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Mechanisms of active control of noise transmission through triple-panel system using single control force on the middle plate

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ABSTRACT

This paper presents an active triple-panel sound insulation structure with an idealized controllable point force acting on the middle plate. A novel analytical approach based on sound energy transmission rule is proposed to achieve the physical mechanism study. The transfer impedance matrix of the incident and middle plate is calculated using numerical approach. And the rule of sound energy transmission through the triple-panel structure is concluded by indirectly analyzing the radiated sound power of the three plates. Finally the physical mechanism of noise insulation is investigated from the point of view of the change in behaviors of energy transmission in controlled and uncontrolled conditions. Results obtained demonstrate that there exist four different energy transmission paths for four panel mode groups. The energy transmission is independent in each path and they are all of band-pass characteristic. The role of the middle plate and two cavities is very similar to the band-pass filter whose pass-band is different for different mode groups. The essence of active noise insulation lies in the fact that the energy transmission in each path is suppressed in its pass-band after control. This greatly improves sound insulation capability of the triple-panel structure and leads to sound propagation being blocked.

1. Introduction

Double-panel structure has superior sound insulation capability and has been widely used in various noise control engineering. Typical examples include aircraft or ship fuselage shells, grazing windows, partition walls in buildings, and so on. The sound insulation performance is better in high and middle frequency, but deteriorates rapidly in low frequency due to vibro-acoustic coupling effects. Traditional methods of low-frequency noise reduction require heavy damping material which leads to significant weight penalties and offsets the performance gains. Hence, active control technique is introduced thereby constituting the active double-panel structure [1–6].

According to type of secondary sources and arrangement locations, the control strategy in existed investigations can be classified into two approaches, i.e., cavity control [1,2] and panel control [2–6]. The cavity control approach can effectively block the noise transmission path and is useful to control broad-band noise or tonal noise with a variable frequency [7]. But arranging bulky sound sources in the air gap is always difficult, which makes the system unimplementable. Though vibration control of skin panel is more efficient than acoustic control for an excitation such as a turbulent boundary layer [8], but there also have some limitations which would impede their practical applications. Incident panel which may be the fuselage shells for the aircraft or ship is usually the heavy structure. Direct force actuation on it requires large amounts of energy and may cause structural fatigue. Also installation and repair of sensors and actuators would be extremely difficult since the fuselage shell is not removable. Direct force actuation on the radiating panel which is usually referred to as the interior trim panel, may lead to the control spillover in the form of significantly increased vibrational energy of this panel. This effect of control on increased sound field close to the panel will go against certain applications such as in aircraft where passengers have to sit close to fuselage trim panels. The active triple-panel structure with controllable point forces acting on the middle plate can effectively eliminate these disadvantages. And the physical characteristics of the middle plate can be designed specially to guarantee it being easily actuated [9].

The physical mechanism study has attracted considerable attention in the field of active control. Exploring the mechanism of noise reduction cannot only provide help for understanding the physical nature inherent in the system, but also offer guidance for system design such as optimal arrangement of secondary sources, implementation of error sensing strategy, and so on. In

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past two decades, much effort has been concentrated on the mechanism study for active control of sound transmission through a double-wall [10,11]. It is well known that there basically exist two mechanisms no matter what type of control strategy is used. For cavity control approach, one mechanism relies on modal suppression of the cavity modes which attenuates cavity sound field. Consequently, this reduces the vibration of the radiating panel. Another involved is the modal rearrangement of cavity modes so as to change vibration pattern of the radiating panel to form a weaker radiator. For panel control approach, there are of similar control mechanisms. The research involved in active structure acoustic control of single plate [12,13] and active control of noise transmission through a panel into a cavity [14,15] also demonstrates these mechanisms.

Usually the two phenomenons coexist. Therefore, the interaction of not only the amplitudes but also the phases of these structural or acoustic modes must be considered to achieve an understanding of noise reduction. And if we consider the power radiated by any one structural mode, we must take into account the amplitudes and phases of all other structural or acoustic modes since they are interdependent. Hence, it is very difficult to gain a clear understanding of how the structural or acoustic modes should be altered to achieve noise reduction. Moreover, the coupling relations for the triple-panel structure will become more complicated after the middle plate is introduced. Therefore, it will make the analytical process incomprehensible if the above two phenomenons are still used here for the triple-panel case.

A more effective method for single plate is using the concept of radiation modes [16]. Upon applying control, the amplitudes of a limited number of the most efficient radiation modes are reduced, which leads to the weakened radiated sound of the plate [17]. Another method is the wave-number approach. The response of the supersonic region in wave number domain, which represents the plate vibration parts that radiates sound into far field, is significantly reduced with control [18,19]. The two approaches are usually introduced to facilitate interpretation of the relationship between the structure response and the corresponding acoustic response of the plate. It may be also valid for the double- or triple-panel case, but can hardly explore the control nature inherent in the energy transmission process. Hence, it will be of limited usefulness. A novel approach exploring the mechanism from the change in behaviors of energy transmission is proposed to make the analytical process clear and intuitive.

