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Sound insulation of composite cylindrical shells: a comparison between a laminated and a sandwich cylinder

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Abstract: The fuselages of aircraft are modeled as a cylinder in this paper, and the sound insulations of a sandwich cylinder and a laminated cylinder are studied both experimentally and numerically. The cylinders are excited by an acoustic pressure and a mechanical force respectively. Results show that under acoustic excitation, the sandwich cylinder and the laminated one have a similar sound insulation below 3000 Hz, but the sandwich cylinder has a much larger sound insulation at higher frequencies. Under mechanical excitation, the sandwich cylinder is also more beneficial, showing a larger sound insulation above 800 Hz.

Keywords: Sound insulation, Sandwich, Cylinder

1. Introduction

Noise control in cabins of the aircrafts has been one of the main considerations during the design stage. The reduction of the cabin noise can be achieved mainly by two means: one is to reduce the noise from the sources such as the quiet engine development; the other one is to improve the sound insulation of the fuselage. Tooren [Tooren,1998] has proven the feasibility of using the frameless sandwich construction for the fuselage in terms of mechanical stability and strain constraints. This paper will discuss the possibility of increasing sound insulation by applying the sandwich structures on the fuselage.

The sound transmission loss of sandwich structures has been studied by many researchers in the past. Tang [Tang, Robinson and Silcox,1996] developed an analytical method to study the infinite sandwich cylinders under different flight conditions. Nilsson [Nilsson,1990] investigated the wave propagation and sound transmission of the sandwich plates and found that the core thickness is very critical for the sound transmission of sandwich plates. Increase of core thickness can shift the coincidence frequency to higher frequencies. Ghinet [Ghinnet, Atalla and Osman,2005] developed a Statistical Energy Analysis (SEA) model to calculate the transmission loss of the curved sandwich composite panels. However, the comparison between the sound transmission of finite sandwich cylinders and laminated cylinders has not been studied yet. To fill this gap, the sound transmission and dynamic properties of a finite laminated cylinder and a sandwich cylinder are compared and analyzed. The research includes the structural response under a mechanical excitation and the structural response under acoustic excitation.

2. The mechanical excitation

The laminated cylinder and the sandwich cylinder were produced by means of the filament winding method. The facings of the sandwich cylinder were exactly same as the laminated cylinder and the fibers are all in the hoop direction. The only difference was the addition of a foam core. The weight of the laminated cylinder and the sandwich cylinder are 7.15 Kg and 10.34Kg respectively. Compared with the laminated cylinder, the additional weight of the sandwich cylinder is the weight of the core. The

mechanical properties of the composite materials and the foam are shown in Table 1. Both the sandwich cylinder and the laminated cylinder were excited by a shaker with a white noise signal, the inner pressure was recorded with a microphone (B&K 4196), and the surface displacements were recorded by two laser beams (Kenyence).

The numerical model was built in Va One and the analysis was conducted with SEA method. A point force was applied on the cylindrical shell subsystem to simulate the force from the shaker. The pressure of the inner cavity and the velocity of the cylindrical surface were computed.

It should be noted that there are two differences between the experimental test and the numerical model for the mechanical excitation. The first is that the velocity of the whole cylindrical surface was computed in the numerical model while the velocity at one point was recorded in the experimental test. The second is that the pressure computed in the numerical model was the statistical result of the whole inner cavity while in experiment only the pressure at one point of the cavity was recorded. In spite of these differences, the mechanism behind the dynamic response and the sound transmission should be the same. Therefore the experimental results and the numerical results are compared and analyzed together here.

Table 1 – Materials properties for the laminated and sandwich cylinder

	$E_1[\text{Pa}]$	$E_2[\text{Pa}]$	ν_{12}	$G[\text{Pa}]$	$\rho[\text{kg/m}^3]$
UD-Glass/epoxy	3.66e+10	5.4e+09	0.3	4.2e+09	1800
Foam	1.51e+08	1.51e+08		6.87e+07	70

Figure 1 – structural response between sandwich and laminated cylinder under a point force excitation

Figure 2 –inner pressure between sandwich and laminated cylinder numerically and experimentally

In Fig.1, it can be seen that the normal surface velocity of the sandwich cylinder is larger than that of the laminated cylinder at all frequencies. In addition, the measured frequency responses show a good agreement with the numerical prediction in spite of the difference that mentioned above. The phenomenon that the sandwich cylinder shows less frequency response than the laminated one is due to its higher bending stiffness.

The sound pressure of the inner cavities for two different cylinders is compared in Fig. 2. We can see that the inner pressure of the sandwich cylinder is not lower than its corresponding laminated cylinder at lower frequencies (below 800Hz), even higher at some low frequencies for the numerical case. However, the sandwich cylinder starts to show a better sound insulation above 800 Hz. This phenomenon is similar with the results in [Tang, Robinson and Silcox,1996], where an infinite sandwich cylinder with aluminum facings and an uniform aluminum cylinder were compared with an analytical method. The relation of sound insulation of the sandwich cylinder and the laminated cylinder with the frequency will be explained in the following.

