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Investigation of sound transmission in composite rectangular panels under the incidence wave with two various angles

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Abstract

Composite panels are widely used in various industries, and the study of the behavior of these panels under acoustic vibrations is one of the important cases in engineering analysis. The critical and coincidence frequencies and sound transmission loss in composite panels are influenced by parameters such as the orthotropic, thickness, incidence and azimuthal angles, Mach number, and transverse shear flexibility of the panel.

Keywords: Sound Transmission Loss, Critical Frequency, Coincidence Frequency, Incidence Angle, Azimuthal Angle.

1. Introduction

When a panel with infinite length is acoustically stimulated, the frequency at which the speed of sound in the air equals the speed of the free bending wave is called the critical frequency ω_{cr}, and the frequency at which the speed of the free bending wave equals the speed of the forced bending wave is called the coincidence frequency ω_{co} [1]. Sound transmission loss near the Coincidence frequency is very high. The vibrational response of a panel to a sound field is around its critical frequency. Therefore, knowing the information about the sound transmission loss, critical and coincidence frequencies of a structure is necessary to study its structural-acoustic interaction. The present article, considering the importance of knowing the sound transmission loss, critical and coincidence frequencies in panels before using them in structures, a new formulation by considering incidence and azimuthal angles, Mach number for the thick orthotropic panels is presented and the effect of orthotropic behavior, transverse shear flexibility, above angles and Mach number on sound transmission loss, critical and coincidence frequencies are discussed. The expressions obtained have been validated with experimental samples and other articles.

2. Critical and coincidence frequencies of sound waves in panels

The equation governing the forced vibration of thick orthotropic panels is as follows [2]:

$$\left(D_{11}\frac{\partial^4 w}{\partial x^4}+2(D_{12}+2D_{66})\frac{\partial^4 w}{\partial x^2 y^2}+D_{22}\frac{\partial^4 w}{\partial y^4}\right)+\rho\left(\frac{\partial^2 w}{\partial t^2}\right)-\left(\frac{\rho}{N}\right)\left(D_{11}\frac{\partial^4 w}{\partial x^2\partial t^2}+D_{22}\frac{\partial^4 w}{\partial y^2\partial t^2}\right)=q \tag{1}$$

Where ρ,D_{ij},q, N and G are the density, bending stiffness, external load, shear stiffness and shear modulus of the plate, respectively. The sound wave hitting the rectangular panel and the reflected and transmitted sound waves from it are shown in Figure 1. The infinite panel problem can be analyzed by setting w as follows:

$$w=Ae^{i(\omega t-k_x x-k_y y)} \tag{2}$$

Where k_x and k_y are components of wave number k in x and y directions, A is displacement amplitude and ω is angular frequency. The wave number in the orthotropic material is dependent on the incidence and azimuthal angles; $k_x=k\cos\beta\sin\theta$ and $k_y=k\cos\theta$ where $0^0\le\theta\le 90^0$ and $0^0\le\beta\le 360^0$ are the incidence and azimuthal angles, respectively (Figure 1). The wave number at frequency ω is defined as $k=\frac{\omega}{c}\left(\frac{1}{1+M\cos\beta\sin\theta}\right)$, where c is the speed of wave propagation in air and M is the Mach number [2]. By putting equation (2) in the free form of equation (1), i.e. $q=0$, we will get the frequency characteristic equation. Expression of critical and coincidence frequencies can be obtained as follows:

$$\omega_{cr}^2=\frac{\frac{\rho c^4}{D}}{\frac{(\psi-\phi)}{(1+M\cos\beta\sin\theta)^4}} \tag{3}$$

$$\omega_{co}^2 = \frac{\dfrac{\rho c^4}{D\sin^4\theta}}{\dfrac{\left(\psi - \dfrac{\phi}{\cos^2\beta\sin^2\theta}\right)}{(1+M\cos\beta\sin\theta)^4}} \quad (4)$$

