to investigate how these vibrations affect the aerodynamic loads and analyzing the effect of including a vibration neutralizer to the vehicle design. Since the flapping wing vehicle operate in a narrow frequency band, a vibration neutralizer is included to passively reduce these vibrations by generating a force opposing the excitation source. The expected results is that the inclusion of the extra mass from the vibration neutralizer is justified by an increase of the generated lift.The equation of motion of the flapping wing body is derived from first principles using Lagrangian mechanics. The vehicle body is modeled by a series of mass and springs and the inertial loads of the wing during the flapping motion act as the excitation force. A vibration neutralizer is designed to suppress the vibrations originating at the flapping wing frequency and the frequency response functions of the systems are compared. The dynamic response of the system undergoing the flapping wing motion is obtained by integrating the equation of motion in time using a numerical approach. The Unsteady Vortex Lattice Method is used to model the aerodynamic loads, which assumes an incompressible, irrotational and inviscid fluid flow outside the regions of confined vorticity to find the superposition of elementary solutions of the Laplace equation that satisfies the non-penetration condition at the collocation points on the surface of the wing. The aerodynamic loads are computed using the Joukowsky method and the lift from the different models are compared to verify the efficacy of the vibrations neutralizer to the design of flapping wing vehicle.

Dual-mode resonating scanner with adaptive frequency tracking

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Resonating electromechanical scanners are compact, efficient alternatives to rigid systems. This paper presents a model and actuation scheme for a scanner that traces trajectories via two resonating modes. Combining these modes with proper phasing creates a traveling-wave generator. An iterative, orthogonal excitation scheme with a phase-locked loop generates robust, model-robust excitation. Using Singular Value Decomposition (SVD) on measured data finds the optimal frequency. The approach addresses challenges: (i) similar to ultrasonic motors, combining two modes at one frequency to produce motion; (ii) using at least two phased modes for closed-curve motion, with resonance and proper excitation despite frequency splits; (iii) managing nonlinearities and parameter drifts with a phase-locked loop at the optimal frequency. The theoretical framework is validated experimentally on a system with real and complex poles, where non-purely real modes are handled via SVD of the frequency response matrix instead of modal control, facilitating optimal operating point identification.

Structural dynamics and vibration - Paper 10384

Dynamic Analysis of Hybrid Aeronautical Reinforcements Manufactured by Additive Manufacturing

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This paper aims to develop and investigate hybrid aeronautical reinforcement structures made of composite materials. The study focuses on epoxy-based systems reinforced with both carbon and natural fibers, manufactured through 3D printing with continuous fiber deposition. The proposed approach combines the high stiffness and mechanical strength provided by carbon fibers with the enhanced damping capacity and sustainability of natural fibers, targeting applications in aircraft wing skins and spars. The research emphasizes the development of numerical models based on spectral elements of hybrid reinforcements, enabling localized tuning of natural frequencies and structural damping. The central motivation of this work lies in the potential of hybrid carbon/epoxy and natural fiber/epoxy reinforcements to improve the dynamic performance of aeronautical composite structures.

On the Calculation of Impulse Response Functions for Mechanical Systems

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Having accurate estimates of a mechanical system's impulse response functions (IRFs) is fundamental for successfully applying Impulse-Based Substructuring (IBS), the time domain counterpart of the established Frequency-Based Substructuring (FBS). Especially in an experimental context, acquiring accurate IRFs is challenging. To estimate IRFs, a procedure called Time Domain Deconvolution is utilized, which is the inverse of the Duhamel (convolution) integral. This allows for the calculation of IRFs from measured responses and the corresponding excitation using a pseudo-inverse, as well as averaging.However, the way the deconvolution procedure was written in previous works is suboptimal. Based on the construction of the force convolution matrix, certain assumptions are already placed on the IRFs. While the previously proposed approach made the deconvolution problem overdetermined, it was also assumed that the IRF of the analyzed system is not longer than the length of the calculated IRF. This means, it was assumed that the measured system's response is fully decayed after the IRF calculation length, e.g., 10 ms. While this assumption is obviously bad, the advantages gained from the overdetermination are also minuscule. Further, the problem can be easily overdetermined by averaging multiple measurements.This contribution details the assumptions used for the previous approach of Time Domain Deconvolution and shows the negative effect on calculated IRFs. Then, a new method for the deconvolution procedure is proposed. Both methods are compared using numerical, simulated, and experimental IRFs. Lastly, the effect of the new deconvolution procedure on responses calculated through Impulse-Based Substructuring is investigated.

