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The Cremer concept for annular ducts for optimum sound attenuation

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A R T I C L E I N F O

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A B S T R A C T

The noise suppression problems within ducts are widespread in aero engines, gas turbines, blowers and various mufflers. It has been well demonstrated that the Cremer impedance can maximize the propagating damping by degenerating the lowest order mode pair into a single mode, and consequently maximize the sound attenuation in both circular and rectangular ducts, however, the Cremer impedance of annular ducts is still unsettled. Therefore, the Cremer concept is further developed to theoretically optimize the acoustic impedance for annular ducts with two degrees of freedom, i.e. inner and outer liner impedances. Through decoupling successfully the radial wavenumber and impedance, the branch point equations are derived in the presence of grazing flow to solve the triple or double eigenvalues, which can be used to design simultaneously the optimal inner and outer impedances. A parametric study is conducted to investigate the effect of the Helmholtz number (kb), the circumferential mode order (m), the radius ratio (RR) and the liner configurations on the optimum radial wavenumber, Cremer impedance and sound transmission loss (TL). Some conclusions are drawn. First, the double eigenvalue solutions can give optimum impedance under more general conditions than triple eigenvalue solution. At small RR, the solutions of outer wall approximate to Cremer impedance of circular ducts, and at large RR and $m = 0$, the double eigenvalue solutions of both inner and outer walls are identical to Cremer impedance of rectangular ducts with zero transverse mode. Second, with the decrease of kb and the increases of m and RR, the optimum TL exhibits a general tendency of growth. Third, higher TL gain leading by inner liner can be achieved for larger RR and lower m, and whether the inner liner works effectively depends on the sound energy densities near inner and outer walls. Fourth, the RR and kb have larger impacts on the optimum TL than m, thus needing to be given priority to consider in design, the utilization of inner liner needs to comprehensively balance the effectiveness, economical efficiency and the realizability.

1. Introduction

The noise pollution, as indicated in a research [1], may lead to sleeplessness, annoyance, social behavior modification and the impairment of reading comprehension and long-term memory for children, and also has some associations with hypertension and some psychological symptoms. With the growing demand for high-quality living, traveling and working

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environments, the noise emission and suppression problems become common social subjects, forcing the stricter controls of noise pollution sources especially in various industrial fields. In aviation industry, the international civil aviation organization (ICAO) upgraded continuously the noise level standard since the first standard of the chapter 2 adopted in 1972, and the latest version of chapter 14 [2] will fully come into effect in 2020 and further lower the allowable cumulative noise level by at least 7 dB on the basis of the current standard. In automobile industry, the European Union began implementing a new strict regulation in 2016, it stipulates that the permissible sound levels of motor vehicles are required to gradually reduce to 68 dB from 74 dB of the prior standard [3] before 2026 for midsize cars, and to 79 dB from 81 dB for heavy trucks with over 12 tons load. In addition, the gas turbines employed in power plants, the blower used in wind tunnel, and the aeroacoustic wind tunnel itself and so on also have more and more stringent requirements of noise emission.

All of these noise problems listed above can be partly considered in terms of the duct acoustics, and transformed into the sound attenuation problem through acoustic treatment within ducts. For a modern commercial airplane, the high bypass-ratio turbofan engines, whose noise can typically reach up to the sound pressure levels of 155 dB [4], are major contributors of noise radiation, thereby needing to be given more sufficient concerns. A usual strategy is to utilize acoustic nacelles to suppress the noise within acoustically treated engine ducts [5–8]. In motor vehicles, the exhaust pipe is usually designed as a dissipative muffler [9] to absorb the internal combustion engines noise, one of the main sound sources for automobiles. For the excellent designs of aeroacoustic wind tunnels, the duct walls of fan section and collector, the turning vanes, and all sound reflecting surfaces should be acoustically treated to minimize the background noise [10,11].