which

$$\psi = (\cos^4\beta\sin^4\theta + 2\alpha\cos^2\beta\sin^2\theta\cos^2\theta + \cos^4\theta)$$

$$\phi = \frac{\rho c^2}{N}(\cos^2\beta\sin^2\theta + \cos^2\theta)(1 + M\cos\beta\sin\theta)^2$$

$$D_{11} = D_{22} = D$$

$$\alpha = \frac{(D_{12} + 2D_{66})}{D}$$

3. Sound transmission loss in panels

Incidence, reflection and transmission harmonic pressure waves in the perpendicular coordinate system are expressed in the form of relation (5) [3]:

$$p_i(x,y,t) = P_i e^{i(\omega t - k_x x - k_y y)} \quad (5)$$

$$p_r(x,y,t) = P_r e^{i(\omega t - k_x x - k_y y)}$$

$$p_t(x,y,t) = P_t e^{i(\omega t - k_x x - k_y y)}$$

where P_i, P_r and P_t are the pressure amplitudes of incident, reflected and transmitted waves, respectively. To obtain the sound transmission loss in the panel, two boundary conditions, i.e. the first condition: the equality of the algebraic sum of the forces acting with the external force acting in the forced vibration equation of the panel and the second condition: the equality of the vertical speed of sound on both sides of the panel, must be observed [1]. From the first condition the relation (6) is obtained:

$$q = (p_i + p_r) - p_t \quad (6)$$

From the second condition, relation (7) is obtained:

$$\frac{p_i(0,y,t)}{\rho c} - \frac{p_r(0,y,t)}{\rho c} = \frac{p_t(0,y,t)}{\rho c} \quad (7)$$

By putting relation (5) in (7), the following relation is obtained:

$$P_i - P_r = P_t \quad (8)$$

Sound transmission loss in a thick orthotropic panel on a logarithmic scale can be calculated as follows [4]:

$$STL = -10\log(1 + M\,cos\,\beta\,sin\,\theta)^2\left|\frac{P_t}{P_i}\right|^2 \quad (9)$$

For composite thick panels, by putting equations (2) and (6) in equation (1) and considering equation (8), a system of equations in terms of A, P_r, P_i and P_t are obtained, and by removing P_r and A among the equations, we reach the dimensionless $\frac{P_i}{P_t}$. By putting this dimensionless in equations (9), the sound transmission loss in composite thick panels is obtained as follows:

$$STL = -10\log\Theta\left|\frac{1}{1 + \eta\dfrac{D}{2}(\Pi - \rho\omega^2\mathrm{E})}\right|^2 \quad (10)$$

where

$$\Theta = (1 + M\cos\beta\sin\theta)^2$$

$$\Pi = {k_x}^4 + {k_y}^4 + 2\alpha {k_x}^2 {k_y}^2$$

$$\mathrm{E} = \frac{1}{D} + \frac{{k_x}^2 + {k_y}^2}{N}, \eta = \frac{A}{P_t}$$

4. Results and discussions

In this section, the obtained relationship is validated by studying the vibro-acoustic behavior of a two-layer CFRP (0,90) composite panel whose physical properties are in [2, 5]. The sound transmission loss obtained by using equation (10) is drawn in Figure 2 to compare with [5]. The effects of incidence angle on the critical and coincidence frequencies, and the effects of the orthotropic parameter on the sound transmission loss can be seen in Figures 3-6, respectively.

5. Conclusion

The results show that in the given range, increasing the incidence and azimuthal angles causes the enhancement of the critical frequency and sound transmission loss, while the orthotropic parameter has the opposite effect. Increasing the Mach number and decreasing the thickness of the panel reduces the sound transmission loss and increases the critical frequency of the panel. Also, with the increase of the transverse shear flexibility of the panel, the critical frequency is increased.

