优秀博士论文摘要

轻质板壳结构振动与声学耦合特性的理论及实验研究*

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复杂板壳/板腔结构被广泛地用作汽车、高速机车、舰艇/潜艇及航空航天飞行器等外壳及内部隔舱结构,其声振耦合特性研究对降低交通工具舱内外噪声至关重要.在民用及国防工业领域减振降噪应用需求的牵引下,围绕典型板壳/板腔结构在静止流体及平均流流场中的声振耦合问题,通过理论建模、实验验证和数值计算分析相结合的研究方法,对由点激励或外部复杂声场和流场作用下产生的结构弯曲波、声波在板壳结构中的传播行为及结构的动力学响应和声振耦合特性进行了系统深入的研究,并对结构进行了力学性能和声学性能综合优化设计方面的有益探索.主要研究内容及学术贡献如下:

第一,基于声波速度势函数分别建立了简支和固支双板空腔结构声振耦合性能的理论模型.相对于传统的刚性空腔模态函数法,该理论模型精确描述了边界条件对薄板和密封空气腔的约束作用,具有更广泛的适用性.研究发现:空腔厚度显著影响结构的声振耦合性能,结构传声损失曲线波峰波谷随空腔厚度的增大向低频偏移,隔声性能随之增强;低频段有限大结构传声损失大于无限大结构,而高频段无限大结构的传声损失为有限大结构提供了可能的上限;增加板厚能显著加强双板空腔结构的隔声能力;入射声波的俯仰角显著影响结构的隔声性能,而方位角的影响可以忽略.开展实验验证研究,证实了简支和固支理论模型的正确性和可靠性.研究表明,固支双板空腔结构的固有频率高于简支结构;在低频段,两种边界下的结构传声损失差别很大,而在高频段,两种边界下的结构传声损失差别取决于入射声波的俯仰角;可采用声波垂直入射情况下简支板的模态振型近似模拟固支板的模态振型,但在声波斜入射情况下,两种模态振型差别显著.

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(《轻质板壳结构振动与声学耦合特性的理论及实验研究》被评为 2013 年全国优秀博士论文提名论文)

第二,针对有限大简支板在两侧存在平均流情况下的声振耦合问题,建立了相关理论模型并分析研究了平均流对简支板传声损失的影响,该模型通过对流波动方程和流固界面上位移连续性条件的应用考虑了气动弹性耦合效应的影响.不同于以往的研究,该模型可分析研究最一般的情况,即简支板的两侧同时存在平均流,为深入研究分析此类问题奠定了理论基础.研究表明,入射声场中的平均流对传声损失的影响明显不同于透射声场中平均流的影响;声波折射角随入射角和平均流流速变化的等高线图存在两个分支,分别为正折射分支和负折射分支;平均流在透射声场情况下的等高线图与平均流在入射声场情况下的等高线图相比,相当于互换了入射角和折射角坐标系;空气动力学阻尼效应对传声损失的影响在两种情况下均可体现,但是两种情况下的结构吻合共振低谷差别显著:随着 Mach 数的增大,平均流在入射声场情况下的吻合共振频率增大,而平均流在透射声场情况下的吻合共振频率保持不变;板两侧同时存在平均流的情况下,反映折射关系的等高线图明显不同于只有一侧存在平均流的情况.另外,声波顺流入射与逆流入射对板的声振耦合特性影响显著.

第三,针对飞机机身典型的双层板壳结构,考虑了飞机在巡航飞行状态时,外部气流对飞机喷气发动机产生的噪声从舱外传入舱内产生影响的物理过程与物理机理.结合板壳振动理论、对流声学波动方程、Navier-Stokes 方程及流固耦合条件,建立了相关的理论模型,给出了不同 Mach 数下气流速度对结构传声的影响,发现了传声过程出现的 4 种新的声学现象;基于基本物理原理给出了 4 种声学现象对应频率的计算公式,并与基于振动理论、对流声学波动方程及 Navier-Stokes 方程的理论模型计算结果取得良好的吻合.研究表明:(i) 声波顺流入射情况下,结构传声损失随 Mach 数的增加而增大;由于平均流的质量增加效应,使得除吻合共振以外的其它 3 种声学模态共振的频率显著地偏向低频;吻合共振频率增大是因为其主要受平均流折射效应的影响;(ii) 声波逆流入射情况下,随着 Mach 数的增加,除吻合共振以外的其它 3 种声学模态共振频率增大直至 Mach 数达到临界值;当 Mach 数超过临界值后,板-空气-板共振、驻波衰减和驻波共振消失,仅剩吻合共振,同时,结构传声损失随 Mach 数的增加而增大;(iii) 板曲率和舱内压的联合作用对结构传声损失具有显著影响,在曲板环频率共振附近的低频区域表现得尤为明显.