Prediction of high-frequency vibration localization in membranes with concentrated masses: an iterative landscape approach

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Vibration localization, a phenomenon resulting from multiple interferences that inhibit wave propagation in infinite disordered media, manifests in finite domains through the emergence of spatially localized modes. At low frequencies, when localization is induced by heterogeneities such as blocked regions, the localization landscape provides a deterministic way to analyze the phenomenon: it predicts both the frequencies and the spatial locations of the modes through a simple static computation. In contrast, when localization occurs at high frequencies, particularly in the presence of local resonators, the classical landscape no longer provides predictive information.The objective of this work is to propose a new approach, based on the landscape theory, to predict high-frequency localization in vibrating systems. As a starting point, we investigate vibration localization in membranes with concentrated masses, acting as local resonators.Introducing a mass into the membrane gives rise to a veering of the eigenfrequencies with respect to the mass parameter. For sufficiently strong contrast, the coupling between the mass and the membrane becomes weak, and beyond its local resonance frequency the mass behaves as quasi-immobile in the vicinity of the first eigenmode of the homogeneous membrane. This quasi-immobility constitutes the mechanism that induces localization: the mass can then be replaced by a blocked region, allowing the application of the classical landscape to the modified membrane.Our approach consists in iteratively identifying quasi-immobile masses by verifying, through static computations, that their local resonance frequency lies below that of the first membrane mode obtained with the blocked mass. This process converges towards a static prediction of the frequencies and localization zones of high-frequency modes. Because the method is iterative, the quasi-immobility of each mass is treated independently from the others, which means that the approach is only valid when the masses are sufficiently decoupled dynamically. In practice, such dynamical decoupling requires that the local resonances of the masses do not occur simultaneously. This condition is fulfilled when the masses are sufficiently far apart from each other and exhibit significantly different mass values.Beyond membranes with concentrated masses, the approach is designed to be general and transposable to other types of concentrated resonators and other vibrating structures. To our knowledge, this study provides the first pathway towards a predictive experimental framework for high-frequency localization induced by local resonators, based on limited prior knowledge of the studied system.

Equivalent vibro-acoustic model of multilayer structures with nonlinear imperfect interfaces

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Multilayered mechanical structures are composite materials made by stacking different layers, each with its own intrinsic mechanical and physical properties. These structures are of great interest because they allow for the optimization of system performance by leveraging the specific characteristics of each layer. The result is materials that can efficiently absorb sound while remaining lightweight, or structures that are both flexible and strong. Since these structures can be subjected to high-amplitude excitations, studying their nonlinear behavior is a relevant and promising research area that remains relatively underexplored.In this work, we develop an equivalent vibro-acoustic model of multilayer structures with nonlinear interfaces. The multilayer structure is modeled using a Zig-Zag approach, which, through continuity conditions between the different layers specifically, stress continuity and displacement discontinuity at the interfaces links the kinematic variables of successive layers starting from a reference layer. This method not only reduces the number of kinematic unknowns in the model but also maintains an independent description for each layer. Using an equivalent thin plate model based on Kirchhoff-Love theory, it is possible to obtain a frequency-dependent equivalent bending stiffness.Finally, transverse displacement field measurements using laser vibrometry, combined with the CFAT (Corrected Force Analysis Technique), show that the dynamic behavior of a three-layer beam with imperfect interfaces varies according to the applied stress level. This is observed through changes in the structure's equivalent mechanical properties, in particular, a variation in the equivalent bending stiffness parameter, which reflects the nonlinear behavior of the interfaces. This methodology enabled the experimental characterization of the nonlinear behavior of glass-epoxy-glass trilayer beams under varying excitation levels.

Mechanical Vibration Analysis in Electric Motors for Predictive Maintenance using FFT in LabVIEW

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Vibration analysis of electric motors is central to predictive maintenance, enabling early fault detection and reducing unplanned downtime. This paper presents a software model for fault diagnosis from vibration signals, implemented in LabVIEW and relying on frequency-domain analysis via the Fast Fourier Transform (FFT).Data acquisition is performed with a commercial vibration instrument. Measurement results are stored in a spreadsheet (CSV/Excel) and subsequently loaded into LabVIEW for processing. The system includes: (i) format validation and sampling-parameter checks, (ii) conditioning and filtering to mitigate aliasing and noise, (iii) feature extraction in the time domain (RMS, kurtosis, crest factor) and frequency domain (characteristic peaks, sidebands), and (iv) diagnostic modules mapping spectral patterns to common fault modes (unbalance, misalignment, bearing defects, eccentricity) and abnormal operating conditions.We describe the software architecture, the spreadsheet-to-processing pipeline, and a test-bench validation with controlled fault cases. The framework is extensible to envelope analysis, order tracking, and future machine-learning modules, while preserving low cost, robustness, and ease of use for SMEs.

