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Prediction of acoustic radiation from functionally graded shells of revolution in light and heavy fluids

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ABSTRACT

This paper presents a semi-analytical method for the vibro-acoustic analysis of a functionally graded shell of revolution immersed in an infinite light or heavy fluid. The structural model of the shell is formulated on the basis of a modified variational method combined with a multi-segment technique, whereas a spectral Kirchhoff–Helmholtz integral formulation is employed to model the exterior fluid field. The material properties of the shell are estimated by using the Voigt's rule of mixture and the Mori–Tanaka's homogenization scheme. Displacement and sound pressure variables of each segment are expanded in the form of a mixed series using Fourier series and Chebyshev orthogonal polynomials. A set of collocation nodes distributed over the roots of Chebyshev polynomials are employed to establish the algebraic system of the acoustic integral equations, and the non-uniqueness solution is eliminated using a combined Helmholtz integral equation formulation. Loosely and strongly coupled schemes are implemented for the structure-acoustic interaction problem of a functionally graded shell immersed in a light and heavy fluid, respectively. The present method provides a flexible way to account for the individual contributions of circumferential wave modes to the vibration and acoustic responses of functionally graded shells of revolution in an analytical manner. Numerical tests are presented for sound radiation problems of spherical, cylindrical, conical and coupled shells. The individual contributions of the circumferential modes to the radiated sound pressure and sound power of functionally graded shells are observed. Effects of the material profile on the sound radiation of the shells are also investigated.

1. Introduction

Functionally graded materials (FGMs) comprise a new class of composite materials in which the material properties vary continuously as a function of position along certain dimension(s) to achieve a required functional performance [1]. This can be achieved by gradually changing the volume fraction of the constituent materials. In recently years, shells of revolution made of FGMs have been utilized in a variety of engineering applications due to their mechanical merits and structural efficiencies. Rocket nozzles, missiles, gas pipelines, spacecraft heat shields and pressure vessels are practical examples of such structures. FGM shells are commonly used in dynamic environments, and the effects of vibro-acoustic behavior of the shells on the performance of the structures are of considerable importance. However, the basic problem of sound radiation

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from FGM shells of revolution when excited by mechanical forces, has not been thoroughly investigated. What is needed is a general numerical method that can be used to predict the characteristics of the sound field radiated by a FGM shell of revolution immersed in a light or heavy fluid.

