RECENT ADVANCES IN VIBRO-ACOUSTICS AND NOISE CONTROL OF AEROSPACE COMPOSITE STRUCTURES

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Abstract

Composite structures are widely used in a variety of industrial applications due to their excellent mechanical properties, such as high stiffness-to-weight ratio, etc. The same characteristics that impart excellent mechanical efficiency, however, also result in efficient transmission and radiation of acoustic noise, posing serious vibro-acoustical problems for a variety of engineering systems in which composite structures are used. The composite structures are efficient radiators of noise mainly due to excitation and propagation of supersonic bending and/or shear waves in the structures. Composite skin-stringer structures mostly support supersonic flexural or bending waves propagating in the laminated structure whereas noise radiation by sandwich structures is dominated by supersonic shear waves in the core. Noise control of composite structures presents a significant technical challenge as the main advantages afforded by these structures, such as low weight and high strength, must not be compromised by added treatments. Recently, research has also been conducted to improve attenuation of vibration and noise radiation from such structure using nano-technology. This paper presents state-of-the-art review of the vibro-acoustics and noise control technology for aerospace composite structures.

Introduction

Composite materials and structures offer great promise to all air vehicles and are being increasingly considered for lightweight advanced applications. Both composite laminated and sandwich construction processes are extensively used for aerospace structures and other applications. For example, composite materials are now being used for aircraft fuselage structures e.g., Beech Premier, Boeing 787, Airbus A350XWB. Application of light-weight high-strength carbon fiber reinforced plastic structure comprises about 50% of the 787 airframe primary structure, see Fig.1 [1, 2, 3]. Composites are lighter, stronger, and more resistant to corrosion and fatigue than aluminum alloys and have also proven their durability in commercial service. Coincidently, the same high stiffness-to-mass ratio that imparts mechanical efficiency also results in efficient transmission and radiation of acoustic noise, posing a serious vibro-acoustical problem for a variety of engineering systems in which composite structures are used. Through analytical modeling and experiments, Blakemore et al showed that increasing stiffness of a structure increases its radiation efficiency; with the stiffest structure having lowest sound transmission loss [4]. The mechanism of sound transmission through composite structures is now fairly well understood. The composite structures are efficient radiators of noise mainly due to excitation and propagation of supersonic bending and/or shear waves in the structures. Composite skin-stringer structures mostly support supersonic flexural or bending waves propagating in the laminates whereas noise radiation by sandwich structures is dominated by supersonic shear waves in the core. Due to the underlying physics of the problem, noise control of composite structures still remains a challenge. A large body of published literature is available on the vibro-acoustics and noise control of composite structures. An attempt is made here to present a very brief description of the recent advances in this field.

Composite Sandwich Structures

Composite sandwich structures used for aerospace applications are typically stiff and lightweight. The higher stiffness-to-mass ratio of a sandwich panel compared to a homogeneous panel results in a lower acoustic critical frequency and supersonic shear waves in the core. Palumbo and Klos compared measured transmission loss (TL) of a stiffened metallic fuselage panel with honeycomb sandwich panel and showed that the honeycomb panel has a much lower TL than that of the conventional stiffened aluminum panel, see Figs.2, 3, 4 [5]. Extensive investigations have shown that pure bending of the entire
panel occurs at low frequencies. At slightly higher frequencies, transverse shear in the core governs the response. At yet higher frequencies, bending in each face sheet occurs and the response becomes highly complex due to coupling with the core. For most noise control applications, the primary concern is at low to mid-frequencies where whole panel bending occurs, along with transverse shear motion in the core. Subsonic shear wave speed design approach was first postulated by Kurtze and Waters [6] and corroborated by Davis [7]. A panel with subsonic shear wave in the core can out perform a heavily damped sonic or supersonic shear wave speed in the core without the penalty of adding damping materials to the manufacturing process. The design criteria for the sub-sonic core was evolved that the core shear wave speed ($C_s$) should be less than $2/3$rd the speed of sound ($C_0$), i.e., $C_s \leq (2/3)C_0$. The expressions for transition frequencies for panel bending to core shear and from shear to face bending wave regimes and for shear wave speed in the form of panel geometry, mass density and the elastic properties of the materials have been derived. Wave number dispersion diagrams have been used to investigate and identify acoustically fast flexural and shear waves in honeycomb structures [8]. The measured dispersion plot, shown in Fig.5, for a Nomex core beam reveals acoustically fast behavior of shear waves above 1600 Hz. Wave number frequency spectra method of identifying wave speed and sound radiation from panels was found to be a very useful diagnostic tool and noise control criteria by previous investigators [9, 10, 11].