For a locally reacting acoustic surface, the boundary is usually characterized by a complex frequency-domain quantity of acoustic impedance at a single sound frequency, which is defined as the ratio of the sound pressure to the local normal acoustic particle velocity. Therefore, the first step of acoustic treatment designs is just to obtain the optimum impedance to maximize the sound attenuation, thus necessitating the efficient design methods of impedance. Subsequently, the sound absorbing constructs is designed to match as closely as possible the optimum impedance for desired frequencies in the second step. The optimum impedance design methods are the subject in this paper, which can be classified into two types in the terms of the optimizing way, i.e. a category of iterative searching methods and the Cremer theoretical method. Currently, the impedance iterative searching methods [12,13] are a class of widely used methods, the methods exhaustively search the optimal impedance in a process of maximizing the objective function, which is usually the acoustic energy transmission loss (*TL*) of a certain mode or combination of modes propagating through a lined duct section with a certain length, when the objective function reaches numerically maximum value, the corresponding impedance is regarded as the optimal acoustic impedance. The methods are suitable for the impedance designs for actual complex geometry and flow conditions, however, there are some inevitable drawbacks in these methods. First, it necessitates a sound propagation model, such as the finite element method (FEM) numerical model [14], mode matching method (MMM) [15], the multimodal propagation method (MMPM) [16,17] and the transfer element method (TEM) [18] analytical models and so on, to solve the sound field in every iteration of impedance, thereby being fairly time-consuming especially in high frequency range. Second, the method is quite sensitive to the selection of initial value, because inappropriate initial impedance can usually lead to locally rather than globally optimal solution. Therefore, the searching method sometimes fails to bring about maximum noise reduction. On the other hand, Cremer [19] proposed another impedance design concept from the perspective of theoretical optimization, referred as the Cremer's concept for optimum attenuation or the Cremer concept for brevity, which can design theoretically the optimal acoustic impedance for a uniform duct with infinite local-reacting liners for a certain incident acoustic mode. In the original Cremer concept, the first derivative of the eigen equation is put to zero in order to create a double root for the eigenvalue and maximize the sound attenuation of the lowest order mode pair. In the present study, the Cremer concept is extended to more general cases. For determining the optimum impedance, the branch point equations are first derived from the eigen equation and its first (j-1)-order partial derivatives, through which the first j modes merge into a j-repeated mode (eigenvalue) and the imaginary part of axial wavenumber of the first-order mode is simultaneously decreased as much as possible, thereby nearly maximizing the sound attenuation, the corresponding impedance is nearly optimum. The value of j depends on the number of lined boundaries with undetermined impedance to be designed and the strategy adopted in design using the Cremer concept. Particularly, $j = 2$ in the prior study by Cremer [19]. Its principle will be further elaborated in Sec. 2.1. The limitation of the Cremer concept is obvious that it cannot be directly used in the design of variable-section or short silencers, since it is derived for the sound propagation in an infinite duct, i.e., no effect of inlet and outlet reflections for the lined duct is considered. However, several advantages of Cremer concept can be taken in the design of silencers. First, such a theoretical design method can fast give the optimal impedance and nearly maximum noise attenuation for uniform lined ducts with relatively large dimensionless length. Second, the Cremer concept has inherent advantage in the parametric research of various factors on the duct sound attenuation due to its high efficiency, which can give beneficial suggestions for the design of silencers. Third, the Cremer concept can provide the initial impedance for the iterative searching method, and their combination can increase the efficiency of the optimization process greatly and circumvent the blind selection of initial value of impedance, in addition, the theoretical optimal impedance and TL can be taken as reference for the searching optimization [20].

Chronologically, Cremer [19] first derived the optimal impedance for rectangular ducts for the lowest mode pair in the absence of flow in 1953. Two decades later, out of the demands of the noise control for aero engines, Tester [21,22] extended the Cremer concept to circular ducts for an arbitrary circumferential mode, and uniform grazing flow is introduced to obtain the high frequency asymptotic solutions under the 'well-cut-on' assumption. In order to extend the Cremer concept to small-scale ducts and low frequency range, such as automobile exhausts, in 2016, Kabral et al. [23,24] further derived the "exact"