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Physical mechanisms of active control of sound transmission through rib stiffened double-panel structure

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ABSTRACT

This paper presents an analytical investigation on physical mechanisms of actively controlling sound transmission through a rib stiffened double-panel structure using point source in the cavity. The combined modal expansion and vibro-acoustic coupling methods are applied to establish the theoretical model of such active structure. Under the condition of minimizing radiated power of the radiating ribbed plate, the physical mechanisms are interpreted in detail from the point of view of modal couplings similar as that used in existed literatures. Results obtained demonstrate that the rule of sound energy transmission and the physical mechanisms for the rib stiffened double-panel structure are all changed, and affected by the coupling effects of the rib when compared with the analytical results obtained for unribbed double-panel case. By taking the coupling effects of the rib into considerations, the cavity modal suppression and rearrangement mechanisms obtained in existed investigations are modified and supplemented for the ribbed plate case, which gives a clear interpretation for the physical nature involved in the active rib stiffened double-panel structure.

1. Introduction

Thin plates stiffened by a set of beams form a class of structural elements that are widely applied in various engineering applications, such as aircraft or ship fuselage shells, partition walls in ground vehicles and so on. These aerospace and marine vehicles are frequently subjected to uncertain dynamic loads [1], which produces excessive vibration levels in the rib stiffened plates and finally results in very high noise levels in the cabin. Compared with single plate case, the rib stiffened double-panel structure can not only provide good improvement in noise insulation [2] but also strengthen the structural rigidity, and therefore is widely used as classical elements in structural designing stage of the aircraft or ship.

Similar with the case of unribbed double-panel system, the rib stiffened double-panel structure also has superior sound insulation performance in middle and high frequency ranges. However, the performance deteriorates rapidly in the low frequency especially under the mass-air-mass resonant frequency due to the vibro-acoustic coupling [2]. Traditional passive methods of low-frequency noise reduction such as adding the sound absorption or insulation materials require excessive heavy damping material which leads to significant weight penalties and offsets the performance gains. These insufficient aspects have prompted the research into applying active control techniques to improve the sound transmission loss of the

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double-panel structure. Much research work has been conducted and some encouraging investigative contributions have been achieved for the unribbed double-panel structure [3–6]. Similarly it is predictable that the active control technique should also been applied for the ribbed double-plate system to improve its low frequency sound insulation. However, until recently most of the existed literatures mainly contribute to investigation on the active unribbed double-panel structure. And the investigation on ribbed double-panel case is rarely appeared. Since the partition walls of the aircraft or ship are usually the complex structure typically represented by the ribbed plate, the consequential absent understanding of the physical insights of the active rib stiffened double-panel structure finally impede the practical applications of such technique. Hence, this paper is aimed at filling these analytical gaps and understanding the sound insulation performance and physical insights for the active ribbed plate case.

As for the active double-panel system, there basically exist two control strategies for different type of control sources used, i.e., panel control approach [3,5,6] and cavity control approach [4–6]. The panel control approach needs direct force actuations acting on either fuselage shells or interior trim panels. Installation and repair of sensors and actuators in these structures would be extremely difficult, and moreover frequently exciting these structures with large energy forces may cause to structural fatigue [1]. On the contrary, the cavity control approach can avoid these disadvantages and is useful to control broad-band noise or tonal noise with a variable frequency [5]. Therefore it is more suitable for suppressing the cabin noise of the aircraft or ship that is induced by rolling machine or turbulent airflow dynamic loads. The main purpose of this paper is to investigate the physical mechanisms of active control of noise transmission through the rib stiffened double-panel structure using sound sources in the air gap. It is hoped that the preliminary investigative results would offer helps for the ongoing research on optimally designing the system, and constructing the error sensing strategy and so on.

As far as the ribbed plate structure is concerned, many techniques, such as the Rayleigh-Ritz energy method [7], finite difference method [8], transfer matrix method [9], and differential quadrature method [10] have been developed to accurately predict free vibrations of finite ribbed plates (resonant frequencies and modal shapes). Also with the help of high-speed computers, finite element methods (FEM) are extensively applied in nowadays due to their high efficiency and accuracy [11]. These investigations greatly improve the understanding of the vibration characteristics of ribbed plate structure, which provides assistances for preventing high levels of vibration and noise radiation of the ribbed plate in preliminary structural designing process. However, as for the ribbed double-panel structure, there are little investigations on modeling such structure with an air gap cavity. Gardonio [2] uses the transfer impedance and mobility approach to model the ribbed double-plate system with complicated mechanical links. Xin [12] applies the space-harmonic and virtual work principle to solve the sets of resultant governing equations so as to model the orthogonally rib-stiffened double-panel structure. These modeling approaches gain accurate predictions of the system response in a wide frequency range. Recently, Lin [13,14] and Dozio [1] successively introduce the modal expansion method to model the ribbed plate structure, which can simply and accurately predict the vibrating response of the ribbed plate in the low frequency range and also gives a deep interpretation of the coupling effects of the rib and plate. Hence, this model may be have predominance in providing a good understanding of the sound energy transmission, and in exploring the physical mechanisms of active control in the rib stiffened double-panel system. Therefore, this paper firstly establish the theoretical model of the ribbed plate by using the above mentioned modal expansion method, and then applies the vibro-acoustic coupling theory to model the rib stiffened double-panel system as that developed for the unribbed plate case. The couplings between the cavity and the ribbed plate are essentially the couplings between the cavity modes and the modes of the base plate. It is conceivable that the physical mechanisms of active control can also be interpreted from the point of view of modal analysis analogous to that developed for the unribbed double-panel case [4–6]. Though the analytical approach adopted is not novelty, but the physical nature involved in the rib stiffened plate case is largely different from the conclusions summarized for the unribbed plate case [4–6,15] due to the coupling effects of the rib. Single rib stiffened structure is used for the incident and radiating plate, and single point source is also introduced in the air gap to actively improve the energy transmission loss. Such simplified model is used as an example to simplify the complicated structure, which allows the efforts to be concentrated on deeply exploring the active control mechanisms. The physical mechanisms of sound transmission through practical n-ribbed double panels are different from this with just one rib, which leads to pass-band (stop-band) phenomena in the transmission properties [14,16]. Also the harmonic plane wave excitation is a rather idealized type of forcing that is hardly met in practice. The performance of active control highly depends on the number of ribs and their spacing, and on the nature of the excitation. Though these factors moderate the engineering relevance of the research, but the paper is also significative for providing guidance for the future research work related to n-ribbed case.

There usually exist two control mechanisms in the active control of noise transmission through double-panel system when using cavity control approach, i.e., modal suppression and modal rearrangement [4–6,15]. The first mechanism suppresses the cavity modes so as to weaken the radiated power of the radiating plate. The second mechanism tries to rearrange the amplitudes and phases of the cavity modes so as to form the radiating plate as a weak radiator which has a lower overall radiation efficiency. As far as the rib stiffened double-panel structure is concerned, though the sound energy transmission is essentially occurred between the coupled base plate and cavity mode pairs, but the transmission rules is distinctly different from the unribbed plate case and change a lot due to the coupling effects of the rib. The physical mechanisms involved are accordingly changed and can no longer been reasonably interpreted with above phenomenon. Therefore, our primary attentions are firstly put on analyzing the specific rules of sound energy transmission under considerations of the coupling effects of ribs. Then, the modal suppression and rearrangement mechanisms are modified and