Chapter 5

Acoustic and vibration damping

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Abstract

The main functionality of composites, namely their high structural stiffness to weight ratio, facilitates the propagation of mechanical and acoustic vibration leading to discomfort and sometimes to mechanical damage. Despite inherent damping capacity, energy dissipation in composites is insufficient for high performance applications. Therefore, new materials and manufacturing processes must be developed to improve the damping performance of high performance composite structures. In this chapter, structural-borne vibration and its relationship to noise are described. The viscoelasticity of composite materials is treated and the techniques used to characterize fundamental material properties are presented. The classical methods for reducing vibration transmission along a structure are discussed. Novel techniques used for vibration damping and noise reduction of composite structures are also presented and practical examples are given. Analytical modeling of novel damping techniques is described.

5.1 Introduction and definitions

In past the three decades, composites materials have been increasingly used in a wide range of engineering fields including aeronautics, automotive, construction, and sports. Composite materials can fulfill precise requirements when the appropriate combination of matrix and reinforcement is chosen. Compared to their metallic counterparts, composite materials offer higher specific mechanical properties, enabling lightweight structures. A good example is the new Boeing 787 Dreamliner. This long-range aircraft is Boeing's most fuel-efficient airliner with up to 70% by volume composite materials parts (fuselage, interior furniture, liners etc.). However, the use of light and stiff materials has a disadvantage, namely, the enhanced propagation of structural vibration, structure-borne and air-borne acoustic vibration which in turn can lead to mechanical damage, passenger discomfort, and environmental noise pollution. Damping (dissipation of mechanical energy into heat) is therefore an important parameter in the dynamic behavior of composite structures. The nature of composite materials (matrix and reinforcement) leads to entirely different damping mechanisms when compared to metals and alloys. To a great extent, damping in composites comes from the viscoelastic nature of the matrix, whereas damping in traditional engineering structures comes from friction in assembly joints. Weak interface between the matrix and the fiber also influences damping. Matrix cracks, broken fibers, and friction due to delamination also contribute to overall damping of composites. But intrinsic damping is still not enough to reduce vibrations when composites are used in the vicinity of rotating machines or noise sources. Moreover, structural damping is strongly reduced when reinforcing fibers are tightened during manufacturing such as filament wound parts.

The term vibration describes a repeating deformation, often periodic, that can be measured and observed in a structure. There are many sources of structural vibration that engineers must deal with during the analysis and design processes of aircrafts. Rotating machines such as fans, turbines, pumps, and propellers are common sources of vibration. They generate unwanted forces that cause significant structural deformation at resonant speeds. Other sources include interaction with air flow, pressure fluctuation in gases and liquids flowing in pipes, impact or sudden variation of forces due to environmental sources, and many others. Depending on the excitation mode, two basic structural vibrations can be distinguished: steady state vibration caused by continually running machines and transient vibration caused by a short impulse. Regardless of the source of vibration, it is generally accepted that vibrating structures can be modeled by a series of masses and springs connected together. For a *single degree of freedom* (SDOF), the differential equation of motion is given by

$$m\ddot{x}(t) + kx(t) = F(t) \tag{5.1}$$

where m is the mass of the vibrating structure and k is the stiffness, $F(t)$ and $x(t)$ are the excitation force and the resulting displacement with respect to time.[1] The spring-mass model predicts that after the excitation is removed (i.e., $F(t) = 0$), the system oscillates freely and indefinitely. However, in practice it is observed that free oscillations die out. For this reason, the differential equation (5.1) must be modified to take into account the decaying motion, or damping, of the vibration. The theory of differential equations shows that adding the term $c\dot{x}$ to the equation results in free oscillations that reduces to zero, as in Figure 5.1. The model is modified to spring-mass-damper and the equation of motion is given by

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t) \tag{5.2}$$

[1]It should be noted that (5.1) is technically correct for lumped (i.e., discrete) systems only. For continuous structures, where mass and stiffness are distributed over the entire surface, the equation of motion is a partial differential equation. For the purpose of the definitions in this chapter, the discrete representation suffices.

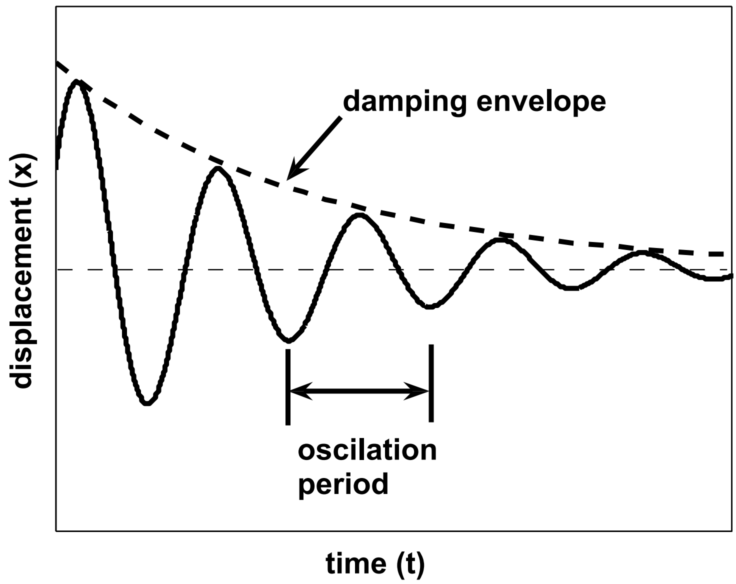

Figure 5.1: Underdamped response of a SDOF oscillating system.