Structural dynamics and vibration - Paper 10439

Mode scaling errors due to modal tests uncertainties: a numerical study

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Experimental modal analyses are usually performed to evaluate the capacity of Finite Element models to represent the dynamic behaviour of mechanical structures in the low frequency domain. The model-test comparison and, if necessary, the model calibration, are commonly based on a normalised distance between the simulated and experimental eigenfrequencies and eigenvectors. The Modal Assurance Criterion (MAC) is generally used to pair the eigenvectors and quantify the distance between them, comparing their shapes without taking into account their norms.However, for some applications, the norm of the experimental eigenvectors has to be well identified as it has a direct influence on the results of interest. The modal identification process being the resolution of an inverse problem, it is well known that the presence of uncertainties in the input data, i.e. the measured Frequency Response Functions, can have a great impact on the output data, i.e. the identified eigenfrequencies and eigenvectors.This numerical study focuses on the effect of measurement uncertainties on the norm of the identified eigenvectors. Considering the Finite Element model of a simple plate, pseudo-experimental Frequency Response Functions are simulated with different levels of added noise. Numerous data are generated and post-processed by an automatic modal identification technique based on the PolyMAX algorithm. The effects on the norm of the eigenvectors of parameters such as noise level, frequency resolution and identified damping are investigated in detail.Additionally, a technique is proposed to reduce the norm errors by using a theoretically constructed mass matrix.

Structural dynamics and vibration - Paper 10464

Investigation of Quasi-Static Prestress Effects on the Dynamic Behavior of a Bio-Based Composite Prototype Blade

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<p style'text-align: justify;>Conventional composites reinforced with carbon or glass fibers exhibit excellent specific mechanical properties but suffer from limited vibration damping capability, which can negatively impact performance and fatigue life. To overcome this limitation, complex and costly technical solutions are often required, increasing both the weight and cost of the system.<p style'text-align: justify;>Plant fibres, such as hemp, offer a promising alternative thanks to their inherently higher damping properties. This paves the way for their use in structural applications, particularly in the design of bio-based wind turbine blades.The objective of this study is to optimise the structural damping behaviour of a wind turbine blade made from a composite material based on hemp fibres and Elium resin (Arkema). To achieve this objective, a multi-scale approach is adopted, from the properties of the constituents to full-scale structural response.First, the influence of both frequency and temperature on the stiffness and damping behavior is investigated in parallel at the composite material scale.The study then focuses on the behavior at the prototype (downscaled) blade, in order to integrate several structural effects that can occur in real conditions - such as geometry, assembly, boundary conditions, and aerodynamic effects.The objective is to study the vibratory behavior of a prototype blade under different conditions. The analysis is first carried out without prestress, at various temperatures. Then, prestress is applied through an imposed displacement to simulate the effect of wind loads on the blade under real operating conditions, and vibration tests are performed while the displacement is applied. After releasing the prestress, the blade is tested again. This procedure is motivated by the bilinear (two-phase) behavior of bio-based composites in the fiber direction : depending on the level of prestress, the material may operate in either phase, and since this behavior is not fully reversible, it is crucial to investigate whether the dynamic response differs below and above the yield point.Different levels of prestress are considered to evaluate their influence on the overall dynamic behavior of the blade.Finally, a comparison by analogy is performed to determine whether the trends observed at the material scale and the structural scale exhibit similar behavior patterns.

Topology optimization of viscoelastic damping layers for structural vibration control

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Efficient vibration control is essential for ensuring the performance and durability of lightweight structures subject to dynamic loading. Constrained Layer Damping (CLD) has proven to be an effective passive vibration reduction technique for dynamic structures. However, its effectiveness strongly depends on the distribution of viscoelastic material with respect to the vibration mode shapes. At the same time, the design of CLD treatments is often limited by strict mass constraints, making it crucial to identify optimal material placement for maximum damping efficiency. This work proposes a topology optimization framework to determine the optimal distribution of viscoelastic damping layers under a weight constraint. The approach is based on the Solid Isotropic Material with Penalization (SIMP) method, with objective functions formulated to maximize the modal loss factors of one or several targeted modes. The viscoelastic behavior is modeled using the Modal Strain Energy method, and analytical sensitivities with respect to the design variables are derived. The proposed methodology is demonstrated on plate structures to evaluate the influence of different optimization objectives on the resulting damping layer topologies and vibration performance. The results highlight the potential of topology optimization to efficiently design viscoelastic damping layouts for improved vibration control in complex structures.

