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Experimental investigation of added mass effects on a hydrofoil under cavitation conditions

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ABSTRACT

The influence of leading edge sheet cavitation and supercavitation on the added mass effects experienced by a 2-D NACA0009 truncated hydrofoil has been experimentally investigated in a hydrodynamic tunnel. A non-intrusive excitation and measuring system based on piezoelectric patches mounted on the hydrofoil surface was used to determine the natural frequencies of the fluid–structure system. The appropriate hydrodynamic conditions were selected to generate a range of stable partial cavities of various sizes and also to minimize the effects of other sources of flow noise and vibrations. The main tests were performed for different sigma values under a constant flow velocity of 14 m/s and for incident angles of both 1° and 2°. Additionally, a series of experiments in which the hydrofoil was submerged in air, partially and completely submerged in still water and without cavitation at 7 and 14 m/s were also performed. The maximum added mass effect occurs with still water. When cavitation appears, the added mass decreases because the cavity length is increased, and the added mass is minimum for supercavitation. A linear correlation is found between the added mass coefficients and the entrained mass that accounts for the mean density of the cavity, its dimensions and its location relative to the specific mode shape deformation.

1. Introduction

The prediction of the dynamic behavior of a structure during its design phase is a key issue. The calculation of modal parameters such as natural frequencies and mode shapes is necessary to anticipate its response to an external dynamic load. An extensive body of academic literature addresses the topics of theoretical, experimental and computational approximations to the dynamic response of solid bodies with multiple configurations. Blevins (1979) summarized many of the most important formulas and principles used in this field.

If a solid structure is partially or completely submerged in a high-density fluid, its dynamic response will differ from its response in vacuum (Blevins, 1979; Brennen, 1982). This phenomenon is due to the added mass effect, which is a result of the inertia of the surrounding fluid entrained by the accelerating structure. This phenomenon has been widely investigated for various solid configurations in air and in both fully and partially submerged in water.

Abbreviations: FFT, Fast Fourier transform; FSI, fluid structure interaction; JTFA, Joint Time Frequency Analysis; PZT, lead zirconate titanate; STFT, Short Time Fourier transform

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Nomenclature

A	constant [N]
A_{fluid}	added mass [kg]
B	constant [N]
B_{fluid}	added damping [kg/s]
C	profile chord length [m]
C	structural damping matrix [kg/s]
C_M	added mass coefficient $=(f_{\mathrm{vacuum}_i}/f_{\mathrm{fluid}_i})^2-1$
CSR	cavitation surface ratio = cavity surface/profile surface
$\overline{d}$	mean displacement [m]
D	diameter [m]
EM	entrained mass $\mathrm{EM}_i=m_i/\Delta Y_{\max\, i}=\sum_j \overline{\rho}_j(\dot{d}_j \mathrm{AREA}_j)$
f	fundamental frequency [Hz]
f_1	first natural frequency
f_2	second natural frequency
f_3	third natural frequency
F	force applied by the entrained fluid [N]
k_i	modal stiffness [N/m]
K	stiffness matrix [N/m]
l	cavity length [m]
L	total number of samples
M	mass matrix [kg]
m_i	modal mass [kg]
N	number of nodes
P_∞	upstream pressure [Pa]
P_v	vapor pressure [Pa]
R^2	coefficient of determination [dimensionless]
t	time [s]
V	flow velocity [m/s]
x, y	function coordinates
X_o	amplitude of vibration in a given direction [m]
y	volume [m^3]
Y	displacement in vertical direction [m]

Greek symbols

ρ	fluid density [kg/m^3]
ω	fundamental frequency [rad/s]
ϑ	kinematic viscosity [m^2/s]
σ	sigma value$=P_\infty-P_v/(1/2\rho V^2)$
α	void fraction$=y_v/(y_v+y_l)$
$\overline{\rho}$	mean density [kg/m^3]$=\rho_v\alpha+\rho_l(1-\alpha)$

Subscripts

air	quantity measured in air
fluid	quantity measured in a generic fluid
half wetted	quantity measured in a structure partially submerged in water
i	mode shape
j	node number
k	sample number
l	quantity measured in liquid phase
max	maximum value
v	quantity measured in vapor phase
vacuum	quantity measured in vacuum
water	quantity measured in water

A study was performed by Lindholm et al. (1965) on cantilever beams both in air and submerged in water. Experimental results with natural frequencies showed reasonably good agreement with plate theory approximations. Consequently, empirical correction factors were obtained for the added mass taking into account the aspect and thickness ratios of the beams. Sewall et al. (1983) successfully compared experimental and analytical data related to the vibration frequency of the fundamental mode of a three-sided membrane in air. They also found that the added mass effect on a cylinder was overestimated when using the same analytical method. More recently, Kimber et al. (2009) studied the interaction between two cantilever structures vibrating in air for various configurations. They verified that resonance frequencies and aerodynamic damping depend on the vibrating phase difference between the plates.

Furthermore, several analytical models have been built to carefully analyze the dependency of the added mass effect on various parameters. For example, Blevins (1979) determined that the added mass of a structure vibrating in a still fluid is essentially a function of the geometry of its surface, its relative position to the boundary conditions, the amplitude and direction of its vibration and a Reynolds-like coefficient as shown in the following formula:

$$A_{\mathrm{still\ fluid}}=\rho f\left(\mathrm{geometry},\frac{X_o}{D},\frac{fD^2}{\vartheta}\right), \tag{1}$$

where X_o is the amplitude of vibration in a given direction, D is the characteristic length, f is the frequency of vibration and ϑ is the kinematic viscosity of the fluid. Amabili (1996) presented a model to estimate the natural frequencies and mode shapes of partially filled shells. Conca et al. (1997) showed that the added mass matrix for a mechanical structure vibrating in an incompressible fluid does not depend on the viscosity. Yadykin et al. (2003) found that for a flexible plate oscillating in a fluid, either an increase of the order of the mode of vibration or a decrease of the aspect ratio leads to a decrease of the added mass effect.

In the field of hydraulic machinery, fluid–structure interaction (FSI) phenomena involving hydrofoils are a major concern, and several investigations have been performed on this topic. Ducoin et al. (2010a) experimentally studied the vibrations induced in a hydrofoil by the laminar to turbulent boundary layer transition and determined their significance and dependence on the vortex shedding frequency. Olofsson (1996) experimentally studied the dynamic performance of partially submerged propellers. Using numerical simulations, Moussou (2005) developed methods and solutions for two