Concerned with the research on sound transmission characteristics, the existed literatures have been mainly focused on the sound insulation of double-panel system [20–22], and multiple-layer structure with complicated mechanical links [23,24] or specific boundary conditions [25]. The emphasis was concentrated on the total sound insulation of the system, but the rule of energy transmission occurred in the process is little understanding. However, this will be the necessary preconditions for the mechanism study of the active triple-panel structure and will also be helpful for optimizing various passive control techniques [26,27]. Hence, the emphasis is firstly put on the analysis of the rule of sound energy flow. An indirect approach adopted is to analyze the radiated power of each plate.

Compared with the plate radiating sound into an acoustic free field, the calculation of radiated power for the incident and middle plate is relative complicated since they radiate sound into a rectangular enclosed space. One of effective methods is so called discrete elemental approach [28,29]. It separates the plate into a number of elemental radiators whose dimensions should be much less in comparison to acoustic wavelength corresponded to the upper limit frequency of interest. The total power output is the sum of the net power of all elemental radiators. The main issue encountered for the incident and middle plate is to calculate the transfer impedance matrix. The impedance or mobility matrix functions have been used in [30,31] to express the relation between the forces acting on elements and the corresponding vibration of the plate at center of elements in enclosed space. Referred to this, the numerical approach is introduced to calculate the transfer impedance matrix of the incident and middle plate.

The objective of the paper is to investigate the physical mechanism of the active triple-panel system. The main contribution is the analysis of control mechanism from the view point of energy transmission in a clear and intuitive way. The paper is organized as follows: the theoretical model is established in Section 2. After the transfer impedance matrix is calculated in Section 3, the rule of sound energy flow is investigated as an important part in Section 4. The physical mechanism is analyzed in Section 5. The designing of the middle plate in applications are discussed in Section 6. Finally, concluding remarks are provided in Section 7.

2. Theoretical model

2.1. Vibrational response of the system

Fig. 1(a) shows an active triple-panel sound insulation structure. Its profile is shown in Fig. 1(b). Name the panel **a**, **b**, and **c** as an incident plate, a middle plate and a radiating plate, respectively. Assume that the three plates are simply supported and baffled in an infinite wall. Let l_x and l_y denote the length and wide, respectively. h_a, h_b and h_c are their corresponding thickness. The depths of two cavities are h_1 and h_2, and the medium in the cavity is air with density ρ_0 and sound speed c_0. Except for the three flexible plates, other surrounding walls of the two cavities are all acoustically rigid.

The primary excitation is assumed to be an oblique incident plane wave. In general, the total pressure acting on the incident plate can be decomposed into three parts, i.e., the incident pressure, the reflected pressure when the plate is assumed rigid, and the radiated pressure. The incident and reflected pressure magnitudes can be assumed equal since the impedance of the plate approximates a rigid boundary for air loading. And it was also found that the radiated pressure is rather low compared to the

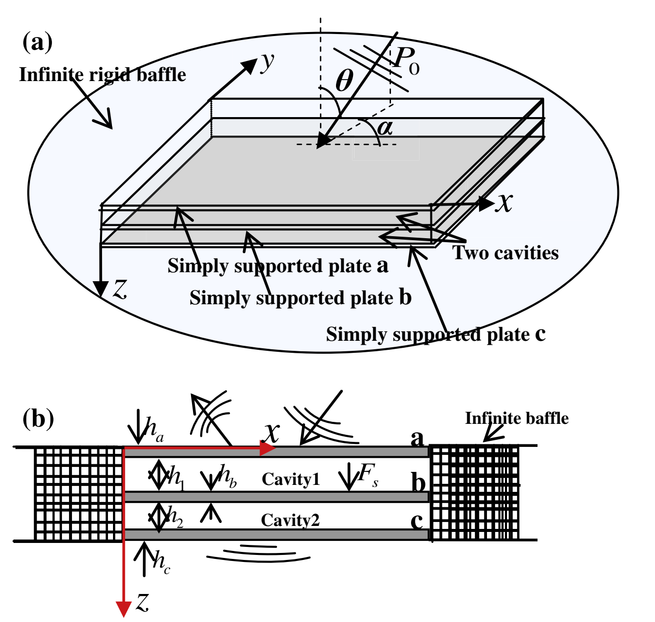

Fig. 1. Systemic model of the active triple-panel structure. (a) Systemic sketch; (b) systemic profile.