where c is the damping coefficient. In this modified model the spring stores and restitutes the kinetic energy causing the vibration while the damper dissipates mechanical energy into heat. A non-dimensional number called the damping ratio, which describes how the oscillations decay after disturbance, can be defined as

$$\zeta = \frac{c}{2\sqrt{km}} \tag{5.3}$$

Vibrating structures can also create sound or noise (unwanted sound) by generating pressure fluctuations in its surrounding medium (e.g., air, water, oil), which in turn can react back to the structure to change its vibration behavior. The loading of the surrounding fluid is called radiation, and the generated pressure variation is the sound pressure (Figure 5.2.a). Mathematically, the sound pressure at any position around the vibrating structure can be calculated using a Green's function.

The reaction of the medium against the motion of the vibrating surface is the radiation impedance. It can be defined as the ratio of the force F, acting on the vibrating surface, to the acoustic velocity u of the surface at the point of application of the force. If a vibrating surface of area S is radiating a uniform sound pressure p at a given position in space, then the radiation impedance at this position can be defined as

$$Z_m = \frac{F}{u} = \frac{pS}{u} = Z_s S \tag{5.4}$$

The complex specific impedance Z_s of the acoustic medium is given by

$$Z_s = \frac{p}{u} = R + jX \tag{5.5}$$

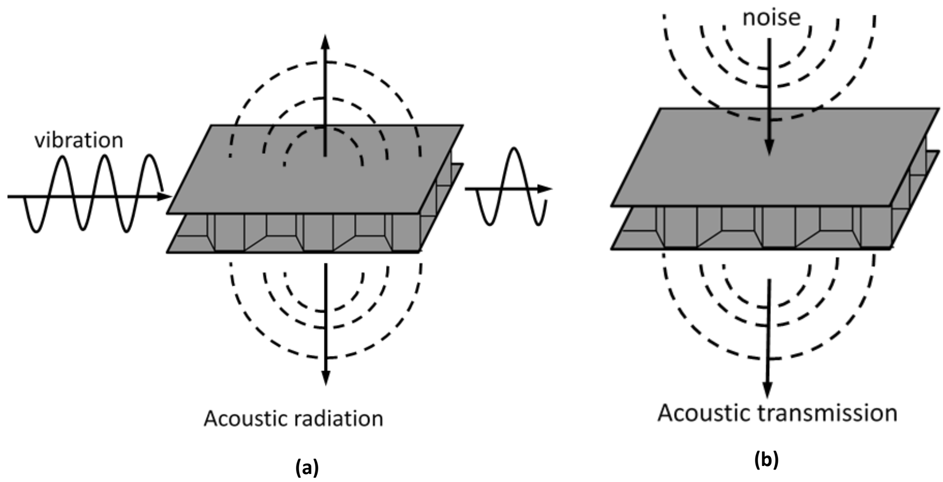

Figure 5.2: Illustration of (a) acoustic radiation, and (b) acoustic transmission.

where R and X represent acoustic resistance and acoustic reactance, respectively.

Moreover, for a given vibration amplitude, the noise radiated from the structure depends on its radiation efficiency, which in turn can be correlated with the shape and texture of the vibrating surface. The radiation efficiency, or radiation ratio, is the non-dimensional ratio of specific impedance Zs and the characteristic impedance of the acoustic medium ($\rho_o c_o$), ρ_o and c_o being the density and sound velocity in the medium. Physically, its represents the ratio of the sound power radiated by the vibrating structure of surface area S to the maximal sound power that could be radiated by the a structure of same surface area under the same vibration conditions.

Sound waves propagate through all mediums, solid or fluid. However, any variations of the medium in the propagation path will lead to reflections. For instance, when a sound wave propagates in air towards a solid wall, part of the wave will be reflected back, another part can be absorbed by the wall, and the rest can be transmitted through the wall (Figure 5.2.b). The total acoustic energy W_i can be written as follows

$$W_i = W_r + W_a + W_t \tag{5.6}$$

where W_r, W_a, and W_t are the power of the reflected, the absorbed, and the transmitted sound waves, respectively. Thus, the following terms can be defined

$$\text{Reflection coefficient}: \; R_x = \frac{W_r}{W_i} \tag{5.7}$$

$$\text{Absorption coefficient}: \; \alpha = \frac{W_a}{W_i} \tag{5.8}$$

$$\text{Transmission coefficient}: \; \tau = \frac{W_t}{W_i} \tag{5.9}$$

$$\text{Transmission loss}: \; T_L = -10 \log \tau \tag{5.10}$$

It should be noted that if the incident wave is normal to the surface of the wall, one speaks of normal transmission loss or normal absorption coefficient.