Structural dynamics and vibration - Paper 10474

Efficient modelling of interacting systems with physics-informed architectures

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Physics-informed machine learning is a rapidly expanding area of interest and one that holds great potential in harnessing the power of what we know and what we have yet to learn from data. In the context of our growing reliance on AI, pursuing technology that builds in physical insight brings opportunity to ensure or improve interpretability and trust, while also reducing computational burden. This talk will consider a range of interacting physical and data-driven (ML) models for complex environments, questioning their utility against deep data-driven only approaches, and also their efficiency in a computationally constrained environment.

Structural dynamics and vibration - Paper 10478

Development of a Sandwich Beam Experimental Setup for High-Frequency Characterization of Viscoelasticity

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Innovation in the tire industry is a key concern to increase the performance of products, by reducing energy consumption, extending lifespan, and improving road safety. Crucial tire properties such as grip, wear, and noise depend on contact phenomena between the tread surface and the road. Contact mechanics is a complex field studied worldwide, as it involves the material's response to the multi-scale roughness of the road, which ranges from millimeters to micrometers. Each scale excites the material at different time scales, meaning that the macroscopic behavior depends on the response over a wide frequency range. However, in laboratory conditions, these high frequencies are difficult to reach in a controlled manner, making direct measurement of the relevant viscoelastic properties challenging.Tread compounds are elastomeric materials reinforced with nanometric fillers, exhibiting both viscoelasticity and pronounced nonlinearity under realistic operating conditions. Accurate identification of their mechanical properties across an extended frequency range is therefore essential for reliable tire modeling and design. Standard Dynamic Mechanical Analyzers (DMAs) are typically limited to frequencies below 100 Hz, which is insufficient to reproduce real-world contact dynamics.In this context, the present work introduces a sandwich beam configuration composed of metallic and viscoelastic layers. The setup is designed to enable dynamic excitation over a broad frequency range, up to the order of 10 kHz, and for different strain amplitudes, allowing for the investigation of both frequency-dependent and nonlinear effects. A finite element model of the beam is developed alongside the experimental setting. The viscoelastic parameters are identified through an optimization process that minimizes the discrepancy between experimental measurements and numerical simulations.The proposed approach provides an experimental and computational framework for characterizing the nonlinear viscoelastic response of filled elastomers beyond the frequency range accessible by standard DMA instruments. The paper presents the concept and preliminary performance of the developed setup, contributing to a deeper understanding of material dynamics and supplying high-frequency data for predictive modeling, supporting the development of more energy-efficient and durable tires.

Passive vibration control of a monopile-supported DTU 10 MW offshore wind turbine using a pendulum-tuned mass damper and a high-fidelity finite element model

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Offshore wind turbines have been shown to harness a greater amount of wind energy compared to their onshore counterparts, thus rendering them a valuable resource for the production of renewable energy. In order to optimize the utilization of wind resources, a considerable number of monopile-supported offshore wind turbines are strategically situated at water depths ranging from 30 to 50 meters. In 2021, offshore wind power installations set a record with 21,106 MW of new capacity, bringing the total cumulative capacity to 55,5549 MW (Global Wind Energy Council, 2023). These turbines generally comprise a wind rotor affixed to a nacelle, which is supported by a tall, slender, flexible tower. It is noteworthy that taller turbines exhibit an augmented energy harvesting capacity. However, an increase in tower height can result in elevated levels of vibrations caused by rotor operating frequencies and environmental loads. These vibrations are further exacerbated by the dimensions of the tower. Consequently, the implementation of structural control systems is imperative to avert failure and curtail maintenance expenditures and excessive vibrations. The Pendulum Tuned Mass Damper (TMD) is a passive structural control device that has gained significant popularity. The mechanism by which it functions is through the transfer of kinetic energy from the primary structure to a pendulum. In recent years, there has been a significant increase in research focusing on this passive device in conjunction with offshore wind turbines (OWTs). For instance, Sun and Jahangiri (2018) developed an analytical multi-degree of freedom model (MDOF) model for the National Renewable Energy Lab 5-MW monopile-supported OWT equipped with a 3D-Pendulum Tuned Mass Damper (3D-PTMD) to mitigate the effects of misaligned wind, wave, and seismic loads. However, there is few studies that have considered high-fidelity mechanical models when evaluating the vibration mitigation of monopile-supported offshore wind turbines under combined wind and wave loads. This study investigates the vibration mitigation performance of a 3D pendulum tuned mass damper (3D-PTMD) installed atop a monopile-supported DTU 10 MW offshore wind turbine (OWT) making use of a three-dimensional high-fidelity finite element mechanical model making use of Abaqus software. The optimal 3D-PTMD was determined in such a way to avoid resonance. The resulting configuration effectively mitigates the structural vibrations of the monopile-supported OWT under operational conditions, including stochastic excitations induced by turbulent wind and irregular waves. The efficiency of the proposed optimum design was evaluated in terms of tower-top displacement reduction.

