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An assessment of fluid compressibility influence on the natural frequencies of a submerged plate via unified formulation

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ABSTRACT

Fluid compressibility of liquids is often neglected in engineering design. However, the error incurred due to this simplification is not well identified. This paper examines the influence of compressibility on the hydroelastic vibration of plates in contact with fluid. An analytical solution for the free vibration of thick rectangular isotropic plates coupled with a bounded compressible inviscid fluid domain is developed. Plate displacement theories with arbitrary order are considered using the 2D Carrera Unified Formulation, which can obtain results very similar to 3D solutions. The eigenvalue problem is obtained by considering the kinetic and potential energy of both the fluid and the plate. The displacement variables are evaluated using the Ritz method. A comparison of the results with open literature and 3D finite element software is performed. Parametric studies are carried out in order to assess the error due to neglecting fluid compressibility as a function of plate geometry, material properties and boundary conditions. The influence of fluid domain size, density and sonic velocity is also assessed. The results indicate that the error due to neglecting fluid compressibility is high when thick, square plates made of light, stiff materials and with rigid boundary conditions are considered.

1. Introduction

The analysis of fluid-structure interaction is very important in many engineering applications such as ships and structures containing fluid. The vibrational behavior of plates in contact with fluid differ considerably from the behavior in vacuum, so an accurate mathematical modeling is required in order to fully understand the mechanical problem and avoid the resonance phenomena. In this kind of problems, the analysis is complex since a coupled hydrodynamic and structural solution is required. Finite element solutions are capable of dealing with this problem, but the high computational cost inhibits its use for preliminary design. Semi-analytical methods help in understanding the interaction problem, and provide accurate results with a low computational cost, being adequate for the analysis of a large number of cases.

The analysis of a plate in contact with a fluid domain has been studied by many researchers. Vibration of circular plates has been analyzed considering an incompressible fluid domain (Jeong et al., 2009), a compressible fluid domain (Jeong and Kim, 2005), and asymmetric conditions (Tariverdilo et al., 2013). Viscosity has been introduced in the analysis by Phan et al. (2013), (Atkinson and Manrique de Lara, 2007). and (Kozlovsky, 2009). Finite element models using 2D plate elements are capable of dealing with arbitrary geometries, and have been developed by Kerboua et al. (2008) and Bermudez et al. (2001). Closed-form solutions considering incompressible fluid and Mindlin plates have been obtained by Hashemi et al. (2012). Hydroelastic analysis considering added mass factors has been investigated by Kwak and Kim (1991), and in the paper by Kwak (1996). Analysis of the modal energy associated with the fluid and the plate has been developed by Gorman and Horacek (2007). Magnetic plates in contact with fluid have been studied by Chang (2013), and in the work by Chang and Liu (2009). Experimental results of vibrational behavior of structures in contact with fluid can be found in Refs. (Carra et al., 2013; Kwon et al., 2013; Stenius et al., 2016). Vibrational analysis of shells containing fluid has been developed for 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) geometries. Analysis of annular plates coupled to a compressible fluid domain has been analyzed by Jeong (2006).

Hydroelastic analysis of rectangular plates using the velocity potential and Kirchhoff plate theory was presented by Cheng and Zhou (Cheung and Zhou, 2000). This model has been further developed in order to consider Mindlin plate theory and 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

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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
$\overline{\mathbf{u}}$	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
$\overline{\omega}$	Non-dimensional 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
$\mathbf{\Psi}$	Ritz shape functions matrix
∇	Del operator

Ranji, 2016), excitation forces (Seung Cho et al., 2015) and geometric non-linearity combined with sloshing effects (Khorshid and Farhadi, 2013). The vibrational behavior of multiple plates in contact with fluid has been developed by Jeong and Kang (2013), being applicable for the analysis of fuel assemblies in a reactor.

In the literature review, almost all the references model the plate displacement using either the Kirchhoff plate theory or Mindlin plate theory. However, more accurate results can be obtained by using higher order shear deformation theories (HSDTs). Other possibilities exist, such as the use of a modified Mindlin plate theory (Senjanović et al., 2014). In order to develop analytical models for a HSDT of arbitrary order, the Carrera Unified Formulation (CUF) is of great help. This formulation is known to obtain results similar to those obtained via 3D finite element analysis, while retaining the computational efficiency of 1D and 2D models. The formulation was presented by Carrera (2003), and has been applied for the analysis of thermal stresses in plates (Carrera, 2002, 2005; Robaldo et al., 2005), multifield problems, (Carrera et al., 2007, 2008a, 2009; Robaldo et al., 2006), functionally graded materials (Carrera et al., 2008b), and shells (Cinefra et al., 2012, 2013). Functions used to interpolate the displacements in the thickness direction can be either simple polynomials or more complex functions, as presented in Refs. (Carrera et al., 2013; Filippi et al., 2016). A detailed description of the formulation is given in Refs. (Carrera et al., 2011a, 2011b, 2014).

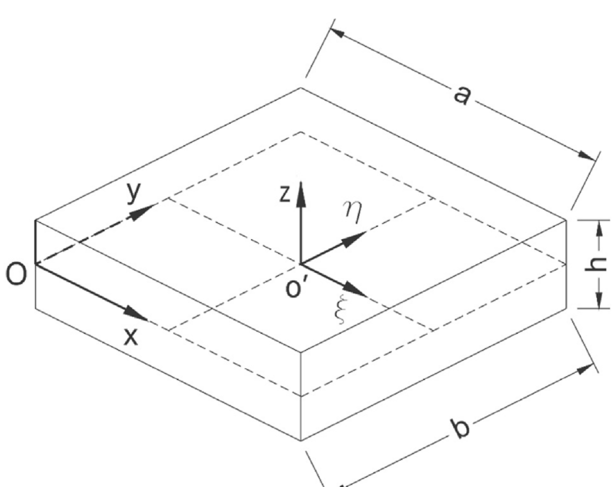

Fig. 1. Coordinate frame of the plate.

In order to approximate the displacement field of the plate, the Ritz method is often used due to its flexibility in the choice of the boundary conditions and low computational cost. Another common approach, the finite element method, is not only computationally expensive but also suffers from a phenomenon known as shear locking, in which a slow convergence is observed when thin plates are analyzed. Reduced and selective-reduced integration procedures have proven to be effective at dealing with shear locking (Zienkiewicz et al., 1971; Hughes et al., 1978; Hughes, 1980). However, these techniques are known to produce spurious energy modes. On the other hand, if high-order interpolation functions are used in the Ritz method, the influence of the shear locking phenomenon is greatly reduced. The fundamentals of the Ritz method is described in Refs. (Leissa, 2005; Gander and Wanner, 2012; Ilanko et al., 2014). It is well known that the accuracy and stability of the results is greatly dependent on the shape functions used. Trigonometric shape functions have been used by Fazzolari and Carrera (2013a; 2011; 2014; 2013b) in order to analyze simply supported plates. Analysis of shells has also developed, as given in Refs. (Fazzolari, 2016; Fazzolari and Banerjee, 2014; Fazzolari and Carrera, 2013c). Using polynomial shape functions, free vibration analysis of plates arbitrary boundary conditions has been developed by Dozio (2013; 2011a; 2011b; 2010), Vescovini and Dozio (2016), and in the work by Dozio and Carrera (2011).

The compressibility of liquids is often neglected, and the error incurred due to this simplification on the hydroelastic vibration of plates is not well identified. Refs. (Jeong and Kim, 2005) and (Liao and Ma, 2016) show that a significant discrepancy between incompressible and