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Identification of Nonlinearities in Mechanical Structure Joints: A Systematic Review

M.S.M Sani[1,2*], M.A. Yunus[3] and M.N. Abdul Rani[3]

[1]Academy for Advanced TVET, Universiti Malaysia Pahang Al Sultan Abdullah,
26600 Pekan, Pahang, Malaysia
[2]Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia
Pahang Al Sultan Abdullah, 26600 Pekan, Pahang, Malaysia.
[1]Structural Dynamics Analysis & Validation (SDAV),
Faculty of Mechanical Engineering, Universiti Teknologi MARA (UiTM),
Shah Alam, Selangor, Malaysia.

[*]Corresponding email: mshahrir@umpsa.edu.my

ABSTRACT

The identification of nonlinearities in mechanical structure joints is essential for improving predictive maintenance, structural health monitoring, and design optimization of engineering systems. Mechanical joints frequently exhibit complex nonlinear behaviors, including friction, backlash, hysteresis, and contact-induced effects, which can significantly influence the dynamic performance and reliability of structures. Although numerous studies have investigated these nonlinear phenomena, a comprehensive synthesis of identification techniques specifically addressing joint nonlinearities remains limited. This systematic review aims to bridge this gap by critically examining contemporary methodologies used to detect, characterize, and quantify nonlinear behavior in mechanical joints. The review focuses on three primary objectives: (i) classifying existing identification approaches, (ii) evaluating their effectiveness, applicability, and limitations, and (iii) identifying current challenges and future research opportunities. A systematic literature search was conducted across major engineering databases, encompassing experimental, numerical, and hybrid techniques for nonlinearity identification. Key methods, including nonlinear system identification, parameter estimation, model updating, and data-driven approaches, were comparatively analyzed. The findings indicate that frequency-domain and time-domain methods remain the most widely adopted techniques, while recent advances increasingly integrate machine learning and artificial intelligence to improve identification accuracy and robustness. Furthermore, the review highlights the growing importance of multi-physics and hybrid modeling frameworks for capturing complex joint behaviors under varying operational conditions. By consolidating and critically evaluating existing knowledge, this study provides a structured reference for selecting suitable identification methods and offers insights to support the development of more reliable mechanical systems, thereby contributing to advancements in structural health monitoring, maintenance, and engineering design.

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INTRODUCTION

Mechanical structures frequently rely on joints to connect individual components, enabling the transmission of loads and motions within complex assemblies. These joints, however, often exhibit nonlinear behaviors due to factors such as friction, clearance, material degradation, and geometric imperfections. Nonlinearities in joints can significantly affect the overall dynamic response and structural integrity, leading to challenges in accurate modeling, prediction, and control of mechanical systems. As such, the identification and characterization of joint nonlinearities have become critical areas of research, particularly in fields such as aerospace, automotive, civil infrastructure, and robotics where reliability is paramount. Despite the importance of joints in mechanical structures, accurately identifying their nonlinear characteristics remains a substantial challenge. The nonlinearities are often subtle and intertwined with other system behaviors, making it difficult to isolate and quantify them using conventional linear system identification techniques. Improper or inadequate identification can result in inaccurate system models, which in turn compromise structural health monitoring, damage detection, and predictive maintenance strategies. Furthermore, the complexity of joint nonlinearities, manifesting as frictional hysteresis, backlash, stiffness degradation, or other nonlinear effects, necessitates advanced identification approaches that can handle nonlinear dynamical phenomena under varying operational conditions. Given these challenges, there has been extensive research focused on developing and applying diverse experimental, numerical, and hybrid for the identification of nonlinear joint behavior. However, these studies tend to be fragmented, with varying assumptions, identification algorithms, and validation procedures. A systematic review that consolidates current knowledge and critically evaluates these identification techniques is therefore essential to guide future research and practical implementations.