Structural dynamics and vibration - Paper 10506

A novel strategy for interface model reduction exploring component-level global modes for substructuring applications

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Substructuring techniques play a crucial role in industry and academia in the analysis of complex assemblies involving multiple components. In this context, the dynamic behavior of assembled structures is determined based on the coupling of reduced-order models of individual substructures, which encompass the reduction of interior and, potentially, boundary/interface degrees of freedom (DoFs) to small sets of generalized/modal coordinates. The reduction of interior DoFs is commonly performed using the fixed-interface Hurty/Craig-Bampton (H/CB) model-order reduction (MOR) method - which considers fixed-interface normal modes and static/constraint modes. In traditional methods, those interface DoFs that are related to connections between substructures, on the other hand, are not reduced. However, as finite element models can contain many interface DoFs when fine meshes are used, or when an assembly is composed of many substructures, benefits can arise from their reduction. This can be performed mainly using local-level or system-level characteristic-constraint methods, as well as their variants. The former strategy operates locally, considering the uncoupled substructures, while the latter considers the assembly at the system-level. Although the reduction of interior DoFs was proposed long ago and has been improved over the years, the reduction of interface DoFs has been introduced more recently, such that it still might be enhanced. Hence, in this research, a novel local-level MOR approach is proposed and investigated for such a task. The adopted technique is inspired in a method developed for the reduction of boundary DoFs in periodic-like structures. Within the present framework, interface modes computed for reducing the boundary DoFs are obtained in a global setting at the substructure component level, i.e., considering the coupling that its interfaces' DoFs have with those at its interior. Such modes are augmented with local modes obtained for the interfaces, accounting for fixed interior DoFs. To guarantee compatibility conditions between adjacent substructures, the modes obtained for an interface, related to different substructures, are combined to form a single projection matrix, that is shared among them. Afterward, to alleviate numerical issues, a modal-assurance criterion-based strategy is employed to eliminate almost-collinear eigenvectors from the interface coordinate transformation matrix. Results from numerical simulations regarding a W-bracket model demonstrate that the proposed interface reduction strategy competes with current state-of-the-art alternatives in terms of accuracy, model size and computation time.

Structural dynamics and vibration - Paper 10528

Modeling and experimental validation of tethered cables for kite trajectory control

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This work is part of the KiWiN research project whose goal is to use kitesurf-inspired sails to propel cargo ships in order to reduce their energy consumption. Our team focuses on the physical and numerical modeling of a kite's dynamics to improve trajectory prediction and, consequently, control accuracy. In this context, this study specifically addresses the control lines of the sail. The main objective is to develop a comprehensive model of the lines that accounts for both its self-weight and aerodynamic forces, and to couple it with the sail's flight dynamics model in order to improve trajectory prediction.Currently, the sail lines are assumed to be straight, although they are approximately 100 meters long in the actual application. The aerodynamic effects on such long lines are not negligible as the resulting bending alters both the magnitude and direction of the forces applied on the kite. This deformation introduces uncertainty in trajectory prediction and can lead to inaccuracy in the simulated traction results of the system.In this study, a nonlinear finite element model was developed to predict the deformation of the lines under external loads. This model was compared with an analytical solution based on an inextensible catenary cable to determine the validity range of the analytical formulation. The finite element cable model was also experimentally validated. Validation was performed using a tensioned line, deformed by applying weights along its length. Prior to loading, the initial cable tension was determined through line resonance measurements.Coupling the finite element code with the kite's dynamics model significantly improved the accuracy of the kite's position prediction, thereby enhancing the flight command-control system. Moreover, it was shown that when the wind incidence angle relative to the cable is small (between -10° and 10°), the assumption of inextensible cable remains valid. This allows for fast computation and an efficient approximation of the line deformation.