The vibro-acoustic behavior and shear wave propagation in sandwich composites has been studied by several investigators. It has been shown analytically that the radiating wave number components increase with increasing plate stiffness, causing increased sound radiation. The calculated wave speed using Mindlin approach for symmetrical laminated sandwich panel along with predictions from the method by Kurtze and Watters [6] are shown in Fig.6. The calculated value approaches the shear wave speed at high frequencies, and the bending wave speed at low frequencies [12]. Liu and Bhattacharya derived expressions for propagation of vibrational waves in a sandwich structure [13]. The lowest three branches of the dispersion relations in the long wavelength and low frequency regime are plotted in Fig.7. Around $k = 0$, it is not surprising that from the bottom to top, they correspond to the out-of-plane flexural modes, the in-plane transverse (shear) modes, and the in-plane longitudinal modes. Since the wavelength of these modes are much larger than the thickness of the sandwich structure, the sandwich structure behaves almost like a "uniform" slab. Similar situation is shown in Fig.8. The horizontal axis is roughly divided into four regimes labeled by "flexural", "flexural-dilatational", "vertical shear" and "horizontal shear". The corresponding typical mode shapes are shown in the bottom. The numbers above the mode shapes are their values in $h/\lambda$. The sandwich structure flexes as a uniform plate when the wavelength is large compared with the thickness of the plate, as shown by the first mode shape, see Fig.8. When $h/\lambda \geq 0.8$, the second mode shape in Fig.8 suggests that coupled flexure-dilatation modes arise from the coupling of the flexural motions of the top/bottom layers and the dilatational motions of the middle layer. Notice that in this regime the wavelength is still large compared with the thickness of the top/bottom layer. By implementing frequency-dependent parameters, the vibration of sandwich composite beams has also been approximated using simple fourth-order beam theory [14]. A different approach to modeling the flexural response of sandwich composites is provided by the concept of apparent bending stiffness. Overall, in the low frequency region, flexural wave dominates sound transmission behaviors of the panel, while in the mid-high frequency region, core shear wave dominates. In the mid frequency region, the vibrational response is in transition from flexural wave to core shear waves, as shown in Fig.9. The TL variation of a honeycomb panel in the low frequency region is most sensitive to the skin and core density variations, while in the high frequency region, it is most sensitive to the core shear moduli and core damping variations [15]. Other researchers have also demonstrated that, for sandwich structures, sound is predominantly radiated by bending deformation of the whole sandwich at low frequencies and shear deformations of the sandwich core at mid to high frequencies [16-23].

Several studies have also focused on design and optimization of quiet sandwich structures. Experimental results have shown that honeycomb cores with lower shear modulus values, translate into slower wave speeds and superior acoustical performance [16]. The shear modulus of the core has been found to have maximum influence on the wave speeds of the samples [7,16]. A genetic algorithm was used to optimize a sandwich panel with a balance of acoustical and mechanical properties at minimal weight resulting with an optimum acoustic design with titanium face sheets and a 72 mm thick honeycomb core [17]. It has been shown that by reducing shear modulus of the core and/or by disrupting the supersonic flexural and shear wave speeds that exist in the baseline panel, the TL of a honeycomb panel can be substantially improved [5, 19,
Currently, there is no easy way of doing so. Since sound composite structures is much more challenging and, curiously, changing sound radiation mechanism in skin-stringer composite structures is highly questionable. Skin-stringer composite structures mostly pose a different but equally challenging noise control problem. In general, sound transmission loss for the composite skin attached with composite stringers has been shown to be lower than that of a metallic panel attached with metallic stringers [25, 26]. During the NASA HSCT (High Speed Civil Transport) program, extensive analytical and experimental investigations of both honeycomb sandwich and skin-stringer type composite structures were conducted. It was shown that the sound transmission loss (TL) for both composite panels were below mass law, with the composite skin stringer panel TL less than that of the composite honeycomb sandwich panel TL [27, 28]. The vibrations and noise transmission analysis of such structures has been conducted using the following numerical methods: in the low frequency range by means of Finite Element Method (FEM), and in the medium-high frequency range by means of Statistical Energy Analysis (SEA) [26, 27, 29]. Extensive experimental investigations are also required to determine vibro-acoustic parameters. Figs. 10 and 11 show the composite skin stringer panel model and a comparison of experimental and numerical (SEA) data [29]. Numerical results seem to show a rather good agreement with the measurements even in the lower frequency range where the validity of the model may be questionable. Skin-stringer composite structures mostly support supersonic flexural or bending waves propagating in the laminates as there is no core to carry shear waves. The problem of reducing bending wave speeds and, in turn, changing sound radiation mechanism in skin-stringer composite structures is much more challenging and, currently, there is no easy way of doing so. Since sound radiation is dominated by acoustically fast resonant modes, damping has beneficial effect. Koo and Lee showed that through-the-thickness variation of in-plane displacements within laminates can have significant effect on the local behavior such as damping characteristics of composite laminates [30, 31]. Most of the applications of passive damping in commercial aircraft have been based on providing local damping treatment in the fuselage using add-on type damping to reduce the overall vibration amplitude. Use of add-on, constrained layer damping (CLD) on fuselage skin surface is an industry wide noise control approach as it is effective over wide frequency range. Conventional CLD works by creating shear deformation in the visco-elastic layer when the structure bends [32, 33]. In recent years, co-curing damping materials in composites has been shown to be successful in increasing the damping of composite structures [32]. However, issues related to loss of visco-elastic properties due to curing at high temperatures and difficulty in obtaining enhanced system damping without penalties in stiffness still remain [34]. Different visco-elastic materials, that can withstand higher curing temperatures, may have to be used [35]. The concept of curvilinear stiffeners has been suggested to reduce sound radiation from stiffened composite panels [36].