The primary objective of this systematic review is to comprehensively examine existing methods for identifying nonlinearities in joints of mechanical structures. Specifically, this study aims to categorize the different identification techniques, assess their respective strengths and limitations, and identify gaps in current methodologies. Additionally, it seeks to highlight emerging trends, such as the integration of machine learning and multi-physics modeling approaches, which hold promise for advancing nonlinear identification capabilities. Ultimately, this review aspires to provide a structured framework to aid researchers and practitioners in selecting appropriate methods for reliable nonlinear joint characterization, thereby enhancing the performance, safety, and longevity of mechanical systems.

LITERATURE REVIEW

The identification of nonlinearities in mechanical structure joints has gained substantial attention over the past decade due to its critical implications in structural health monitoring, dynamic analysis, and reliability assessment of engineering systems. Joints often exhibit complex nonlinear behaviors arising from friction, clearance, material plasticity, and contact mechanics, which pose challenges for accurate modeling and diagnosis. This literature review synthesizes key contributions from fifteen recent studies, critically analyzing their methodologies, findings, and limitations, and aligning them with the objective of improving nonlinear identification techniques in structural joints.

Overview of nonlinearity in mechanical joints including bolted, welded, and adhesive types, constitute weak points in structures due to their propensity to introduce nonlinear response characteristics. As Ruotolo et al. [1] discussed about frictional forces and micro-slip at joint interfaces typically produce nonlinear stiffness and damping effects that influence the overall dynamic response. Recent studies emphasize that capturing these nonlinearities accurately is essential not only for predictive modeling but also for detecting early damage stages [2-3].

Experimental identification methods inluded various experimental approaches have been adopted to characterize nonlinear joint behavior. For instance, Utilization of harmonic excitation coupled with frequency response function (FRF) analysis to detect joint nonlinearities experimentally [4]. Similarly, Doranga and Wu [5] proposed an impact-testing method with nonlinear system identification algorithms to isolate joint nonlinear stiffness. These approaches excel in capturing real-world nonlinear effects but often suffer from sensitivity to measurement noise and challenge in distinguishing multiple simultaneous nonlinear mechanisms [6]. A notable advancement is the use of nonlinear output-only identification methods, as showcased by [7], who leveraged operational modal analysis combined with Volterra series modeling. This method offers effective detection of joint nonlinearity under ambient excitation, thus mitigating the need for controlled input forces. However, the complexity of these nonlinear models can reduce interpretability and computational efficiency, limiting widespread practical application.

Analytical and numerical modeling computational remains a cornerstone in understanding joint nonlinearities. Finite element modeling (FEM) techniques have incorporated frictional contact laws and material plasticity to simulate nonlinear joint behavior [8-9]. Development of a parametric FEM framework for bolted joint assemblies that accounts for contact nonlinearity and preload variations, achieving close correlation with experimental data [8]. Yet, these models require precise joint parameter calibration and are computationally expensive, which restricts their use in real-time monitoring systems. Reduced-order models have been proposed as alternatives to high-fidelity FEM. For example, Zhong et al. [9] constructed nonlinear lumped-parameter models incorporating joint gap and friction nonlinearities, thus facilitating faster simulations. While these models improve efficiency, their accuracy depends on the adequacy of nonlinear term selection, which remains a significant modeling challenge.

Signal processing and system identification techniques through the extraction of nonlinear characteristics from vibration signals has been enhanced by advanced signal processing methods. Wavelet transforms and Hilbert-Huang transforms have been adopted to highlight nonlinear signatures in joint vibration responses [10-11]. Hassan et al. [11] demonstrated that empirical mode decomposition combined with fractal dimension analysis effectively differentiates nonlinear joint behavior from other system nonlinearities. Machine learning approaches are increasingly integrated into nonlinear identification. Zhang et al. [12] applied support vector machines (SVM) and neural networks to classify friction-induced nonlinear responses in bolted joints with high accuracy. However, these data-driven techniques require extensive datasets for training and may lack physical interpretability.