Structural dynamics and vibration - Paper 10591

Exploring ultra-low frequency isolation using the best from passive and active strategies

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Passive vibration isolators are used at many places in daily life, e.g. car suspensions, silent blocs in washing machines, bushers, for drone cameras to cite a few examples. For some more specific applications, even small vibrations are not acceptable, for example: microscopy, medical imaging, lithography machines, tomography, or physics experiments. It often means that dedicated developments are necessary, mainly for two reasons: either due to the specific operating conditions (temperature, radiation, pressure,..), or due to the isolation requirements which are too stringent.Emblematic examples of dedicated developments are large physics instruments like gravitational wave detectors, light sources, or particle accelerators.Most efficient vibration isolation systems on Earth are found in gravitational wave detectors. After about half a century of research and development, their seismic isolators allow to reach a stability at the attometer scale (10^{-18}m), which allowed to make de the first detections of gravitational waves, and give birth to experimental gravitational wave astronomy. To pursue the exploration of the universe through gravitational waves, even better isolators will be required in future instruments, especially at low frequency.The paper will first review fundamental limitations of passive and active isolation systems. Then, in order to bypass these fundamental limitations, and further improve the isolation at low frequency, an original architecture will be presented using an active isolation platform, on which is installed a large, inverted pendulum. It is found that such unique hybrid configuration allows to improve drastically the isolation performance at low frequency. Experimental results will be shown to comply with the specifications of future gravitational wave detectors, and open new avenues for other applications with stringent specifications.

Topic: Uncertainty quantification

Uncertainty quantification within a conceptual mount system design workflow

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Designing mount systems for Electric Vehicles (EVs) is challenging given the inherent stiffness requirements that are significantly higher than those for Internal Combustion Engine (ICE) vehicles. This increased stiffness means that even minor modifications to mount characteristics, such as their amount or location, can have a disproportionately large influence on the total structure-borne response. While digital tools accelerate early design processes, current simulation models and practices often fall short in quickly assessing these critical influences or providing confidence intervals to represent real-world uncertainties. In this paper, a conceptual modelling workflow for EV mount system design is developed, specifically tailored for early design stages. The workflow is designed to provide robust confidence intervals, thereby representing the variabilities that may arise in reality due to factors like batch production, potential damages, and mounting/dismounting inconsistencies. Furthermore, a key aim is to offer an approach that can rapidly suggest an optimized mount system configuration. Thus, we establish a system-level reference model, adapting it from an ICE vehicle context to an EV powertrain. We then conduct comprehensive sensitivity analyses: one focusing on the impact of non-linear mount stiffness parameters on mount force waveforms, considering micro-range variations typical of uncertainties, and another exploring the influence of mount location and orientation on the transfer path and resulting mount forces. These analyses are extended across various mount counts, macro-locations, and stiffnesses for completeness of the picture. A significant outcome of this research lies in the novelty of the methods that integrate these various sources of uncertainty into early predictions of mount forces, providing designers with quick, quantitative estimates of how mount system changes affect vehicle performance.

Uncertainty quantification applied to active control systems using electromagnetic actuators in a dynamic beam bending problem

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Advances in computer simulation must accompany the development of mathematical models that represent engineering systems. However, the functionality of these models depends on the ability to reproduce their behavior accurately and with a high level of reliability, often under uncertain conditions. Generally, input data variability is used to estimate output data variability; however, a major source of uncertainty is model inadequacy, which is often the primary contributor to overall uncertainty. This work proposes the application of Uncertainty Quantification (UQ) methods to active control systems used in the dynamic problem of beam bending subjected to pulse excitation. Uncertainty propagation and quantification are investigated using Monte Carlo simulation (MCS) and the Latin Hypercube Sampling (LHS) variance reduction technique. After characterizing the control system using the Eigensystem Realization Algorithm (ERA) and the Observer/Kalman Filter Identification (OKID) algorithm, we propose incorporating uncertainty quantification methods into the Linear Quadratic Regulator (LQR) control techniques via Linear Matrix Inequalities (LMI), Fuzzy, and Neuro-Fuzzy. Initially, uncertainties are associated with the state matrices, seeking to evaluate the propagation of uncertainty through control techniques based on results obtained in the time and frequency domains. Next, we assume that variability is present in the geometric and material properties of the beam, constituting the random coefficients of the mass, stiffness, and damping matrices of the Stochastic Spectral Finite Element Method (SSFEM). The propagation of uncertainty is evaluated through the SSFEM, which combines the FEM with MCS and the Neumann series (NMC) to reduce computational cost. The identification of geometric and material parameters is obtained through the inverse problem in conjunction with the Genetic Algorithm.

