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Discrepancy on the free vibration of laminated composite plates coupled to a compressible and incompressible fluid domain

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ABSTRACT

This paper examines the free vibration of laminated composite plates in contact with a water-filled cavity. The fluid compressibility is considered in the analysis. The main objective is to evaluate the natural frequencies of the plate-fluid coupled system, compare the results with those obtained assuming an incompressible fluid domain, and examine the influence of the laminate stacking sequence. Classical and refined plate theories are considered in a compact manner. The Ritz method is used to obtain approximations of the kinetic and potential energy of both the fluid and the plate. The accuracy of the formulation is demonstrated by comparing the results to 3D finite element solutions obtained via commercial software. Parametric studies are carried out to examine the influence of the geometry, lamination angles and boundary conditions on the natural frequencies and the error incurred due to neglecting fluid compressibility. The error is higher when thick, stiff plates with rigid supports are considered. The effect of the fluid domain depth on the natural frequencies depends on the symmetric or antisymmetric nature of the mode shape. The orientation of the laminas becomes highly relevant when rectangular plates with mixed supports are considered.

1. Introduction

The dynamic response of structures in contact with fluid can be very different from the response in vacuum. This is because the fluid adds inertia to the system, reducing the natural frequencies of the system. In order to avoid resonance phenomena, an accurate analysis with hydrodynamic-structural coupling is required. Many approaches have been used for this purpose, varying from analytical to semi-analytical methods as well as the finite element method. While finite element models can deal with arbitrary geometries, analytical methods are more appropriate for performing parametric studies and obtaining insight in the problem.

The vibration of structures coupled to a fluid domain has been studied considering various geometries and physical assumptions. The hydroelastic vibration of circular plates has been analyzed considering an incompressible fluid domain (Jeong et al., 2009) and a compressible fluid domain (Jeong and Kim, 2005), as well as asymmetric conditions (Tariverdilo et al., 2013). A study of the vibration of annular plates coupled to a compressible fluid domain has been presented by Jeong (2006). The vibration of cylindrical (Askari and Jeong, 2010; Thinh and Nguyen, 2016; Paak et al., 2014; Alijani and Amabili, 2014) and conical (Rahmanian et al., 2016; Kerboua et al., 2010) structures in contact with fluid has been studied considering shell kinematic assumptions. Using various simplifications, it is possible to introduce viscosity in an analytical hydroelastic model, as presented by Phan et al. (2013), Atkinson et al. (Atkinson and Manrique de Lara, 2007) and Kozlovsky (2009). A finite element approach using 2D plate elements has been developed by Kerboua et al. (2008) and Bermudez et al. (2001). The hydroelastic vibration of rectangular plates using the velocity potential and classical plate theory was presented by Cheng and Zhou (Cheung and Zhou, 2000). This approach has been extended in order to consider plate stiffeners (Cho et al., 2015), fluid compressibility (Liao and Ma, 2016), plates in elastic foundations and with in-plane loads (Hashemi et al., 2010a, 2010b; Shahbaztabar and Ranji, 2016), and geometric non-linearity combined with sloshing effects (Khorshid and Farhadi, 2013). The frequency response of plates in contact with a fluid domain and subjected to excitation forces has been presented by Cho et al. (Seung Cho et al., 2015).

Most of the references about the hydroelastic vibration of plates consider the Kirchhoff plate theory (also known as the classical plate theory) or the Mindlin plate theory (also known as the first-order deformation theory) due to simplicity and low computational cost.

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Nomenclature

a,b	Plate length and width
c,d	Length and width of fluid domain
c_0	Speed of sound in the fluid
C_{ij}	Constitutive matrix coefficients
D	Flexural rigidity of the plate
$\mathbf{D}_p$,$\mathbf{D}_{np}$,$\mathbf{D}_{nz}$	Linear differential operators
e	Depth of fluid domain
E	Young's moduli
$\mathbf{F}$	Fluid mass matrix
$\mathbf{F}_{\tau sij}$	Fluid mass nucleus
F_τ	Plate thickness expansion function
h	Plate thickness
$\mathbf{K}$	Stiffness matrix
$\mathbf{K}_{\tau sij}$	Stiffness nucleus
j	Imaginary unit
$\mathbf{J}$	Jacobian matrix
k	Wavenumber
M	Ritz expansion order
$\mathbf{M}$	Solid mass matrix
$\mathbf{M}_{\tau sij}$	Solid mass nucleus
N	CUF Expansion order
p,q	Indexes of trigonometric terms in x and y directions
P	Polynomial degree of Ritz expansion
Q_W	Total fluid energy
t	Time
T	Kinetic energy of plate
T_W	Kinetic energy of fluid
u,v,w	Plate displacements in x,y,z coordinates
$\mathbf{u}$	Plate displacement vector
$\bar{\mathbf{u}}$	Plate amplitude displacement vector
U	Potential energy of plate
U_W	Potential energy of the fluid
W	Amplitude of plate deflection in z coordinate
x,y,z	Coordinates of plate
$\tilde{x}$,$\tilde{y}$,$\tilde{z}$	Coordinates of fluid domain
X, Y, Z	Assumed solutions of the velocity potential in $\tilde{x}$,$\tilde{y}$,$\tilde{z}$ axes
$\boldsymbol{\varepsilon}_n$,$\boldsymbol{\varepsilon}_p$	Vector of in-plane and out-of-plane strain components
φ	Velocity potential
Φ	Amplitude of the velocity potential
Γ_P,Γ_W	Plate and fluid area in the bottom
ν	Poisson's ratio
ρ, ρ_W	Density of structure and fluid
$\boldsymbol{\sigma}_n$,$\boldsymbol{\sigma}_p$	Vector of in-plane and out-of-plane stress components
ω	Frequency of vibration
Ω	Fluid domain
ξ, η	Non-dimensional x and y coordinates of plate
$\tilde{\xi}$,$\tilde{\eta}$,$\tilde{\zeta}$	Non-dimensional $\tilde{x}$,$\tilde{y}$,$\tilde{z}$ coordinates of fluid domain
ψ_u,ψ_v,ψ_w	Ritz shape functions of the plate displacements u,v,w
$\boldsymbol{\Psi}$	Ritz shape functions matrix
∇	Del operator