第四,应用空间谐波分析法理论研究了波纹层芯夹层板结构的声振耦合特性,揭示了波纹层芯结构对整体结构隔声能力的影响;同时考察了其频散特性,发现声波在夹层板结构中传播时存在禁带和通带现象,并且传声损失曲线上的波峰和波谷与频散曲线存在内在联系.研究结果主要包括:(i) 声波入射角对夹层板结构的隔声性能具有重要影响,夹层板对垂直面板入射的声波具有最好的隔声效果;(ii) 波纹层芯的结构倾角对三明治夹层板的隔声性能影响显著,即随着波纹层芯结构倾角的增大,结构传声损失 STL 曲线上的所有隔声波峰与隔声波谷均向高频推移,传声损失整体增大,同时传声损失曲线上低频平滑段逐渐向高频扩展;(iii) 对夹层板结构频散特性及传声损失的分析研究,深入揭示了传声损失曲线上出现的波峰波谷的本质的物理机理:即波峰的出现对应于驻波振动而波谷的出现对应于结构波的吻合共振;(iv) 定义了综合力学和声学性能的评价指标,并据此对夹层板结构的质量、力学刚度和隔声能力进行了综合的优化设计.

第五,基于 Fourier 积分变换法和空间谐波分析法,分别建立了正交加筋三明治

夹层板结构的声辐射理论模型和结构传声理论模型.不同于以往的研究,该理论模型通过在面板的振动控制方程中引入加筋板对面板的拉力、弯矩和扭矩及其相应的惯性项,精确描述了加筋板振动对面板的作用.研究表明:(i) 入射声波俯仰角对夹层板结构的传声损失影响显著;斜入射的声波比垂直入射的声波更容易穿透夹层板结构,这是因为斜入射的声波与结构中的弯曲波可以发生相长干涉;(ii) 加筋板惯性效应的引入使理论预测结果捕捉到更多的物理细节,进而更准确地预测结构的声振耦合特性;(iii) 作为夹层板结构周期特性的关键参数,加筋板周期间距对结构声振耦合特性影响显著,即结构的固有频率随周期间距增大而减小,特性曲线上的波峰波谷向低频偏移,但特性曲线总体形状趋势相似.

最后,针对航空航天飞行器中常用到的轻质三明治复合材料夹层板结构,应用等效流体模型模拟声波在多孔纤维吸声材料中的传播,分别建立了层芯空腔填充多孔纤维吸声材料的正交加筋三明治夹层板结构的声辐射理论模型和结构传声理论模型.通过引入材料动态密度和动态体积模量,考虑了声波在纤维材料中传播时空气与纤维间的粘性拖曳力和热交换作用.研究发现,流固耦合效应对结构声辐射/传声有较大影响,而加筋板间距的增大会加剧该影响;纤维材料通过自身的刚度和阻尼损耗效应的共同作用来影响结构的声振耦合特性,而这两种作用的平衡受到结构周期间距的显著影响;提出了综合结构质量、刚度和隔声能力综合性能的夹层板结构优化设计准则,以结构的关键尺寸参数为优化设计变量,对结构进行了初步的优化设计.

总之,在国家民用工业及国防工业减振降噪重大应用需求的牵引下,该文通过理论分析、实验验证和数值计算,研究了汽车、高速机车、舰艇/潜艇及航空航天飞行器中常用典型结构的声振耦合特性,建立了相对完善可靠的结构声振耦合特性理论表征体系,分析了关键结构参数对结构声振耦合特性的影响,揭示了弯曲波在结构中的传播规律及结构的声辐射/传声特性,提出了轻质、高强度、声辐射小及隔声性能优良的复杂板壳结构的创新优化设计概念,建立了综合结构质量、力学刚度和声振耦合特性的优化设计理论和判据,为典型板壳/板腔结构在民用工业及国防工业中的应用奠定了理论基础、实验依据并提供了技术支撑.