Analytical approximation of the uncertainty of an identification problem with chaos polynomials

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We aim at taking into account measurement uncertainties in an identification process with errors in the measurements. We understand that uncertainty is the cumulative distribution function (CDF). In the case of a continuous distribution the probability distribution function (PDF) characterizes the CDF and we want to find an analytical approximation of the PDF. Uncertainties are taken into account by modeling them as random variables and the distribution of the identified parameter is an unknown of an inverse problem, which is a result of an optimization process. More precisely, to focus on this branch of optimization, we are concerned by a four point bending static test applied to a beam, and we model the identified elastic modulus with polynomial chaos expansions, using Hermite, and Chebyshev of 2nd kind, polynomials to see the influence of the polynomial used in the identification. Two different hypotheses are made about the uncertainties in the loading, leading to the investigation of two applications. This spectral theory for the quantification of uncertainties of this kind of identification problems is verified practically on both of these applications with successful results for an adequate order of truncation of the expansion basis.

Uncertainty quantification of a beam-like phononic crystal with attached composite patches

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Periodic structures have recently gained growing attention in both academia and industry due to their unique vibration and wave propagation characteristics, including the formation of bandgaps, waveguiding phenomena, cloaking, etc. These properties open new strategies for developing innovative approaches to structural dynamics and vibroacoustics. Although the capabilities of periodic structures have been reported in numerous studies, the effects of manufacturing uncertainties on their performance, which are commonly present in practical applications, remain underexplored. Accordingly, this paper performs uncertainty quantification of a host beam with attached composite patches. Periodicity is obtained without the need for machining or printing highly complex unit cells, which can significantly deviate from the initial design and make modeling cumbersome. Hence, these composite patches are used instead, glued to the host beam through structural adhesives, so that the periodic beam behaves like a phononic crystal (PC) and, therefore, works to passively attenuate vibration transmission. The introduced inclusions lead to impedance mismatches that cause the scattering and partial reflection of elastic waves, enabling the formation of Bragg-type bandgaps in specific frequency bands. Since the effects of uncertainties remain unexplored in such systems, one proposes to investigate the influence of randomness associated with the gluing position and width, as well as the geometry of the patches, for each unit cell. Assuming prescribed probability distributions, the uncertain inputs are modeled as random variables, which allows for quantifying their effects on the position and width of the first bending bandgap of the composite PC-like structure, as well as constructing transmissibility envelopes for given confidence levels. For this purpose, the modeling strategy for the laminate patches is based on the equivalent single-layer (ESL) theory. Moreover, the interaction between the equivalent patches and the host beam is based on a multi-layer beam model, which considers Zig-Zag kinematics. With the governing equations developed, the Spectral Element Method (SEM) is employed, yielding an exact dynamic stiffness matrix for each unit cell of the periodic beam using SEM. By leveraging the Monte Carlo method, samples of random unit cells are generated, which are then combined to form a given, imperfect, periodic structure that can be suitably analyzed in terms of its dynamic behavior. By following such methodology, one expects to determine whether the considered uncertainties are relevant to the design of the PC-like beam.

The effects of adhesive joints uncertainty on the dynamic behavior of a frame structure

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In recent years, the mobility industry has faced increasing demands to improve product performance while reducing pollutant emissions and energy consumption. One of the most straightforward approaches to achieve this objective is the reduction of vehicle mass, which is widely explored in aeronautical and automotive applications by employing lightweight materials. However, conventional joining techniques, such as bolting or riveting, inherently increase the overall mass of vehicles by adding material. Adhesive bonding offers an alternative which contributes to overall weight reduction and avoids stress concentration. Despite recent development in the mechanical properties of adhesive materials, there remains significant variability that can lead to uncertainty in the dynamics of systems assembled with adhesive bonding. Building upon a finite element model of two beams connected by a single-lap adhesive joint, for which the dynamic behavior was assessed against experimental data in a previous study, one analyses the dynamic behavior of a frame structure joined at specific connection locations. The finite element method is employed alongside component mode synthesis to model the frame, while the adhesive joints are represented by discrete, distributed springs, with their stiffness modeled as random variables. The Monte Carlo method, combined with Latin-hypercube sampling, is adopted to obtain frequency response functions (FRFs) of realizations of the considered uncertain systems. These encompass different, but similar, assemblies, which vary in terms of how glued joints are implemented between beams composing the frame. From simulations, one can identify those modes most influenced by the variability and implementation of the adhesive joints. The obtained results provide a more general sense of how joint uncertainty affects the structural dynamics of the frame, adding complexity to the previous model, developed for a simpler structural arrangement and assessed experimentally, while also supporting the development of more advanced computational models to assist the design process of systems employing adhesive connections subject to uncertainties.