Nonlinear dynamics and damage detection study focused on leveraging nonlinear dynamic phenomena such as subharmonic resonance, jump phenomena, and bifurcations to identify joint nonlinearities and related damage. Wang et al. [13] exploited the jump phenomenon in forced vibration of bolted joints to detect preload loss. This approach benefits from the clear nonlinear signatures but is sensitive to operational conditions.

Liang et al. [14] combined nonlinear dynamic indicators with extreme learning machine algorithms to detect early-stage damage in adhesively bonded joints. Their method improved sensitivity, demonstrating the advantage of coupling nonlinear analysis with machine learning. A limitation is that nonlinear dynamic responses could be masked by environmental variations, necessitating robust feature extraction techniques.

Although considerable advancements have been achieved in the study of nonlinear joint behavior, several important gaps and challenges continue to hinder the development of reliable and universally applicable identification techniques. Most studies address isolated joint nonlinearities under simplified loading conditions, lacking comprehensive frameworks to analyze complex assemblies with multiple interacting nonlinear joints [8,15]. Then, the robustness of identification methods under varying environmental and operational parameters remains underexplored. Third, many machine learning-based approaches rely heavily on large labelled datasets, which are often impractical in real structural testing scenarios. Moreover, real-time monitoring and identification of joint nonlinearities continue to be a challenge due to computational demands and the need for noise-resilient algorithms. Fang et al. [16] have recently proposed hybrid physics-informed neural networks to address this challenge, combining data-driven learning with physical model constraints, marking a promising research direction that warrants deeper exploration.

This systematic review highlights that the successful identification of nonlinearities in mechanical joints requires a balanced integration of experimental validation, accurate modeling approaches, and efficient signal processing techniques. The integration of physics-based and data-driven methods emerges as a fertile area for advancing joint nonlinearity characterization. Future research aligned with these insights should aim to develop robust, scalable, and interpretable identification frameworks capable of handling multi-nonlinear joint systems under realistic conditions, thereby directly supporting the research objectives of enhancing monitoring and diagnostic capabilities in mechanical structures. The reviewed literature collectively advances understanding and methodologies for identifying nonlinearities in mechanical structure joints, highlighting innovations in experimental, analytical, and computational approaches. Despite impressive progress, challenges remain in addressing complex multi-joint interactions, environmental variability, and real-time applicability. Bridging physics-based and machine learning frameworks offers a promising pathway, directly supporting ongoing research efforts aimed at developing robust, efficient, and interpretable nonlinear joint identification systems.

Table 1. Representative studies on the identification and characterization of nonlinearities in mechanical joints, highlighting methodologies, strengths, limitations, and future research opportunities.

Author(s)	**Year**	**Methodology**	**Joint Type**	**Nonlinearity Focus**	**Strengths**	**Weaknesses**	**Research Gaps**
Ruotolo et al.	2003	Harmonic excitation analysis	Various	Nonlinear stiffness	How crack-induced energy dissipation	Does not fully capture real microslip friction	Extension to joints with distributed contact, wear evolution, and multi-scale frictional effects
Arda et al.	2016	Harmonic excitation and frequency response function (FRF) analysis	Bolted joints	Nonlinear stiffness	Direct experimental detection of nonlinear behavior	Sensitive to measurement noise	Detection of multiple concurrent nonlinearities
Doranga & Wu	2021	Restoring force surface (RFS) and nonlinear system identification techniques	Bolted joints	Nonlinear stiffness	Isolates joint nonlinear stiffness and damping using experimentally validated FRF-based identification	Less directly applicable to complex real-world multi-joint systems.	Extension to the method to complex multi-joint or large-scale structures.
Zhou et al.	2019	Experimental and numerical investigation	Bolted joints	Friction and clearance nonlinearities	Combines experimental validation with numerical modeling	High methodological complexity	Scalability to large and complex structures
Chen et al.	2020	Volterra series and output-only identification	Bolted and welded joints	Nonlinear dynamic behavior	Applicable under ambient excitation conditions	Computationally intensive	Improved model interpretability
Liu et al.	2019	Finite Element Method (FEM) with nonlinear contact modeling	Bolted joints	Contact and preload nonlinearities	High-fidelity modeling and validation capability	High computational cost	Adaptation for real-time monitoring applications
Gong et al.	2019	Finite element model under transversal vibration loading	Bolted joints	Contact base nonlinearity	Accurate representation of contact mechanics	Requires extensive model calibration	Real-time or reduced-order predictive models
Zhong et al.	2022	Lumped-parameter nonlinear modeling	Bolted joints	Nonlinear stiffness	Computationally efficient simulations	Dependent on appropriate nonlinear term selection	Balancing model accuracy and efficiency