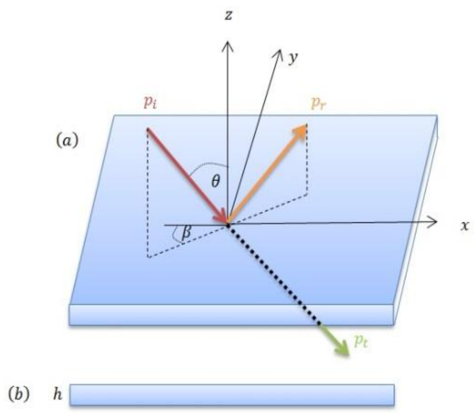

Figure 1: Sound transmission through composite rectangular panel

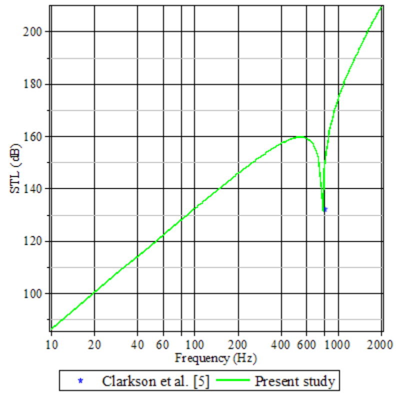

Figure 2: Comparison of critical frequency with [5]

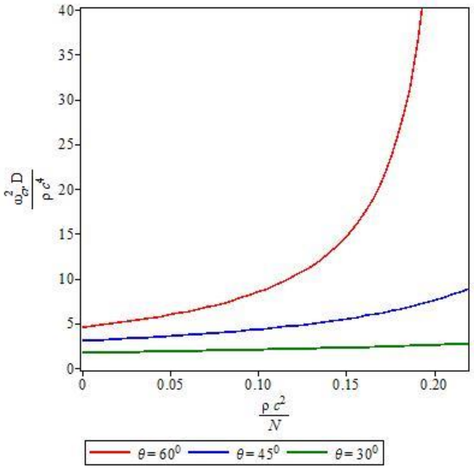

Figure 3: Effect of incidence angle on critical frequency of composite panel

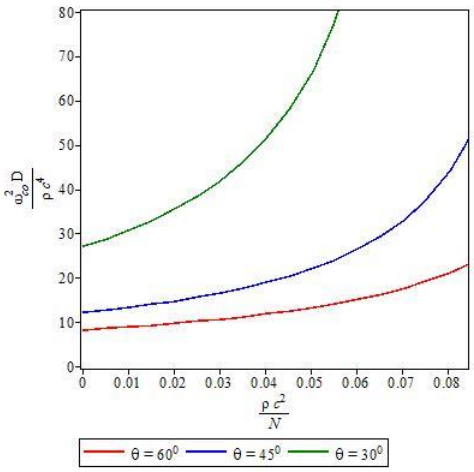

Figure 4: Influence of incidence angle on coincidence frequency of composite panel

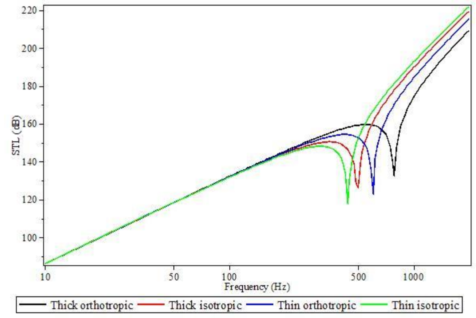

Figure 5: Sound transmission loss in thin and thick isotropic and orthotropic panels

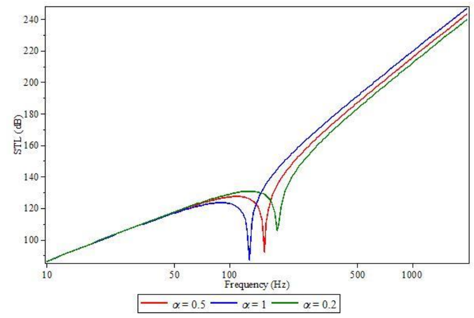

Figure 6: Effect of orthotropic parameter on sound transmission loss of composite panel

6. References

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