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High frequency multimode radiation from ducts with flow

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Multimode sound radiation from hard-walled semi-infinite ducts with uniform subsonic flow is investigated theoretically. An analytic expression, valid in the high frequency limit, is derived for the multimode directivity function in the forward arc for a general family of mode distribution functions. The multimode directivity depends on the amplitude and directivity function of each individual mode. The amplitude of each mode is expressed as a function of cut-off ratio for a uniform distribution of incoherent monopoles, a uniform distribution of incoherent axial dipoles and for equal power per mode. The modes' directivity functions are obtained analytically by applying a Lorentz transformation to the zero flow solution. The analytic formula for the multimode directivity with flow is derived assuming total transmission of power at the open-end of the duct. This formula is compared to the exact numerical result for an unflanged duct, computed utilizing a Wiener–Hopf solution. The agreement is shown to be excellent.

I. Introduction

Background: Duct power estimation from limited far-field data

Various common noise sources radiate sound into finite length ducts containing a uniform mean flow, from which the sound escapes into the far field via radiation from an unbaffled open end. Examples are exhaust mufflers, large exhaust stacks, and aircraft turbofan engines. Often one wishes to determine the sound power radiated from the duct opening, either as an index of insertion loss in order to assess silencer performance, or as a means of quantifying and ranking the total noise output for predicting community annoyance. The sound power may, in principle, be determined by integrating the normal component of sound intensity over a surface enclosing the duct exit at a large distance from the duct where the flow is quiescent. However, sometimes not all measurement locations required to perform the integration are easily accessible, as in the case of large exhaust stacks which may be tens of meters high. In this example, the only measurements which are easy to make are close to the ground, corresponding to the rear-arc or backward-radiated sound radiated at angles approaching 180° to the duct axis. It is clear that a method of inferring the radiated power, at any frequency, from a small number of far-field mean square pressure measurements would be extremely useful to the noise control engineer.

Scope of investigation

This paper presents a theoretical and numerical study of the non-dimensional directivity factor $Q(ka, \theta)$ for multimode sound radiation from the open end of a semi-infinite duct, in the presence of a uniform mean flow. This paper extends earlier work by the second author of this paper in which the effects of flow were neglected.[1] The directivity factor relates the mean square far-field pressure, at any polar angle θ to the duct axis including the rear arc, and at any flow Mach number, to the net sound power transmitted along the duct. The non-dimensional frequency ka equals $2\pi fa/c$, where f is the frequency, a is the duct radius, and c is

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