Author(s)	Year	Methodology	Joint Type	Nonlinearity Focus	Strengths	Weaknesses	Research Gaps
Jayakumar & Rama	2015	Wavelet transform analysis	Various	Nonlinear signal features	Effective noise filtering and feature extraction	Limited to signal characterization	Joint-specific nonlinearity identification
Huang et al.	2019	Empirical Mode Decomposition (EMD) and fractal dimension analysis	Bolted joints	Nonlinear vibration signatures	Effective differentiation of nonlinear vibration characteristics	Extensive signal processing required	Automation of feature extraction and analysis
Zhang et al.	2020	Support Vector Machine (SVM) and neural network approaches	Bolted joints	Friction-induced nonlinearity	High classification and prediction accuracy	Requires large training datasets	Improved physical interpretability of models
Wang et al.	2017	Nonlinear dynamics and jump phenomenon analysis	Bolted joints	Preload loss detection	Provides clear nonlinear indicators of preload degradation	Sensitive to operating conditions	Enhanced robustness under varying environments
Liang et al.	2021	Nonlinear dynamics combined with Extreme Learning Machine (ELM)	Adhesively bonded joints	Early damage detection	Improved sensitivity to early-stage damage	Susceptible to environmental effects	Robust feature extraction methodologies
Fang et al.	2023	Physics-Informed Neural Networks (PINNs)	Various	Multi-source nonlinearities	Integrates physical knowledge with data-driven learning	Limited datasets and early-stage development	Real-time implementation and validation
Zhang et al.	2018	Review and experimental studies	Various	Joint interface nonlinearities	Integrates findings from multiple studies and experiments	Limited emphasis on data-driven approaches	Comprehensive investigation of multi-joint systems

THEORETICAL AND CONCEPTUAL FRAMEWORK

The identification of nonlinearities in mechanical structure joints is founded on several interrelated theoretical domains, including nonlinear dynamics, system identification, and structural mechanics. These disciplines collectively provide the scientific basis for understanding, modeling, and characterizing complex joint behaviors that deviate from ideal linear assumptions. In practical engineering systems, joints are often the primary sources of uncertainty and energy dissipation, significantly influencing the overall dynamic response of structures. Consequently, the accurate identification of joint nonlinearities has become increasingly important for structural health monitoring, predictive maintenance, fault diagnosis, and design optimization.

Mechanical joints are rarely perfectly rigid. Instead, their behavior is governed by complex contact interactions occurring at mating surfaces, which can lead to nonlinear stiffness, damping, friction, and hysteretic effects. These nonlinear phenomena may arise due to preload variations, surface roughness, wear, manufacturing tolerances, or environmental conditions. As engineering structures become lighter, more flexible, and increasingly subjected to dynamic loading, the influence of joint nonlinearities becomes more pronounced. Therefore, a robust theoretical framework is essential to guide the development of effective identification methodologies and support accurate interpretation of measured dynamic responses.

Theoretical Foundations

1. Nonlinear Dynamics and Joint Behavior

The theory of nonlinear dynamics forms the fundamental basis for understanding the behavior of mechanical joints. Unlike ideal linear systems, where the response is directly proportional to the applied excitation and the principle of superposition holds, nonlinear systems exhibit complex relationships between input and output. Mechanical joints frequently introduce nonlinear characteristics such as friction, backlash, clearance, hysteresis, contact separation, and stiffness degradation, all of which can substantially alter the dynamic behavior of a structure.

