Uncertainty-Aware Vibration Control in Laminated Composite Structures: A Comprehensive Review

Abstract

This paper presents a comprehensive review of recent advancements in the vibration control of laminated composite structures, with a specific focus on studies that account for the presence of damage and material uncertainties. Given the inherent flexibility and critical applications of these structures, effective vibration suppression is paramount. The review systematically examines the foundational laminate theories employed in modeling, including Classical Laminate Theory, First-Order Shear Deformation Theory, and Higher-Order Shear Deformation Theories. It further delves into the prevailing vibration control strategies, categorizing them into active, passive, and hybrid methods, and discussing their respective advantages and limitations. The governing equations of motion and associated boundary conditions, derived from fundamental principles such as Hamilton's principle and the Euler-Lagrange equation, are also summarized. A significant portion of this review is dedicated to analyzing contemporary studies on the vibration control of real-world structures in aerospace, naval, and civil engineering (e.g., bridges). The synthesis focuses on the methodologies used to determine critical system parameters like damping ratios, achieve system stabilization, and characterize mode shapes under conditions of uncertainty and damage. Finally, the paper concludes by identifying key research gaps and proposing potential directions for future work in this evolving field.

Keywords: Laminated composites, vibration control, damage, material uncertainty, active control, passive control, laminate theory.

1. Introduction

Laminated composite materials have become indispensable in modern engineering, particularly in the aerospace, marine, and automotive industries, due to their exceptional properties. These include a high strength-to-weight and stiffness-to-weight ratio, excellent corrosion resistance, and superior fatigue life compared to traditional metallic counterparts, leading to enhanced performance and lower maintenance costs [1]. Structures ranging from aircraft wings and fuselage panels to ship hulls and wind turbine blades are now routinely fabricated from these advanced materials.

However, the very attributes that make them desirable—their high strength and low weight—also render them inherently flexible and susceptible to vibrations. Even minor external disturbances, such as aerodynamic loads, acoustic noise, or wave impacts, can induce significant and persistent oscillations. These vibrations can lead to a host of detrimental effects, including structural fatigue, reduced operational precision, acoustic discomfort, and, in severe cases, catastrophic failure. Consequently, the implementation of robust vibration control strategies is not merely desirable but a critical requirement for ensuring the safety, performance, and longevity of laminated composite structures.

The challenge is further compounded by two inherent characteristics of composite materials: their susceptibility to damage and the presence of material uncertainties. Damage, such as delamination, matrix cracking, or fiber breakage, can occur during manufacturing or in-service operation and can drastically alter the structural stiffness and damping characteristics, thereby affecting the dynamic response and the efficacy of any control system. Simultaneously, material properties like fiber orientation, ply thickness, and constituent material moduli are often not precisely known due to manufacturing tolerances and inherent statistical variations. These uncertainties can lead to unpredictable dynamic behavior, making the design of reliable and robust vibration control systems a complex task.

Given the rapid growth of research in this domain, a structured review is necessary to consolidate recent findings and identify emerging trends. This literature review is therefore organized into four interconnected thematic areas to provide a holistic overview:

1. **Laminate Theories:** An examination of the various theoretical frameworks used to model the kinematic behavior of composite laminates, from simple Classical Laminate Theory to more sophisticated Higher-Order Shear Deformation Theories, highlighting their suitability for different structural configurations and control applications.
2. **Vibration Control Strategies:** A detailed discussion of the principal techniques employed for vibration suppression, distinguishing between passive methods (e.g., constrained layer damping, tuned

mass dampers) and active methods (e.g., using piezoelectric sensors and actuators), as well as emerging hybrid approaches.