These definitions help clarifying the notion of acoustic attenuation, which is the action of reducing acoustic energy at a given position in space. The strategies for acoustic attenuation depend on the sound source and transmission path. If the sound is airborne, then it is necessary to isolate the space from the source. Insulation of the source or insertion of a sound barrier will restrict sound propagation. The ability of the barrier to reflect sound back is correlated to the mass law. This means that heavier materials insulate better than lighter materials. However, part of the sound is transmitted through the vibration of the barrier, which depends on the elastic behavior (i.e., stiffness) of the material. Therefore, sizing must be performed on both the mass and the stiffness of the barrier. The general term *sound isolation* is used to include insulation, and is characterized by the sound *transmission loss* (TL), which is the amount of sound decibels not transmitted through a barrier.

If the sound is structure borne, for example through the radiation of vibrating structures within the space, then the sound needs to be absorbed or the vibration itself be reduced (at the source). In sound absorbing materials, the sound wave is neither reflected nor transmitted. Sound absorption is achieved by successive interactions and viscous friction of the moving air within the cavities of the material, leading to heat dissipation. For this particular reason, porous and fibrous materials are used as noise absorbent material (see Section 5.2.1). Sound absorption is also used on the source side of sound barriers to reduce the amount of reflected energy while maintaining the transmission loss.

Any attempt to reduce structural or acoustic vibration must be preceded by the identification of the main sources. As an example, in aircraft engines with low bypass ratio (first generation turbofans from the 70's), the dominant jet noise is associated with the turbulent mixing of the high speed exhaust with ambient air. In the case of modern engines with high bypass ratio, fan noise is more relevant than jet noise. According to the source of noise, the spectrum of acoustic pressure at the intake or duct of an aircraft engine can be divided in two major components: the discrete tones and the broadband component. Acoustic pressure of discrete rotating parts is periodic, deterministic, and composed of harmonic tones corresponding to the *blade passage frequency* (BPF) and its harmonics (the BPF of a fan is given by the number of blades times the fan's angular velocity). Thus, discrete tones characterize fan noise of aircraft engines, as shown in Figure 5.3 with harmonics at 1000 Hz, 1250 Hz, and 1500 Hz. The broadband component of the noise is caused

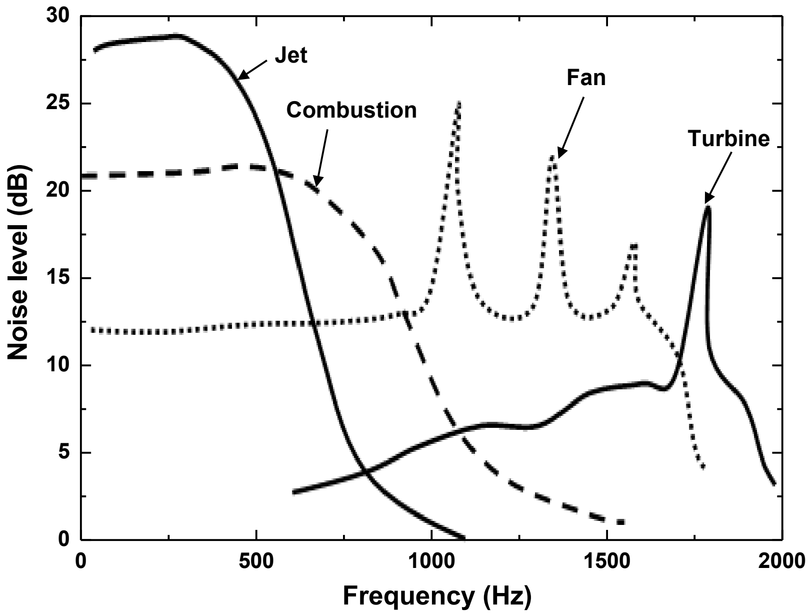

Figure 5.3: Noise spectrum in a turbofan engine: contribution of various components.

by turbulent mixing of high speed exhaust with ambient air at low pressure, as well as the interaction between the moving blades and incident turbulent air flow (boundary layer on walls of the nacelle), and the interaction between *outlet guide vanes* (OGV) and the rotor blades. Looking at Figure 5.3, it can be seen that jet noise and combustion noise can be considered as low frequency broadband noise.

In this chapter, passive damping techniques used to reduce structural vibration and noise are presented. An actual issue is the integration of acoustic and structural damping within composite structures instead of traditional add-on solutions. Aircraft manufacturers are struggling with conflicting requirements such as weight, mechanical performance, and the consequent dynamics of the structure. Functionalizing composite structures with damping capabilities is key to mass reduction, and thus to savings in fuel consumption while improving cabin comfort. This chapter also focuses on different damping materials including their characterization. Design guidelines to integrate such materials into composite structures are also discussed. Vibration reduction techniques can be applied in various fields of engineering but the concepts presented in this chapter are oriented towards aeronautic engineering where high performance composites combined with autonomic damping capabilities are needed.

5.2 Aircraft engine acoustic damping

Aircrafts noise has been intensively investigated due to its impact on public health. Noise generated by aircrafts can affect the hearing of passengers and is a source