The theory of sound radiation from a vibrating structure has been developed extensively as a part of classical acoustics, and the basic principles are well explained in textbooks such as Junger and Feit [2], Fahy and Gardonio [3], Ohayon and Soize [4]. For the sound radiation problem of elastic shells, the acoustic field is directly coupled to the vibration of the shells. The coupling is characterized by the strength of the influence between the shell and the acoustic field. For a high acoustic impedance mismatch between the shell and fluid, the structural and the acoustic problem can be solved subsequently one after the other. This is a weak coupling scheme since the radiation loading exerted by the fluid may be small enough to have a negligible effect on the shell vibrations. The simulation of the sound radiation of an elastic shell surrounded by a light fluid (e.g., air) is a typical example where a weak coupling is applied. In contrast to this, for the prediction of the sound radiation from an elastic shell totally submerged in a heavy fluid (e.g., water), a strong coupling scheme has to be applied, since the feedback of the radiation loading can no longer be neglected. Hence the structural and acoustic problems must be solved simultaneously. The literature concerning the sound radiation of FGM shells in light or heavy compressible fluids is rather limited, though considerable attention has been paid to the acoustic problems of elastic shells made of conventional metal materials. Analytical solutions to the sound radiation problems of elastic shells are mostly concerned with spherical or infinite cylindrical geometries for which the classical method of separation of variables is available. Important results from the application of analytical methods to the sound radiation problems of elastic cylindrical and spherical shells have been described in Stepanishen [5], Fuller [6], Burroughs [7], Lauchle [8], Gaunaurd and Werby [9], and Caresta and Kessissoglou [10]. The non-uniformly distributed material property of FGM shells implies that the well-established analytical vibro-acoustic models for shells made of conventional materials must be re-worked to a certain extent to include the material heterogeneity of FGM shells. Daneshjou et al. [11] presented an analytical solution for acoustic transmission through an infinitely long FGM cylindrical shell using a third-order shear deformation shell theory. The scattering of plane acoustic waves by a hollow FGM cylinder submerged in and filled with compressible fluids was examined by Hasheminejad and Rajabi [12]. The cylinder was approximated by a laminate model, for which the solution is expected to gradually approach the exact one as the number of layers increases. Jamali et al. [13] performed a wave function expansion for the analysis of scattering and radiation force caused by a plane wave incident upon a thick FGM cylindrical shell immersed in and filled with compressible ideal fluids. Hasheminejad and Ahamdi-Savadkoohi [14] investigated the sound radiation characteristics of an arbitrarily thick hollow FGM cylinder of infinite length subjected to concentrated mechanical excitations. The linear three-dimensional elasticity theory in conjunction with the transfer matrix method was employed for the structural modeling of the cylinder. Later, Hasheminejad and Alaei-Varnosfaderani [15,16] examined the sound radiation and scattering characteristics of an infinitely long FGM circular cylinder coupled with an inner or outer layer of functionally graded piezoceramic material. Hasheminejad et al. [17] developed an analytical model for predicting the acoustic radiation from a FGM spherical shell suspended in and filled with fluids. It should be noted, however, that the practical FGM shells rarely match true spherical and infinite cylindrical configurations, and even when they do the calculations are difficult because of the complexity of the Hankel and Bessel wave functions. Moreover, the successful implement of an analytical method to the sound radiation problem of FGM shells is restricted to the type of external exciting forces and boundary conditions. Consequently, for the vibro-acoustic problem of an arbitrarily shaped FGM shell of revolution subjected to complex mechanical excitation forces, numerical methods are more desirable than analytical schemes.

Much previous research has been directed towards the development of numerical methods for vibro-acoustic analysis of elastic structures. Useful information on these methods can be found in Marburg and Nolte [18], Ohayon and Soize [19], and Ciskowski and Brebbia [20]. For the exterior sound radiation of an elastic structure immersed in an unbounded fluid medium, the coupled finite element/boundary element method is probably the most practical approach, in which the dynamic behavior of the structure is described by the finite element method (FEM), whereas the boundary element method (BEM) is used to represent the acoustic loading acting on the structure. The interface conditions imposed on the surface between the structure and the fluid are the continuity of normal velocities and the sound pressure acting as a loading on the structural surface. The FEM is recognized as a general approximation method for complex structures, whereas for the acoustic modeling, the BEM has the advantage that all discretization and numerical approximations are placed on the surface of a vibrating structure. Moreover, when the fluid is of an infinite extent, the outgoing radiation condition at infinity is automatically satisfied in the BEM [3]. However, the finite element models of FGM shells have not yet been coupled with the BEM to address the problem of determining the acoustic responses of FGM shells. Instead, most of the previous investigations are limited to the application of the coupled FEM/BEM to acoustic problems of conventional metal shells. Practically, two- or three-dimensional (3D) finite elements and 2D boundary elements can be used to discretize the shell and the acoustic boundary to achieve reasonably accurate results. The use of such elements as a means of obtaining a numerical solution to the acoustic radiation problem of elastic shells has been investigated by Everstine and Henderson [21], Jeans and Mathews [22], and Chen and Liu [23], to name a few. However, the drawback of these elements is that they generally lead to a system of equations with a large number of unknowns, and may not offer a clear physical insight into the vibration and acoustic behavior of the shells. Peters et al. [24,25] developed a modal decomposition technique to analyze the individual modal contributions to the sound power radiated from a structure submerged in a heavy fluid by using fluid-loaded structural modes based on the coupled FEM/BEM. An alternative way is to expand the shell displacement and pressure variables by means of a Fourier series in the circumferential direction. Such a treatment leads to 1D semi-analytical

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