3. **Modeling and Governing Equations:** A review of the fundamental principles, such as Hamilton's principle and the Euler-Lagrange equation, used to derive the equations of motion and boundary conditions for composite structures. The role of beam theories (e.g., Timoshenko, Euler-Bernoulli) and plate/shell theories in this context is also discussed.
4. **Applications and System Identification:** A focused analysis of recent studies that apply these modeling and control techniques to practical engineering structures in aerospace, naval, and civil engineering. This section pays particular attention to how researchers determine critical system parameters, such as natural frequencies, damping ratios, and mode shapes, especially when accounting for damaged states or uncertain material properties, and how they achieve system stabilization.

By synthesizing findings across these four areas, this review aims to provide a clear and concise picture of the current state-of-the-art in the vibration control of laminated composites under realistic conditions. The paper concludes by summarizing the key takeaways and outlining promising avenues for future research to address the remaining challenges in this critical field.

Different Lamination theory developed:

In modern era with the increase in the application of laminated composite various laminated plates theories have been developed Classical theory of plates was initiated by Kirchhoff [2] in the nineteenth century, and then was continued by Love and Timoshenko [3] during the early twentieth century, but due to certain limitation this theories are not suited to derive all transverse shear stress of laminated composite plates, So Reissner [4] and Mindlin [5] in 1951 have given the idea of First-order shear deformation theory. In this theory a shear correction factor is needed to adjust the transverse shear stiffness and the accuracy of results of the FSDT will depend significantly on the shear correction factor. The limitations of the CLPT and the FSDT, A new higher-order shear deformation theory has purposed. higher-order shear deformation theory (HSDT) for laminated composite plates described in the journal published in 1988 by B.N.Pandya and T.Kant [6] .As the year passes away a Zig-zag theory for laminated late has introduce to keep continuity in plate theories [7]. The application based development of laminated plate theories has purposed in 2011 by Khandan R Noroozi S,swell P

Vinney J [8]. Recently in 2013 F.Azhari , B.Boroomond &M Shahbati has given an idea for higher-order zig-zag theory for laminated composite plates [9].

Vibration control of laminated composite structure:

Composite structures are flexible in nature and vibrate with minimum disturbance. So, it is needed to control the vibration effect. Many researchers have done lot of experiment to vibration control like active and passive ways. Bailey and Hubbard Jr. in 1985 have purposed the control theory of distributed piezoelectric actuators [10]. Khdeir and Librescu has analyse the symmetric cross ply plate for vibration purpose with the help of higher-order shear deformation theory in 1988 [11]. The vibration control by piezoceramic actuator and piezo film sensor was done by Han et al [12] in 1997. As the year passes away the research on vibration control is going advance form e.g by Khdeir and Reddy [13] and by M. Eissa and M. Sayed in [14]. The vibration control induced by people walking on large span composite decks has analysed by Wendell.D Varela and Ronaldo C.Battista [15]. The efficiency of active vibration control of smart plates using directional actuation and sensing capability of piezoelectric composite is derived by S.Kapuria, M.Yaqoob Yasin in 2013 [16]. He was applied the linear quadratic Gaussian control strategy for active vibration control. Recently in 2013, Hesam Hajheidari, Hamid Reza Mirdamadi, derived the spectral finite element formulation for vibration analysis of rectangular symmetric cross -ply of laminated composite plates [17]. Khan and Kim [18] investigate the active vibration control of a piezo-bonded laminated composite in the presence of sensor partial debonding and structural delamination. They develop an electromechanically coupled finite-element model and analyze how these damage mechanisms influence the performance of a constant gain velocity feedback controller. Their results show that sensor debonding degrades vibration suppression, whereas structural delamination can enhance control authority due to reduced structural stiffness. Sharma et al. [19] investigated the static and free vibration behavior of smart curvilinear fiber laminated composite plates with delamination using a first-order shear deformation theory–based finite element model. Their study demonstrated that delamination significantly reduces structural stiffness and natural frequencies, while curvilinear fiber paths can mitigate this reduction by tailoring stiffness distribution. Additionally, the integration of piezoelectric actuators and sensors with active feedback control was shown to effectively suppress vibration in delaminated smart composite plates. Liu et al. [20] developed a theoretical and experimental framework for adaptive active vibration control of composite laminated plates using macro fiber composite (MFC) piezoelectric patches. By incorporating electromechanical coupling effects and implementing a filtered-x least mean square (FxLMS) algorithm, they demonstrated significant suppression of vibrations near natural frequencies as well as under multi-frequency and random excitations. Experimental and FEM validations confirmed the accuracy and effectiveness of the proposed adaptive closed-loop control system.