Kurtze [G. Kurtze,1959] derived the governing equation of the speed of the sound wave transmission c in sandwich structures, as shown in Eq.1. On the other hand, the transverse wave speed of the laminated panel c_l is expressed as Eq. 2. And it is compared with the wave speed of the sandwich panel in Fig.3.

$$\frac{c_s^2}{c_b^4} c^6 + c^4 - c_s^2 c^2 - c_{bf}^4 = 0 \quad (1)$$

$$\text{With } c_b = \sqrt{\omega^4 B / M}, c_s = \sqrt{G_c t_c / M}, c_{bf} = \sqrt{\omega^4 2B_f / M}$$

$$c_l = \sqrt{\omega^4 B_l / M_l} \quad (2)$$

where, c_b is the bending wave of the sandwich panel, c_s is the shear wave, c_{bf} is the bending wave generated by the facing. B is the bending stiffness of the sandwich panel, M is mass per unit area of sandwich. B_f is the bending stiffness of the facings.

As shown in Fig. 3, the mechanism of sound transmission of the sandwich structure is changing as the frequency increases. At low frequencies, the sandwich panel behaves like an equivalent uniform panel in

bending, and the bending wave of the sandwich structure is the main means for the sound propagation. At this stage, the sandwich structures do not show much advantage on the sound insulation, a higher stiffness core even leads to lower TL and greater noise radiation. At middle frequencies, the wave speed is mainly controlled by shear deformation within the core [ESI-group,2007]. A softer core with lower shear modulus leads to smaller wave speed. At higher frequencies, the wave speed agrees well to the bending wave speed of the facings. The strain energy of the structure is concentrated in the skins (and associated with separate bending wave propagation in each skin). The sandwich structure shows much larger sound insulation than the laminated one at this stage.

We can find that the curve (c_l/c_s) representing the relative laminated panel wave speed locates between the curves c_b/c_s and c_{bf}/c_s . At low frequencies, c_l/c_s is lower than the relative sandwich structure wave speed c/c_s . However, as the frequency increases, it is higher than c/c_s . This can explain why the laminated cylinder exhibit similar of even better sound insulation than the sandwich cylinder at lower frequencies but show worse sound insulation at higher frequencies. The relative sound speed in air c_a/c_s is also shown in Fig. 3 to determine the coincidence frequency of the two kinds of structures. The coincidence frequency of the laminated panel f_{c1} is lower than that of the sandwich panel f_{c2} . Actually the coincidence frequency of the sandwich panel can be improved by reducing the shear stiffness of the core to make it occur beyond the interested frequency range.

Figure 3 the transverse wave speed in the laminated and the sandwich panels

3. The acoustic excitations

Under the acoustic excitations, the two tested cylinders are the same as those under the mechanical excitations. For the experimental test, the cylinders are assumed to be excited with a diffused acoustic field because the test was conducted in an environment with a high reverberation. This causes the noise level to be nearly the same at different positions. The noise reduction between the pressure outside and the pressure inside at the point $(r=R/2, l=L/2)$ was recorded with two microphones.

For the numerical method, the cylinders are also excited by diffuse acoustic field. However, one

difference from the experimental one is that the characterization of the sound insulation is not noise reduction but the transmission loss (TL). Because the models were analyzed with SEA method, in which the energy within one subsystem is assumed to be equal. The effective Transmission Loss was used to characterize the sound insulation using the following equation [ESI-group,2007]:

$$TL = 10 \log_{10} \left[\frac{A\omega}{8\pi^2 n_1 c_1^2 \eta_2} \left(\frac{E_1}{E_2} - \frac{n_1}{n_2} \right) \right] \quad (3)$$

where A is the junction area, E_1 is the energy of the source cavity, and E_2 is the energy of the receiving cavity. n_1 and n_2 are the mode density in source and receiving cavities respectively. c_1 is the acoustic wave velocity in the source cavity. η_2 is the loss factor in the receiving cavity.

Figure 4 sound insulation of the laminated cylinder and sandwich cylinder

The sound insulation of the sandwich and cylinder under the acoustic excitation is shown in Fig. 4. Similar to the situation under the mechanical excitation, the sandwich cylinder does not show higher transmission loss than the laminated one at low frequencies, while it exhibits a larger transmission loss at higher frequencies. One thing should be noted is that the frequency where the sandwich cylinder shows better sound insulation performance is about 3000 Hz, compared with 800 Hz in the case of mechanical excitation. Moreover, the difference between the sandwich cylinder and the laminated cylinder is less under the acoustic excitation than that under the structural excitation. This may be because the acoustic excitations cause less difference of structural response because of the damping from fluid-structure interaction. In addition, the critical point is equal to the coincidence frequency of the laminated cylinder [Yuan, Bergsma and Beukers,2011]. Therefore, another reason should be that the transmission loss is mainly stiffness-controlled and mass-controlled below the coincidence frequency, and sandwich does not show much advantage in these areas.

4. Conclusion

In both cases of the structural and the acoustical excitation, the sandwich cylinder only shows a larger sound insulation than the laminated cylinder above a threshold. The threshold is 800 Hz for the structural excitation and is 3000 Hz for acoustical excitation. The difference of sound insulation under the structural excitation can be explained by the wave speed theory. The threshold under the acoustical

excitation is equal to the coincidence frequency of the laminated cylinder.

In conclusion, the addition of foam core can improve the sound insulation at both middle and high frequencies under the structural excitation, while it can improve the sound insulation only at high frequencies under the acoustic excitation. In this experiment, compared with the load case of the mechanical excitation, the sandwich cylinder exhibits less advantage than the laminated cylinder under the acoustic excitation. The difference of sound transmission mechanism from a structural-born source and that from an acoustic-born source still needs to be studied in the future.

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