关　键　词: 板壳结构; 声振耦合特性; 优化设计; 减振降噪

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Abstract of a 100 Excellent Ph.D. Dissertations Award* (*Nomination*) *of China

Vibration and Acoustic Responses of Lightweight Sandwich Structures: Theoretical and Experimental Investigations

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Lightweight sandwich structures have been increasingly used in a wide range of engineering applications (e.g., automobiles, express trains, ship/submarine hulls and aircraft fuselages), and hence their vibroacoustic characteristics are of paramount importance for interior noise reduction. In the pursuit of vibration and noise reduction in civil and military applications, this dissertation deals with the vibroacoustic problems of lightweight sandwich structures immersed in either static or convected fluid. Specifically, structural wave and sound wave propagation as well as dynamic responses and vibroacoustic performances of these structures are systematically investigated by incorporating theoretical modeling, experimental measurement and numerical simulation. An integrated optimal algorithm toward lightweight, high stiffness and superior sound insulation capability is subsequently proposed, based on which preliminary optimal design of prototype sandwich structures is performed. The contents and contributions of the dissertation are summarized below.

Firstly, built upon the basis of sound velocity potentials, analytical models are separately developed for the transmission of sound across simply supported and clamped double-panel partitions. The proposed models are capable of describing more accurately air cavity coupling than the commonly used method of rigid cavity modal function, thus more applicable for vibroacoustic studies. It is found that the overall vibroacoustic behavior of a double-panel partition can be significantly changed by altering the thickness of the enclosed air cavity, without changing other geometrical dimensions of the structure. The peaks and dips in the STL (sound transmission loss) versus frequency curves shift to low frequencies as the air cavity thickness is increased, resulting in enhanced STL. Within the low frequency range, the STL of a finite structure is higher than that of the corresponding infinite structure, whereas at high frequencies the infinite structure provides an upper bound estimate of STL for finite configurations. Increasing the panel thickness can effectively enhance the sound insulation capability of double-panel structures. Moreover, whilst the elevation angle of the incident sound affects significantly the sound insulation capability of finite double-panel structures, the influence of incident azimuth angle is negligible.

Experimental measurements subsequently are performed to validate the applicability and feasibility of the proposed analytical model, with good overall agreement achieved. It is demonstrated that the natural frequencies of a fully clamped double-panel partition are higher than those of a fully simply supported one. At low frequencies, the STL values exhibit noticeable discrepancies between the two boundary conditions (simply supported versus clamped), while at high frequencies the discrepancies are dependent upon the incident elevation angle. Further, the vibration mode shapes of a simply supported panel can be approximated as those of its clamped counterpart only in the case of normal sound incidence, and dramatic distinctions exist between them in the case of oblique sound incidence.

Secondly, an analytical approach is formulated to account for the effects of mean flow on sound transmission across a simply supported rectangular aeroelastic panel. The application of the convected wave equation and the displacement continuity condition at the fluid-panel interfaces ensures exact handling of the complex aeroelastic coupling between panel vibration and fluid disturbances. Unlike existing theoretical studies, the model is capable of dealing with the general case that the fluids on both sides of the panel are convective, laying hence theoretical basis for further investigation of the issue. It is found that the influence of incident side mean flow upon sound penetration is significantly different from that of transmitted side mean flow. The contour plot of refraction angle versus incident angle for the case when the mean flow is on the transmitted side is just a reverse of that when the mean flow is on the incident side. The effects of aerodynamic damping upon sound transmission are well captured by plotting the STL as a function of frequency for varying Mach numbers. However, as the Mach number is increased, the coincidence dip frequency increases when the flow is on the incident side but remains unchanged when the flow is on the radiating side. In the most general case when the fluids on both sides of the panel are convective, the refraction angular relations are significantly different from those when the fluid on one side of the panel is moving and that on the other side is at rest.

Thirdly, an analytical study is carried out for the transmission of external jet-noise through a double-leaf skin plate of aircraft cabin fuselage in the presence of external mean flow. An aero-acoustic-elastic theoretical model is developed by applying the structural vibration theorem, the convected wave equation, the Navier-Stokes equation and the displacement continuity condition at the fluid-plate interface. Four distinct acoustic phenomena (i.e., mass-air-mass resonance, standing-wave attenuation, standing-wave resonance, and coincidence resonance) for a flat double-leaf plate as well as the ring frequency resonance for a curved double-leaf plate are identified. Independent of the proposed analytical model, simple closed-form formulae for the natural frequencies associated with the above phenomena are derived using physical principles. Excellent agreement between the model predictions and closed-form formulae is achieved. It is demonstrated that: (i) In the case of sound incidence along the downstream direction, as the Mach number is increased, the STL values increase over a broad frequency range and the natural frequencies for the associated acoustic phenomena (except for coincidence resonance) are shifted considerably to lower frequencies, due mainly to the added-mass effects of the mean flow. The exception of the coincidence resonance is attributed to its strong dependence on refraction angle but not on convected fluid loading. (ii) For sound incidence along the upstream direction, the corresponding frequencies increase until the Mach number is increased up to a critical value, except again for the coincidence resonance. Further increase of the Mach number beyond the critical value results in the disappearance of mass-air-mass resonance, standing-wave attenuation and standing-wave resonance, whereas coincidence resonance is always existent. Increasing the Mach number induces a noticeable enhancement of STL due to the total reflection effects. (iii) The combined effects of panel curvature and internal pressurization significantly affect the STL, which are particularly noticeable in the low frequency range adjacent to the ring frequency.