Material uncertainty of the composite structure:

The meaning of uncertainty is the incompleteness in knowledge and the inherent variability of the structures and its environment. In early 1955, Uncertainty-based design and optimization technique is derived [21, 22]. Uncertainty in the composite structures under load can be broadly addressed through material, geometric and structural considerations [23], based on probabilistic design methodology in 1999. In aerospace engineering the meaning of uncertainty is best defined by DeLaurentis & Mavris (2000) [24]. Probabilistic strength analysis of uncertain rectangular FRP plates using Monte Carlo simulation is briefly described by Jeong & Shenoi[25]. A non-deterministic approach is applied to improve robustness of aerospace vehicle and decrease its sensitivity to maintain the stability [26, 27]. The uncertainty based design of aerospace structures is describe in 2004[28, 29]. The non-linear free vibration analysis of laminates composite with random material properties is also analyzed by Onkar and Yadav(2004) [30]. He applied the classical laminate theory in the Von Karman views. The effect of uncertainties on the prediction of fatigue failure of aerospace and mechanical components is presented by Koutsourelakis et al in 2006 [31]. In 2007 Onkar et al have given an idea on the probabilistic failure of uncertain laminated composite plates [32]. The effect of uncertainty in composite material properties on non linear aero-elastic response was studied by Murugan et al (2008) [33]. The uncertainty in mechanical properties in FRP laminates and its effect in failure prediction is studied by Lekou & Philippidis in 2008 [34]. A modal for free vibration analysis of laminated composite which are kept on elastic foundation with random system properties by Lal et al(2008) [35], they have taken Green Lagrange strain vector for derivation of the nonlinear strain-displacement relation [36], and the governing equation of motion is based on Hamilton principle.

In the year 2009, Sriramula & Chryssanthopoulos have taken an attempt to quantify the uncertainty in FRP composites and summarize the different stochastic modeling [37], his approach is based on stochastic computational mechanics approach. Material uncertainty of composite plates and matrix cracking effect is derived by Gayathri et al in 2010 [38]. Morales et al has derived the finite element method for active vibration control of uncertain structures they also introduce the fuzzy design method [39]. A stochastic dynamics application system for monitoring the real time material damage or unertainty in aerospace structures system is derived by Prudencio et al recently in 2013 [40]. He has given an overview of the experimental data that he was collected, for the damage models. The problem of uncertainty propagation in composite laminate structures is studied by Conceiçao et al (2013). His approach is based on the optimal design of composite structures by using the Uniform Design Method to achieve a reliability level [41]

Conclusion and future scope:

The literature reviews of variety of analytical and numerical model for composite laminate plates has been developed to predict the damage (matrix crack and delamination). Analytical models mostly considered classical beam, plate and shell theories, extending them to include induced strain actuation. There are many authors also worked on vibration control with uncertain material properties. Extensive amount of research works have been carried out on the numerical methods to develop smart finite element models with extension-bending of piezoelectric coupling using both classical and shear deformation theories. The second author also had done a great job on vibration control of composite structure and aircraft structure [42-44]. But there are still needed extensive works on Vibration control of composite structure when there is some damage or the material properties are uncertain.

In this regard the authors are planning to work on the efficient reduced order model of composite structure and smart structure. It will be helpful to do component wise modeling of real structure with minimum number of degrees of freedom. The authors are looking for the analysis of damage structure or structure with uncertain material properties. This will helpful to prevent catastrophic failure of structure and avoid accident.

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