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Sound power radiation from a vibrating structure in terms of structure-dependent radiation modes

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ABSTRACT

As a good supplement of conventional acoustic radiation modes (a-modes), a set of so-called "structure-dependent radiation modes" (s-modes) is introduced to describe the sound power radiation from a vibrating structure. Differing from a-modes, s-modes are determined by not only the acoustic resistance matrix of the structure but also the frequency-independent normal modes of the structure. Such a new definition has the following main advantages over the conventional one: (1) it can reflect directly the influences of dynamic properties (e.g., boundary conditions) of the structures on its sound power radiation; (2) the number of s-modes generated is generally less than that of a-modes since the former depends on the number of structural modes involved in the vibration while the latter depends on the number of segmented elemental radiators of the structure, and consequently, the demand for large data storage can be greatly alleviated, especially for large structures and/or higher frequency vibrations; (3) the set of s-modes possesses a better convergence than that of a-modes because the higher ordered s-modes can decay more rapidly than the same ordered a-modes. Two baffled, finite, models, i.e., a simple beam and a thin plate, are employed to investigate numerically the acoustic properties of s-modes, and then compared with those of a-modes. It has been shown that the two sets of radiation modes share a very similar frequency-dependent behavior in that the radiation efficiency falls off very rapidly with increasing mode order at low frequency range (typically with $kl < 1$). Meanwhile, the number of s-modes required to describe the total sound power radiation is found to be the same as that of a-modes. Consequently, an appropriate truncation of a-modes can be achieved by using the number of vibrational modes involved. Nevertheless, the odd-ordered (even-ordered) s-modes are found only associated with the odd-numbered (even-ordered) structural modes. In case of only few of the s-modes dominating, each s-mode tends to be largely affected either by the same ordered structural mode for a non-resonant frequency or by the resonant mode for a resonant frequency. As a result, the coupling relations between the dominating radiation modes and the associated structural modes can be revealed explicitly. In general, s-modes are recommended to be used to describe the sound power radiation from a vibrating structure whose geometry sizes are much larger than the acoustic wavelength, should its structural modes and the associated modal amplitudes have been somehow obtained.

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1. Introduction

Acoustic radiation modes (a-modes) are defined through an eigenfunction or eigenvalue decomposition of the radiation operator, in which each a-mode represents a particular velocity pattern on the surface of the radiator, while the associated eigenvalue is directly proportional to the radiation efficiency of that radiation mode [1–3]. In the past decades a-mode approaches have been extensively studied and widely used both in academic and in engineering, mainly for acoustic radiation prediction, active noise control, source re-construction, acoustic design optimization, etc., e.g., in Refs. [4–16] and references thereafter. Overviews of these early developments and applications can be found in Ref. [17]. However, since a-modes, from their definition, are strictly only functions of geometry of the structure and frequency of interest but independent of the dynamic characteristics of the structures, the a-mode description is found to be unsatisfactory on revealing the inner-relationship between the sound radiation modes and the structural modes [12]. Meanwhile, since the number of a-modes depends on the number of elemental radiators, it usually demands huge data storage for large scale structures, especially at higher frequencies [17,18]. It would be desirable if a new set of radiation modes can be formed which can help to alleviate the above two main application issues of the existing a-mode techniques [19].

It is known that the forms of the radiation modes depend on how the surface velocity is represented [4,5]. For instance, if the surface velocities are represented in terms of the velocity amplitudes of structural modes rather than the velocity amplitudes of a number of elements, the acoustic modes can be re-formed as superposition of the structural modes [4–6]. Such a re-formulation of acoustic modes thus provides a direct link between the modes in vibration and the modes in radiation for a vibrating structure and, at the same time, provides a great potential for acoustic modal reduction.

With these in mind, a similar re-formulating technique as adopted in [4] is used in the present study to generate a new set of independent radiation modes in terms of a set of uncoupled, modal velocity distributions. To distinguish from the conventional acoustic radiation modes (a-modes) which were given in terms of a set of independent velocity distributions, these new radiation modes are named “structure-dependent radiation modes” (s-modes). The acoustic properties of s-modes are then discussed and compared with those of a-modes both theoretically and numerically. The potential advantages of s-modes over a-modes are highlighted.

In the contents below, the definition of a-modes is first reviewed in Section 2. It is then re-formulated to generate a set of s-modes in Section 3, together with a theoretical comparison with a-modes. Numerical examples are presented in Section 4 on two types of baffled, finite structures, i.e., a beam (1-dimensional) and a thin plate (2-dimensional). The main acoustic modal properties as well as some other interesting aspects of s-modes are illustrated.

2. Conventional acoustic radiation modes of a vibrating structure: theoretical review

The concept of acoustic radiation modes (a-modes) of a structure has been clearly introduced in [1]. It is briefly reviewed here for the readiness of the reader.

For a vibrating structure, the radiated sound power can be expressed in the formulation of the amplitudes of an array of elemental radiators, as

$$W = \frac{S}{2}\mathrm{Re}\{\mathbf{v}^H \mathbf{p}\} \tag{1}$$

where $\mathbf{v}$ is the vector of complex linear velocities of each of these elemental sources at a single frequency, the superscript H represents the Hermitian transpose, $\mathbf{p}$ is the resultant complex acoustic pressure, and S is the area of the elementary radiators which are assumed to be of equal size for convenience. Note that Eq. (1) can be readily extended to more general cases where the elements may be of different areas [1–3], provided each element size is small enough so that each element can be simply treated as vibrating entirely in phase, i.e., as a small piston [4,5].

The acoustic pressure vector and the velocity vector are related with each other by

$$\mathbf{p} = \mathbf{Z}\mathbf{v} \tag{2}$$

where $\mathbf{Z}$ is a matrix of acoustic impedances which is symmetrical and independent of the physical properties of the structure but its geometrical size.

Substituting Eq. (2) into Eq. (1), the radiated power from the vibrating surface of a structure can therefore be written as

$$W = \frac{S}{2}\mathrm{Re}\{\mathbf{v}^H \mathbf{Z}\mathbf{v}\} = \mathbf{v}^H \mathbf{R}\mathbf{v} \tag{3}$$

where $\mathbf{R} = (S/2)\mathrm{Re}\{\mathbf{Z}\}$. It is seen from Eq. (3) that $\mathbf{R}$ is real, symmetrical and positive definite, and proportional to the radiation resistance matrix for the elemental radiators. $\mathbf{R}$, of course, is also independent of the physical properties of the structure. Eigen-decompose $\mathbf{R}$ as

$$\mathbf{R} = \mathbf{Q}^H \mathbf{\Lambda} \mathbf{Q} \tag{4}$$

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