Nonlinear vibration theory explains several phenomena commonly observed in jointed structures. These include amplitude-dependent natural frequencies, nonlinear resonance, harmonic generation, bifurcation, modal coupling, and energy transfer between vibration modes [17]. For example, a bolted joint subjected to increasing excitation levels may exhibit a shift in resonance frequency due to changes in contact stiffness, a behavior that cannot be explained using conventional linear vibration theory. Similarly, frictional interfaces within joints often generate stick-slip motion, resulting in energy dissipation and hysteresis loops in force-displacement relationships.

Several mathematical models have been developed to represent these nonlinear effects. The Preisach model is widely used to describe hysteresis behavior, while the Bouc–Wen model provides a flexible framework for representing a variety of nonlinear hysteretic responses. Backlash and clearance nonlinearities are often modeled using piecewise-linear functions, whereas frictional interactions are commonly represented using Coulomb, Dahl, or LuGre friction models. These mathematical representations allow researchers to quantify nonlinear behavior and establish relationships between physical joint mechanisms and observed dynamic responses.

Understanding nonlinear dynamics is crucial because the presence of nonlinearities often serves as an early indicator of joint degradation, loosening, wear, or damage. Consequently, nonlinear dynamic analysis has become an important tool for assessing structural integrity and supporting condition-based maintenance strategies.

2. Nonlinear System Identification

System identification theory provides the mathematical framework for developing models that describe system behavior using measured input-output data [18]. In the context of mechanical joints, system identification seeks to determine the underlying parameters and mechanisms responsible for observed nonlinear dynamic responses. The objective is not only to model system behavior accurately but also to extract physically meaningful information related to joint properties such as stiffness, damping, friction coefficients, and hysteretic characteristics.

Traditional linear identification methods, including modal analysis and linear parameter estimation, are often inadequate for capturing the complex behavior associated with nonlinear joints. As a result, various nonlinear system identification techniques have been developed. These approaches can generally be classified into parametric and nonparametric methods. Parametric methods assume a predefined mathematical structure and estimate the corresponding parameters, while nonparametric methods rely on data-driven relationships without imposing explicit model assumptions.

Among the most widely used nonlinear identification techniques are nonlinear state-space models, Volterra series representations, nonlinear autoregressive models with exogenous inputs (NARX), and restoring force surface methods. More recently, machine learning and artificial intelligence approaches have emerged as powerful alternatives for capturing highly complex nonlinear relationships. Artificial Neural Networks (ANN), Support Vector Machines (SVM), Random Forests, and Deep Learning architectures have demonstrated considerable potential in identifying nonlinear joint behavior from large datasets.

An important advantage of nonlinear system identification is its ability to isolate and quantify joint-specific nonlinear parameters. This capability enables engineers to distinguish between different sources of nonlinearity, such as friction, clearance, or material degradation, thereby improving diagnostic accuracy. Furthermore, advances in data acquisition systems and computational resources have facilitated the application of real-time identification techniques for continuous structural monitoring.

3. Structural Mechanics and Joint Modeling

Structural mechanics provides the physical foundation for understanding how joints influence the behavior of assembled structures. Mechanical joints serve as interfaces between structural components and play a critical role in transferring loads, dissipating energy, and modifying global dynamic characteristics. From a structural perspective, joints introduce localized flexibility and damping that can significantly affect vibration modes, stress distributions, and overall structural performance.

In many engineering applications, joints are modeled as nonlinear boundary conditions or interface elements possessing nonlinear stiffness and damping properties (Fritzen et al., 2011). These properties are often influenced by contact pressure, surface roughness, preload levels, temperature, and material characteristics. Because joint behavior is inherently localized yet capable of affecting global structural dynamics, accurate modeling remains a challenging task.

Finite Element Method (FEM) has become one of the most widely adopted tools for investigating nonlinear joint behavior. Modern FEM formulations incorporate sophisticated contact algorithms capable of simulating frictional sliding, separation, impact, and micro-slip phenomena. These models enable researchers to investigate the influence of joint parameters on system-level dynamic responses and evaluate different identification strategies.

However, numerical models alone are often insufficient due to uncertainties in material properties, contact conditions, and boundary constraints. To address this issue, model updating techniques have been developed to improve numerical predictions using experimental observations. Through inverse analysis, optimization algorithms are employed to adjust model parameters until simulated responses closely match measured data. This process enhances model accuracy and provides valuable insights into the physical mechanisms governing joint nonlinearities.

Recent developments have also emphasized multiscale and multi-physics modeling approaches that account for interactions between mechanical, thermal, and material effects. Such approaches are particularly relevant for aerospace, automotive, and energy applications, where joints operate under complex loading and environmental conditions.

Conceptual Framework

The conceptual framework integrates the theoretical foundations of nonlinear dynamics, system identification, and structural mechanics into a systematic methodology for identifying and characterizing nonlinearities in mechanical joints. As illustrated in Figure 1, the framework begins with experimental testing, where vibration measurements, load-cycle experiments, or operational monitoring data are collected from the structure of interest. These measurements provide the raw information required to assess the dynamic behavior of the joint.

The acquired signals subsequently undergo data processing and feature extraction, where relevant nonlinear indicators are identified through time-domain, frequency-domain, or time-frequency analyses. Common features include harmonic distortions, nonlinear resonance shifts, higher-order spectral components, and hysteresis-related parameters. These features serve as inputs for subsequent identification and modeling stages.

The next stage involves model formulation, where appropriate analytical, numerical, or data-driven models are constructed to represent the observed behavior. Depending on the application, these models may range from simplified lumped-parameter representations to high-fidelity finite element models or advanced machine learning architectures.

Nonlinear system identification and parameter estimation techniques are then employed to estimate the parameters governing joint behavior. This stage constitutes the core of the framework because it enables the quantification of nonlinear characteristics such as friction coefficients, stiffness degradation rates, damping parameters, and hysteresis properties.

Following parameter estimation, model validation and updating are performed by comparing predicted responses with experimental observations. Any discrepancies are addressed through iterative refinement of model parameters until acceptable agreement is achieved. This validation process ensures reliability and enhances confidence in the identified nonlinear characteristics.

The validated models subsequently facilitate nonlinearity characterization, where the specific mechanisms responsible for nonlinear behavior are identified and quantified. These mechanisms may include friction-induced energy dissipation, backlash, hysteresis, contact separation, or degradation-related stiffness changes.

Finally, the outcomes of the identification process support various engineering applications, including structural health monitoring, predictive maintenance, fault diagnosis, digital twin development, and design optimization. By providing a systematic pathway from data acquisition to engineering decision-making, the conceptual framework serves as a comprehensive guide for future research and practical implementation in the field of nonlinear joint identification. Figure 1 shows the conceptual framework for the identification of nonlinearities in mechanical joints, illustrating the workflow from experimental testing and data processing to nonlinear system identification, model validation, nonlinearity characterization, and engineering applications.