Fourthly, the transmission of sound through all-metallic corrugated core sandwich panels is investigated using the space-harmonic method, with focus placed upon the influence of core topology on STL. The predicted dispersion relation of the structure exhibits the typical pass/stop band phenomena in wave propagation, providing intrinsic physical interpretations for the appearance of various peaks and dips on the STL versus frequency curves. The main conclusions drawn are: (i) Sound incident angle exerts a significant effect on the sound insulation capability of the sandwich structure, with the best sound insulation performance achieved under normal incident sound. (ii) The core topology plays a noticeable role. The STL peaks and dips shift to higher frequencies as the core geometry angle is increased, leading to enhanced STL. (iii) The appearance of STL peaks and dips is attributable to the standing-wave vibration of the face panel and the coincidence resonance of the bending waves, respectively. (iv) By defining an integrated index for evaluating both the structural stiffness and sound insulation capability of the sandwich, optimal structure design can be performed toward lightweight, high stiffness and superior sound insulation.

Fifthly, the sound radiation and transmission characteristics of infinite sandwich structures reinforced by two sets of orthogonal rib-stiffeners are theoretically formulated in terms of Fourier transform technique and space-harmonic approach, respectively. Unlike previous researches on rib-stiffened panels without considering the inertial effects of the rib-stiffeners, the vibration motion of the rib-stiffeners is accurately described by introducing their tensional forces, bending moments and torsional moments as well as the corresponding inertial terms into the governing equations of the face panels. It is established that: (i) Incident elevation angle has a significant effect on the STL of the sandwich, i.e., oblique incident sound transmits through the structure more easily than that of normal incident sound, which may be attributed to the constructive interference between incident sound wave and structural bending waves in the former. (ii) With the inertial effects of the rib-stiffeners accounted for, the model can capture more detailed physical features, thus much helpful for accurately predicting the vibroacoustic characteristics of the structure. (iii) As a key parameter describing the periodic nature of the sandwich, rib-stiffener spacing plays a dominant role. The

natural frequencies of the structure decrease as the spacing is increased and, as a result, the peaks and dips on the characteristic curves are shifted to lower frequencies. Nonetheless, the overall tendency of these curves remains unchanged.

Finally, regarding lightweight composite sandwich structures commonly used in aircraft fuselage constructions, two comprehensive theoretical models are separately developed for sound radiation and sound transmission of infinite orthogonally rib-stiffened sandwiches filled with fibrous sound absorptive material in the partitioned cavities. The process of sound penetration across the fibrous material is characterized by adopting the equivalent fluid model, in which the viscous forces between air and fibers as well as the thermal exchanges are taken into account by introducing two variables, i.e., dynamic density and dynamic bulk modulus. It is found that fluid-structure coupling effect induces remarkable changes of the STL versus frequency curves, especially for relatively large stiffener separations. The fiberglass-filled cavity affects sound penetration via the combined effects of fiberglass stiffness and damping (both frequency dependent), the balance of which is significantly affected by stiffener spacing. As a highlight of this research, an integrated optimal algorithm toward lightweight, high stiffness and superior sound insulation is proposed, based on which preliminary optimal design of prototype sandwich structures is carried out.

In summary, drawn by the important requirement of vibration and noise reduction in civil and military applications, the vibroacoustic characteristics of typical hull (sandwich) structures of automobiles, express trains, ships/submarines, aircrafts and so on are systematically investigated by incorporating theoretical modeling, experimental measurements and numerical simulation. Apart from establishing a relatively rigorous and reliable theoretical system for the vibroacoustic characteristics of typical lightweight sandwich structures, the effects of key structural parameters are systematically quantified and the physical mechanisms underlying the various vibroacoustic phenomena explored. Moreover, an integrated algorithm for optimal structural design toward lightweight, high stiffness and superior sound insulation is proposed. The study paves a solid theoretical and experimental foundation for investigating vibroacoustic problems associated with lightweight sandwich structures and provides useful technical guidance for their practical applications in a wide range of civil and military fields.

Key words: sandwich structures; vibroacoustic characteristics; optimization; noise reduction

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