However, more accurate results can be obtained by using higher order shear deformation theories (HSDTs), albeit at a higher computational cost. The analysis of composite plates using an isogeometric analysis and HSDTs is presented in Refs. (Thai et al., 2013, 2014, 2016). While many different HSDTs can be proposed and developed, a compact formulation is preferable, allowing the user to obtain a theory of arbitrary order according to the accuracy desired. The Carrera Unified Formulation (CUF) is a formulation that condenses classical and refined plate theories in a compact manner using index notation. This formulation is capable of reaching an accuracy similar to that obtained via 3D analysis, while retaining the computational efficiency of 1D and 2D models. The formulation was presented by Carrera (2003), and has been applied for thermal stress analysis of plates (Carrera, 2002, 2005; Robaldo et al., 2005), multifield problems (Carrera et al., 2007, 2008a, 2009; Robaldo et al., 2006), analysis of structures with functionally graded materials (Carrera et al., 2008b), and shell geometries (Cinefra et al., 2012, 2013). The displacements are interpolated in the thickness direction with either simple polynomials or more complex functions, as presented in Refs. (Carrera et al., 2013; Filippi et al., 2016). The formulation is presented in detail in Refs. (Carrera et al., 2011a, 2011b, 2014).

In order to obtain approximations of the displacement variables, the Ritz method is popular due to the capability of considering arbitrary boundary conditions, while having lower computational cost than a 2D finite element model. The fundamentals of the Ritz method is described in detail in Refs. (Leissa, 2005; Gander and Wanner, 2012; Ilanko et al., 2014). The accuracy of this method is highly dependent on the choice of shape functions used. The dry modes of the structure are a common choice for the mode shapes, although the addition of the fluid may change considerable the mode shapes (Kwon et al., 2013) and consequently compromise the convergence characteristics of the method. Within the framework of CUF, trigonometric shape functions have been used by Fazzolari and Carrera, 2011, 2013a, 2013b, 2014 for the analysis of simply supported plates. Shell geometries have also been considered in Refs. (Fazzolari, 2016; Fazzolari and Banerjee, 2014; Fazzolari and Carrera, 2013c). Plates with arbitrary boundary conditions can be analyzed using polynomial shape functions, as presented by Dozio, 2010, 2011a, 2011b, 2013, Vescovini and Dozio (2016), and in the work by Dozio and Carrera (2011).

While the compressibility of liquids is often neglected, the error incurred due to this assumption may not be justified in all the cases. Some examples where the error between incompressible and compressible fluid theory is considerable in the vibration of isotropic plates in contact with a fluid domain have been presented in Refs (Jeong and Kim, 2005). and (Liao and Ma, 2016). However, a study of laminated plates coupled to a compressible fluid domain is currently not available in the literature, nor is there assessment of the error due to fluid incompressibility assumptions. Recently, the authors have used the compact formulation known as CUF to perform an accurate hydroelastic vibrational analysis of laminated plates considering incompressible fluid theory (Canales and Mantari, 2017). In the present work, the model developed previously is extended in order to consider fluid compressibility,

The novelties of the present work are as follows:

- The natural frequencies of a laminated composite plate coupled to a compressible fluid domain are presented for a variety of arrangements.
- The error due to the fluid incompressibility assumption in the vibration of laminated plates coupled to a fluid domain is assessed, considering various stacking sequences.

The accuracy of the formulation when compared with 3D solutions is demonstrated in the comparison study. Afterwards, parametric studies are done in order to evaluate the influence of various geometric and material parameters.

2. Analytical modeling

2.1. Preliminaries

A rectangular plate with length a, width b and thickness h is