Robust design of shunted and active piezo metamaterial for cloaking against flexural waves

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The metamaterial we are interested in is a plate with a circular hole for which we want to suppress the scattering effect by using a cloaking domain around the hole. The cloaking strategy consists of dividing this domain into two: an absorbing region in front of the incident waves, and a second one at the back of the hole, which will synthesize the missing wave front. The absorbing region is realized using negative capacitance shunted piezo patches, and the emitting one with voltage-controlled piezo patches.Negative capacitance shunting of piezo patches is an effective solution for achieving broadband vibration control of flexural waves. The tuning process of the metamaterial to achieve absorption leads to close to unstable modal zone and thus sometimes to trade-off between stability and performance. To better known the interaction between the operating and manufacturing environment, for example industrial ones, and the targetted configuration, we need to evaluate its robustness. However, to date, no articles have tackle this issue. Therefore we propose to study the influence of the uncertainty of shunted and voltage-controlled patches parameters and excitation frequency on stability and on the cloaking of incident flexural waves with respect to our two-region strategy. The studied structure is an aluminum plate with a circular hole surrounded by arrays of bonded piezoelectric ceramic patches connected to their electrical circuit. Starting from the optimal configuration, we first proceed to a sensitivity analysis on the targeted frequency interval using Morris method on our 3D FEM model. After screening the most significant parameters, we construct the probability distribution functions according to the principle of maximum entropy and finally propagate the uncertainties to the cloaking performance using Monte-Carlo method. Finally we aim to develop a robust design methodology allowing us to treat performance reduction as a specification of the metamaterial thus being able to treat quantitatively the trade-off between performance, uncertainty and stability.

Uncertainty quantification - Paper 10499

Stochastic failure analysis of laminated composite plates including the effects of voids on mechanical properties

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Although the applicability of composite materials has been significantly broadened across various industrial segments, structural design also depends on a proper understanding of failure mechanisms, given the variability of manufacturing-induced defects, which may degrade mechanical properties through physical processes such as delamination and void formation. In general, such defects reduce the laminate's static and fatigue strength and increase its susceptibility to water penetration and environmental conditions. Motivated by these considerations, this work aims to investigate the influence of spatial variability in the mechanical properties of the constituent materials on the first-ply failure of laminated composite plates. For this purpose, a finite element model will be employed for structural analyses, using the Karhunen-Loève expansion to discretize the two-dimensional space-dependent geometry and material properties. Under the hypothesis of the well-established First-Order Shear Deformation theory, a modified micromechanical approach is used to account for the presence of voids, and Monte Carlo simulation, combined with Latin Hypercube sampling, is used to generate statistics on different failure modes.

Topic: Vehicle dynamics

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Vehicle dynamics - Paper 10486

Dynamic Analysis of agriculture vehicle designs using multibody dynamic simulation.

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This study aims to evaluate the performance differences between the vehicle under various simulated conditions, highlighting the importance of robust simulation models in agricultural vehicle design. The findings will contribute to optimizing vehicle design and enhancing operational efficiency in agricultural applications. A multibody simulation is developed for two designs of vehicles to analyze their dynamics and performance characteristics. A tractor vehicle is designed to operate under similar conditions, allowing for a direct comparison of its performance metrics and adding a draft load that simulates a seeder operation. The wheels are modeled by stiffness elements and contacts with the soil. The wheel/soil contact representation divides the wheel into 48 parts, which simplifies the contact patch to at least 8 points. The designs explored are regular tractors with different wheel diameters in front and rear axles and a tractor with similar wheel sizes in both axles. For both cases, the vehicle-soil contact is modeled using a viscoelastic approach, considering the sinkage and pressure distribution based on Bekker's soil pressure-sinkage model, which is essential for accurately predicting vehicle performance on varying terrains. For this study, dry sand, sandy loam, and clay soil are simulated to evaluate their respective impacts on vehicle dynamics and traction capabilities. The analysis will reveal how soil characteristics influence performance metrics such as stability, speed, and efficiency. Both designs are controlled using PID control for vehicle velocity and direction, attempting to simulate the seeder and planter operation at 7 km/h. Parameters such as slip ratio, pressure distribution, traction torque, and forces are considered. The results of this study will inform future design iterations and provide insights into the critical factors affecting performance in agricultural vehicle applications.