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Hydroelastic analysis of two degree of freedom hydrofoil using a reduced-order hydrodynamic model considering unsteady partial sheet cavity flows

S.M. Alavi, H. Haddadpour [*], R.D. Firouz-Abadi

Department of Aerospace Engineering, Sharif University of Technology, Tehran, 11115-8639, Iran

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ABSTRACT

In the present study a new, fast, precise algorithm for studying hydroelastic stability of a typical section with two degrees of freedom (2DOF) is proposed based on the finite element method (FEM), while the partial sheet cavitation effects are considered. For this means, the steady cavity boundary is calculated by some conventional iterative procedures, developed based on the potential flow simulation. Thereafter, assuming that the amplitude and the frequency of the body oscillations are altered so that the cavity length in unsteady flow remains unchanged, the simulation of the unsteady hydrodynamic flow is performed by imposing some velocity fluctuations over the rigid cavity boundary. For the next step, according to the modal analysis of this model, the hydrodynamic eigen modes, which are employed to construct governing hydrodynamic system of equations, are calculated. Using this model along with the structural model the governing hydroelastic set of equations are introduced. According to this simulation approach, numerous calculations are preformed over the considered hydrofoil and the effects of various parameters including the cavitation number, initial angle of attack and structural parameters such as the elastic axis location, radius of gyration, static unbalance, structure to fluid density ratio, and the frequency ratio, over the stability range are surveyed and some conclusions are outlined.

1. Introduction

Aero-elastic stability analysis of different aerospace structures is one of the most common and significant problems in the aerospace engineering field (Zhao, 2009; Firouz-Abadi et al., 2013; Li et al., 2017). A similar instability might happen to a marine structure, known as the hydroelastic instability. However, this challenge was considered of a less importance due to high strength and relatively low velocity involved in marine structures. The recent tendency towards structural weight reduction followed by a reduced strength, as well as increased velocity achieved by advances in technology, have brought the need for such studies in the marine area (Akcabay and Young, 2014). Also, it should be noted that the higher density of the water compared to air can amplify the significance of hydroelastic evaluations. Accordingly, the hydroelastic analysis of a structure with two degrees of freedom 2DOF is aimed at this study. For this means, the mutual effects of fluid/structure should be considered and a profit model for dynamic simulation of each medium has to be chosen and developed. Finally, the resulted governing system of equations are solved simultaneously to evaluate the stability boundaries. On this basis, simple and efficient mass and stiffness model is carried out for simulation of 2DOF structural model, while obtaining the hydrodynamic equations are more complicated due to the cavitation phenomenon.

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[*] Corresponding author.
E-mail addresses: SM_Alavi@ae.sharif.ir (S.M. Alavi), Haddadpour@sharif.edu (H. Haddadpour), firouzabadi@sharif.edu (R.D. Firouz-Abadi).

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Nomenclature

a	Elastic axis location
b	Half chord length
dl	Element length
h	Hydrofoil longitudinal displacement
I_{ea}	Hydrofoil's moment of inertia along the elastic axis
k_θ	Hydrofoil torsion stiffness
k_h	Hydrofoil plunging stiffness
m	Hydrofoil's mass
p_∞	Far field pressure
p_v	Vapor pressure
r_α	Dimensionless radius of gyration
S_b	Hydrofoil wetted area
V_0	Steady flow velocity
V_n	Perpendicular components of the flow velocity
V_s	Tangential components of the flow velocity
C_a	Cavitation numbers
N_i and $\bar{N}_i$	2D and 1D shape functions
S_∞	Far field boundary
S_w^L	Lower wake surface
S_w^U	Upper wake surface
x_α	Dimensionless static unbalance
$\mathbf{X}$	Matrix whose columns contain the right hydrodynamic eigenvectors
$\mathbf{c}$	Generalized coordinate vector
$\mathbf{I}$	Identity matrix
$\mathbf{r}$	Position vector of each point over the hydrofoil from the elastic axis
$\mathbf{f}_a$	Generalized force vectors
$\mathbf{n}^{(0)}$	Undeformed normal vector
η	Cavity thickness
$\hat{\phi}$	Perturbation potential
Λ	Diagonal matrix containing the eigenvalues of the generalized hydrodynamic eigenvalue problem
μ	Density ratio
ω_α	Torsion frequency
ω_h	Bending frequency
ϕ	Flow potential
ρ	Density of the fluid
σ	Uncoupled bending–torsion frequency ratio
θ	Hydrofoil twist-angle displacement along the Elastic axis
$\hat{\phi}_c$	Perturbation potential on the cavity boundary
ϕ_0	Uniform potential
2DOF	2 Degree Of Freedom
CFD	Computational Fluid Dynamics
FEM	Finite Element Method

Cavitation usually takes place at high Reynolds numbers, where the inertia effect is large compared to the viscous effects. One of the most common approach for study of the cavitation flow is the usage of computational fluid dynamics (CFD), which may impose a high time penalty along the simulation process. Moreover, according to the nature of the problem, stabilizing the computation process is difficult in such methods. An alternative solution is to apply the potential flow approaches. Literature review confirms that, the flow outside the cavity boundary can be assumed non-viscous, incompressible, and irrotational with a good accuracy, which is identical with the potential flow assumptions (Nouri and Eslamdoost, 2009; Kinnas et al., 2003; Kinnas and Fine, 1993a). The critical point in this solution is the cavity boundary. Researchers tend to define two kinematic and dynamic boundary conditions, which assure the tangency of the fluid flow vector to the cavity boundary and equality of the pressure over boundary with the water vapor, respectively, in an iterative solution to find the cavity surface. For this aim, a vast domain of numerical solutions including the linear (Tulin, 1963; Fabula, 1962; Kinnas, 1985), partially non-linear (Kinnas and Fine, 1993a; Vaz, 2005), and fully non-linear (Dang, 2001; Vaz, 2005) approaches have been proposed for the problem. However and in general, the solution process is so that either the cavity length or the cavitation number (Kinnas and Fine, 1993b) is defined, and another parameter is altered so that all the boundary conditions over the cavity boundary are satisfied and the convergence condition, which commonly is the zero thickness at the cavity end, is satisfied.