**Nano-composites**

Recently several studies have reported the feasibility of utilizing nano-materials such as carbon nano-tubes or nano-fibers in damping enhancement [37-39]. However, there is no practical nano damping solution currently available for industrial strength composites which can replace conventional noise control treatments. In a breakthrough study, Veedu et al demonstrated remarkable improvements in the inter-laminar fracture toughness, hardness, de-lamination resistance, in-plane mechanical properties, and damping in 3D nano-composites with nano-tube forests [40]. They grew well-aligned multi-walled carbon nano-tubes perpendicular to 2D woven fabrics of Si-C to produce 3D fabrics. These fabrics are then infiltrated by a high-temperature epoxy matrix, and are subsequently stacked to form multilayered 3D composites. The results indicate that carbon nano-tube engineered 3-D composite structures show great promise for multifunctional applications along with improved structural damping.

**Conclusions**

Research in the last decade has elucidated the physics of wave propagation and sound radiation from composite structures. Design criteria for quiet sandwich structures, in terms of subsonic core shear wave speeds, have evolved.
Sound radiation from laminated composite skin-stringer strutures, on the other hand, is dominated by a different mechanism, i.e., by supersonic flexural waves and resonant modes. Noise control of aerospace composite structures, thus, is still a challenge to structural design and noise control engineers as demands for mechanical strength, weight and noise must be addressed and balanced. Innovative structural design features and lightweight, noise control methods need to be developed to keep their lightweight advantage and make composite structures inherently less noisy. Nano-composite technology has shown some nascent promise in the form of 3-D structures which may, however, take time to come to fruition.

References


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37. Suhr, J and Mathur, G. P., "Nanotechnology Enabled Multifunctional Damping for Aerospace Composite


Fig. 4 Composite Materials, such as the Graphite Epoxy Honeycomb Panel, Used in Beech Premier Aircraft [5]

Fig. 5 Measured Wave Number Dispersion Plot of Nomex Honeycomb Sandwich Beam [8]

Fig. 6 \( \Delta \)-Calculated Speed of Flexural Waves; \(-\nabla\)-Method by Kurtze and Watters [6]; \(\ldots\) \(C_b\); \(\ldots\ldots\) \(C_s\) [12]

Fig. 7 The Lowest Three Branches of the Dispersion Relations in the Long Wavelength and Low Frequency Regime. (*) The Transfer Matrix Method; (--) Perturbation Method; \((\times)\) The Kirchhoff-Love Plate Theory; (\(\diamondsuit\)) The Mindlin Plate Theory [13]
Fig. 8 Dispersion Relation of the Sandwich Structure and Wave Regimes [13]

Fig. 9 Dispersion Relation of Honeycomb Sandwich Panel [15]

Fig. 10 Composite Skin Stringer Panel Model [29]

Fig. 11 Experimental and Numerical TL Results Comparison [29]