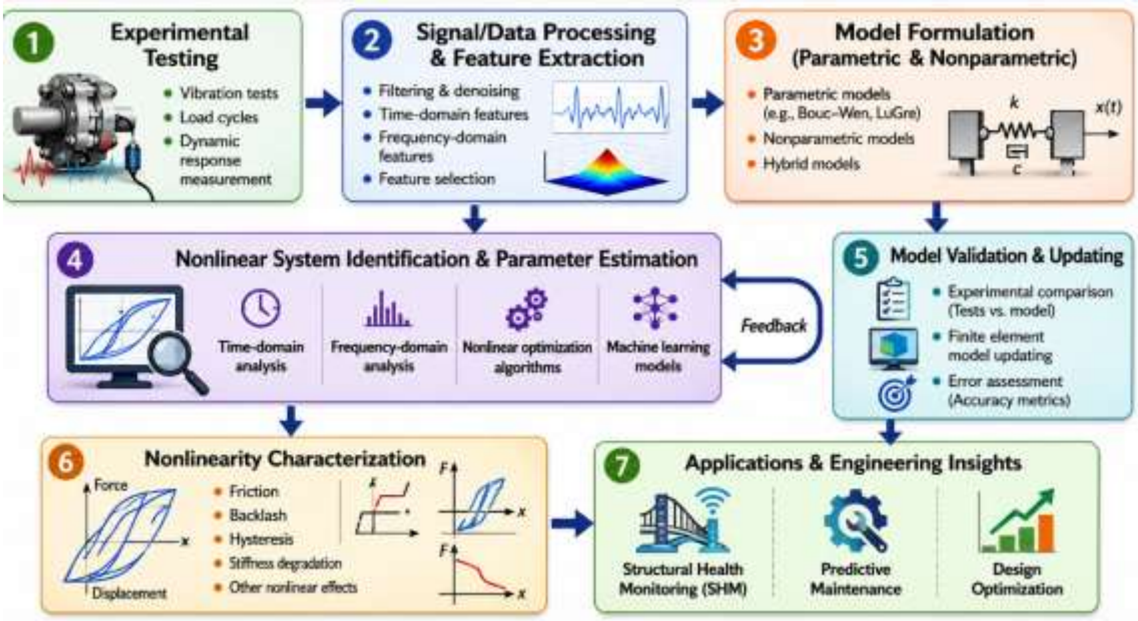

Figure 1: Illustration of Conceptual Framework for Identification of Nonlinearities in Mechanical Joints

CONCLUSIONS

This systematic review examined the current state of research on the identification of nonlinearities in mechanical structure joints, encompassing experimental investigations, theoretical developments, numerical simulations, and emerging data-driven approaches. The reviewed literature demonstrates that mechanical joints are significant sources of nonlinear behavior in engineering structures due to complex interactions involving friction, contact mechanics, material degradation, geometric discontinuities, and varying operational conditions. These nonlinearities have a profound influence on the dynamic response of structures, affecting vibration characteristics, energy dissipation, structural integrity, and overall system performance.

A major finding of this review is the widespread adoption of vibration-based techniques for identifying and characterizing joint nonlinearities. Methods based on experimental modal analysis, frequency response functions, nonlinear system identification, and time-frequency signal processing have shown considerable effectiveness in detecting nonlinear phenomena such as hysteresis, stick-slip motion, stiffness degradation, and amplitude-dependent modal properties. In particular, advanced nonlinear identification methods, including nonlinear state-space models, Volterra series, nonlinear normal modes, and parameter estimation techniques, have significantly improved the ability to quantify joint-specific nonlinear characteristics.

The review also highlights the increasing integration of computational modeling and data-driven methodologies. Finite element models incorporating nonlinear contact mechanics provide valuable insights into the physical mechanisms governing joint behavior, while machine learning techniques offer promising capabilities for pattern recognition, anomaly detection, and automated identification. More recently, hybrid approaches that combine physics-based modeling with artificial intelligence have emerged as attractive solutions for addressing the limitations of purely analytical or purely data-driven methods.

Despite these advances, several challenges remain. Existing studies employ diverse experimental setups, identification algorithms, and validation procedures, making direct comparison and benchmarking difficult. Furthermore, many investigations are conducted under controlled laboratory conditions, limiting the transferability of findings to real-world applications where environmental variability, operational uncertainties, and measurement noise can significantly influence system behavior. The absence of standardized datasets, benchmark structures, and universally accepted evaluation metrics further restricts reproducibility and objective performance assessment.

The findings of this review have important implications for both research and industrial practice. Accurate identification of joint nonlinearities can enhance structural health monitoring systems, improve predictive maintenance strategies, facilitate early fault detection, and support the development of more reliable and efficient engineering structures. Applications span a broad range of sectors, including aerospace, automotive, civil infrastructure, energy systems, and advanced manufacturing.

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