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Acoustic source reconstruction and visualization based on acoustic radiation modes

Jiawei Liu [a], Yangfan Liu [b], J. Stuart Bolton [b, *]

[a] *Cummins Inc, Cummins Technical Center, 1900 McKinley Avenue, Columbus, IN, 47201-6414, USA*
[b] *Ray W. Herrick Laboratories, School of Mechanical Engineering, Purdue University, 177 S. Russell Street, West Lafayette, IN, 47907-2099, USA*

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ABSTRACT

Fourier-based Nearfield Acoustical Holography (NAH), Statistically Optimized Nearfield Acoustical Holography (SONAH) and the Equivalent Source Method (ESM) are widely used in noise source identification and as important tools to guide design modification for noise control purposes. Fourier transform-based NAH requires the sound field to fall to negligible levels outside the measurement aperture, which is a requirement that is rarely met in practice. To overcome this difficulty, SONAH and ESM have been developed. In addition, the Inverse Boundary Element Method (IBEM) can also be used, given sufficient computational resources. Unfortunately, none of these methods can directly guide the design modifications required to unequivocally reduce noise radiation from sources. Previously, radiation mode analysis has been primarily associated with the forward prediction of sound power radiated from noise sources. Since radiation modes contribute independently to the sound power radiation, it is only necessary to modify the surface vibration so that it is not strongly coupled with those modes having high radiation efficiencies in order to ensure sound power reduction. In the current work, an inverse method based on radiation modes was investigated, in which the radiation modes were used as the basis functions to describe surface motion of a source. Thus, this procedure allows the surface vibration that results in the majority of the radiated sound power to be identified unequivocally, and so will, in turn, guide the design changes needed to reduce radiated sound power.

1. Introduction

In the field of inverse acoustics, current practices can generally be divided into two categories, non-modal-based and modal-based methods. The main difference between these two categories is whether a certain type of mode of the source surface (such as structural modes, etc.) is used as the basis functions to represent the total sound field. In the non-modal-based category, Fourier transform-based Nearfield Acoustical Holography (NAH), Statistically Optimized Nearfield Acoustical Holography (SONAH), and the Equivalent Source Method (ESM) are three widely implemented methods. Conventional NAH is based on the discrete spatial Fourier transform of the sound pressure field measured at a microphone array. Ideally, the microphone array should extend well beyond the measured object so that the sound pressure is small at the edges of the microphone array, so that leakage effects in the discrete Fourier transform are not significant [1]. Unfortunately, in industrial

* Corresponding author.
E-mail address: bolton@purdue.edu (J.S. Bolton).

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applications, the measured objects are usually larger than the microphone array, which makes it impossible to avoid the leakage problem. To circumvent that disadvantage of Fourier-based NAH, Statistically Optimized Nearfield Acoustical Holography (SONAH) was developed [2]. The planar SONAH procedure avoids the direct implementation of the spatial Fourier transform by using a transfer matrix approach which is only dependent on the relative locations of the measurement plane and the reconstruction plane. More specifically, the sound pressure at a reconstruction location is obtained as a linear combination of the measured sound pressures with the weightings chosen so that the prediction achieves the best average estimate among all basis functions. The Equivalent Source Method (ESM) is another method which was developed to minimize the errors in traditional NAH. In the classical ESM, the sound field is assumed to be generated by a series of low order simple sources, with fixed locations, and then the source strengths can be calculated by inverting the system matrix relating the equivalent source strengths to the measured sound pressures [3]. Recent developments of the ESM involve the use of non-collocated higher-order multipoles as the basis functions which can reduce the number of equivalent sources needed to describe an actual sound field [4–6]. The Inverse Boundary Element Method (IBEM) [7] can also be treated as a variant of the traditional ESM since the Green's function and its derivative in the BEM formulation can be interpreted as a layer of monopoles and dipoles, respectively, sitting on the vibrating surface.

Having briefly reviewed the non-modal-based approaches, here a modal-based inverse acoustical method is proposed which involves utilizing acoustic radiation modes as the basis functions to describe the sound field. Since the acoustic radiation modes are a set of velocity distributions that radiate sound power independently [8], this procedure can easily be used to identify how a reduction in surface vibration at particular locations on the source surface will affect the radiated sound power, and thus can guide how to make design modifications for noise control purposes. However, NAH based on this approach is computationally more intensive than the classical ESM, since it usually first requires the construction of a Boundary Element model of the source object, in order to obtain the acoustic radiation modes.

In this paper, the fundamentals of radiation modes are first reviewed in Section 2 before describing their implementation in an inverse procedure. The requirement to apply appropriate regularization treatment is emphasized and an iterative procedure to eliminate non-contributing radiation modes from the basis set is also described. Finally, the proposed procedure was applied in two case studies as described in Section 3, one a simulation of sound radiation from a flat vibrating panel, and the other involving the visualization of sound radiation from a loudspeaker. In both instances, good reconstruction results were obtained.

2. Formulation of inverse acoustical method by using radiation modes

This section is divided into three parts. In Section 2.1, the formulation of acoustic radiation modes by using the elementary radiator approach is reviewed. Though acoustic radiation mode calculations can also be based on structural modes, the formulation derived from elementary radiators is usually simpler, and can be easily performed by using computational techniques such as the Boundary Element Method (BEM). The proposed inverse acoustical method is described in Section 2.2. The need for appropriate regularization methods in the inverse calculation is discussed in Section 2.3.

2.1. Formulation of acoustic radiation modes

A planar vibrating surface is considered here first. The surface is meshed into small elements, and each element is assumed to have a constant normal velocity, $\widetilde{v}_{eN}$, and a constant sound pressure, $\widetilde{p}_{eN}$, so that each element is radiating a sound power of

$$\overline{P}_{eN} = \frac{1}{2}A_{eN}\mathrm{Re}\left\{\widetilde{v}^*_{eN}\widetilde{p}_{eN}\right\}, \tag{1}$$

where A_{eN} is the area of the N^{th} element. The total sound power radiated by this vibrating surface is then a sum of the sound powers radiated by all the elements. The total sound power is expressed most compactly as:

$$\overline{P}(\omega) = \frac{S}{2M}\mathrm{Re}\left(\{\widetilde{\mathbf{v}}_e\}^{\mathrm{H}}\{\widetilde{\mathbf{p}}_e\}\right), \tag{2}$$

where the notation {} is used to indicate a vector quantity, and the superscript H denotes the Hermitian transpose. Here, S is the total source area and M is the total number of elements (and here it is assumed that all the elements have the same area). With the help of the discretized Rayleigh Integral, the sound pressure can be expressed, when using index notation, as

$$\widetilde{p}_{ei} = \frac{\mathrm{j}\rho_0\omega A_e \mathrm{e}^{-\mathrm{j}kr_{ij}}}{2\pi r_{ij}}\widetilde{v}_{ej}, \tag{3}$$

where r_{ij} is the distance between the ith and jth elements. Thus, the sound pressure vector on the surface can be expressed as

$$\{\widetilde{\mathbf{p}}_e\} = \left[\widetilde{\mathbf{Z}}\right]\{\widetilde{\mathbf{v}}_e\}, \tag{4}$$

where the notation [] also represents a matrix quantity; the components of $[\widetilde{\mathbf{Z}}]$ are expressed as: $\widetilde{Z}_{ij} = \frac{\mathrm{j}\rho_0\omega A_e}{2\pi r_{ij}}e^{-\mathrm{j}kr_{ij}}$. The substitution of Eq. (4) into Eq. (2) then yields: