



A simplified approach for predicting interaction between flexible structures and acoustic enclosures



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ARTICLE INFO

Keywords:

Acoustoelasticity
Acoustic–structure interaction
Coupled mode theory
Eigenvalue veering
Acoustic enclosures

ABSTRACT

The natural frequencies of acoustic–structure systems can be approximated by a closed-form expression that accounts for the interaction between two uncoupled component modes: a given structural mode and the acoustic mode with which it couples most strongly. This expression requires spatial integration of the component mode shapes. In practice, the effort to determine the component mode shapes and compute the necessary integrals negates the simplicity afforded by the closed-form expression. Here, with the use of coupled mode theory, a new nondimensional expression for the coupled natural frequencies is derived. The derivation includes the definition of a new dimensionless number that quantifies the natural propensity of two component modes to couple, irrespective of the enclosure size or the fluid and structural properties. Values of this dimensionless number are presented for common geometries and boundary conditions. With these values, approximations of the coupled natural frequencies can be calculated by hand without explicit knowledge of the component mode shapes or their spatial integrals. The accuracy of these hand calculations is shown for two common acoustic–structure systems: a plate coupled to a rectangular air-filled enclosure and a cylindrical shell containing water.

1. Introduction

Acoustic–structure interaction refers to the dynamic interplay between acoustic pressure fields and flexible structures. Given the ubiquity of acoustic media and their inevitable contact with natural or man-made structures, it is not surprising that acoustic–structure interaction is relevant to the dynamic analysis of many physical systems. When air is the fluid of interest, it is often convenient and accurate to solve the acoustic and structural problems independently (i.e., neglecting any mutual influence between the acoustic fluid and the structure). This strategy involves formulating the acoustic problem under the assumption that any adjacent structure is perfectly rigid. The corresponding structural dynamic problem is then solved by treating the structure as though it were in a vacuum.

While classical acoustic and vibration analysis treats the acoustic and structural problems independently, there are a host of common scenarios in which this strategy is not appropriate. Such cases arise when the fluid of interest is dense or when the structure is highly flexible. In these situations, the fluid and the structure influence each other in a non-negligible manner, and it may be necessary to solve the acoustic and structure problems simultaneously. Excellent introductions to problems of this nature can be found in the texts of [Junger and Feit \(1993\)](#) and [Fahy \(1985\)](#). Classes of problems that may require an acoustic–structure interaction approach are numerous; here, the focus is on the dynamics of structures in contact with an enclosed acoustic fluid, referred to here as *acoustoelasticity* ([Dowell et al., 1977](#); [Dowell and Tang, 2003](#)). (This is not to be confused with the *acoustoelastic effect*, a term

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<http://dx.doi.org/10.1016/j.jfluidstructs.2017.02.003>

Received 19 July 2016; Received in revised form 16 November 2016; Accepted 9 February 2017

Available online 17 February 2017

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Nomenclature

A_F	area of fluid–structure interface	V	shell volume of fluid cavity
a_0	radius of shell from origin to middle surface	W	width of rectangular enclosure
a_j	acoustic modal coordinate	w	displacement of structure in normal direction
c_0	acoustic speed of sound	x, y, z	Cartesian coordinates
$D_{1,2}, D_{1,2}^*$	modal coordinates in coupled mode form	Y_{n_α}	n_α th-order Neumann function
E	Young's modulus	α	scaling parameter
$d_{0,1,2}$	coefficients of shell characteristic equation	$\alpha_{n_\alpha p_\alpha}$	roots of characteristic equation for rigid cylindrical duct
F_j	acoustic normal mode	β_{jk}	coupling strength parameter
g	system equation coefficients in coupled mode form	Γ	radial variation of rigid wall acoustic mode in an annulus
G_k	structural normal mode	Δ	dimensionless component frequency separation
H	height of rectangular enclosure	δ_{n_α}	= 1 if $n_\alpha = 0$, = 0 otherwise
h	thickness of plate	η_{ijk}	energy transfer factor
J_{n_α}	n_α th-order Bessel function	ϵ	= 1 if subscript= 0, = 2 otherwise
$k_{n_\alpha p_\alpha}$	roots of characteristic equation for rigid annular cavity	$\lambda_{n_\alpha p_\alpha}$	$= \pi^2 \left(n_s^2 + m_s^2 \left(\frac{W}{H} \right)^2 \right)$
L	length of rectangular enclosure	$\kappa_{1,2}$	dimensionless separation between coupled and uncoupled natural frequencies
L_{jk}	coupling coefficient	ϕ	fluid velocity potential
ℓ	cylindrical shell length	Ψ	dimensionless coupling parameter
M_j, M_k	acoustic, structural modal normalization factor	ρ, ρ_s	density of structure per unit volume, per unit area
$m_\alpha, n_\alpha, p_\alpha$	acoustic wavenumber indices	ρ_0	density of fluid per unit volume
m_s, n_s	structural wavenumber indices	ν	Poisson's ratio
q_k	structural modal coordinate	$\overline{\Omega}$	cylindrical shell frequency parameter
R_i	inner radius of cylindrical shell or annulus	$\omega_{c1,2}$	coupled natural frequencies
R_o	outer radius of annulus	ω_j, ω_k	uncoupled natural frequency of cavity, structure
r, θ, z	cylindrical coordinates		
t	time		
u, v	axial, circumferential displacement of cylindrical		

used to describe changes in wave velocity in elastic structures due to static stress fields.)

Many existing acoustoelasticity studies present a theoretical framework followed by results corresponding to systems with specific geometry, material, and fluid characteristics. While it is possible to draw upon these studies to make qualitative observations on the nature of acoustoelastic coupling, their results are generally not suitable for direct or broad application. These studies can be used to implement a numerical algorithm that solves a particular problem of interest, but such an effort may not be efficient for the practicing engineer attempting to perform a preliminary design or troubleshoot a failing component. In these time-critical situations, it may be similarly impractical to employ discretization techniques. While the ability of commercial finite element software to model acoustoelasticity problems has advanced considerably, setting up and verifying a working model is not trivial. Further, the acoustic–structure coupling inherent to these problems typically requires the solution of unsymmetric eigenvalue problems, which can be computationally expensive for models with a moderate or high number of degrees of freedom.

Given these difficulties, there is a need for approximate techniques that can be used to quickly assess the extent to which a structure couples to an adjacent acoustic cavity. Here, a theoretical framework to make these assessments is presented. The approach begins by modifying the acoustoelastic equations of motion to consider two component modes: a single structural mode of interest and the acoustic mode with which it couples most strongly. The modified equations of motion lead to a closed-form expression that can be used to approximate coupled natural frequencies. This expression, which has been reported elsewhere (Fahy, 1985), can be cumbersome to implement because it requires spatial integration of the component mode shapes. By writing the model equations in their so-called *coupled mode form* (Louisell, 1960), and invoking an approximation known as the *weak coupling assumption*, a new approximate acoustoelastic natural frequency expression can be derived. This expression can then be cast in a simple nondimensional form that provides insight into the fundamental nature of acoustic–structure coupling. The nondimensional expression includes the definition of a new dimensionless number quantifying the natural propensity of a structural mode to couple with a given acoustic mode, irrespective of cavity size, fluid properties, or structural properties. Values of this dimensionless number are calculated for common geometries and boundary conditions. With these values, approximations of the acoustoelastic natural frequencies can be calculated by hand without the need to compute integrals. This approach is attractive to practitioners wishing to quickly determine the importance of acoustic–structure interaction before implementing a more rigorous analysis. The presented approach can also be used to perform parametric studies or design optimization analyses that are too computationally expensive via any other method. Another advantage of the approach is the physical insight it affords the analyst, thus providing a means by which to perform physics-based checks on complex models.

The remainder of this paper is organized as follows: Section 2 discusses relevant previous work in the areas of acoustoelasticity and coupled mode theory. Section 3 derives two approximate closed-form expressions for the coupled natural frequencies of an

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