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Influence of cavitation on the hydroelastic stability of hydrofoils

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ABSTRACT

This work numerically examines the effect of turbulent and cavitating flow on the hydroelastic response and stability of a hydrofoil. A cantilevered, rectangular, chordwise rigid hydrofoil is modeled as a 2-degrees-of-freedom structure for its spanwise bending and torsional flexibilities. The fluid flow is modeled with the incompressible, Unsteady Reynolds Averaged Navier–Stokes equations using an eddy-viscosity turbulence closure model that is corrected for the presence of cavitation, and with a transport equation based cavitation model. The results show that, in general, massive cavitation tends to: (i) reduce the mean lift, (ii) increase the mean drag, (iii) lower the mean deformations, and (iv) delay static divergence, while unsteady sheet/cloud cavitation promotes flow induced vibrations. Such vibrations and load fluctuations could be as large as (and even greater than) the mean values for cases with unsteady cavitation, so dynamic and viscous fluid–structure models are needed to simulate flexible hydrofoils in cavitating flows. In general, the flow induced vibrations, and hence the drag force, are higher with decreasing stiffness. For small leading edge partial cavitation, increasing foil flexibility increases the maximum cavity length and reduces the cavity shedding frequency; however, the influence of foil flexibility is limited for cases where the maximum cavity length is near or beyond the foil trailing edge, because of the relocation of the center of pressure at the elastic axis, near the mid-chord. The results show that the mean deformations are generally limited by stall, and by the quasi-steady linear theory predictions at the fully-wetted and supercavitating limits. Furthermore, frequency focusing can occur when the cavity shedding frequency is near the fundamental system resonance frequencies, and broadening of the frequency spectrum can occur due to excitation of the sub-harmonics and/or modulation induced by the fluctuating cavities, if the cavity shedding frequency is away from the fundamental system resonance frequencies.

1. Introduction

High-speed and near-surface operations of lift or thrust providing devices (e.g. hydrofoils, turbine blades, propellers) in water make them prone to hydrodynamic cavitation, which can lead to vibration, noise, performance breakdown, and erosion if uncontrolled (Franc, 2006; Franc and Michel, 2005). Cavitation induced vibrations and load fluctuations can be more critical for such structures made of flexible materials, which have been shown to have performance advantages over

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Nomenclature

a	nondimensional distance (as a fraction of b) from the mid-chord position to the EA
b	half chord length ($=c/2$)
CFL	Courant–Friedrichs–Lewy number
C_D	drag coefficient
C_L	lift coefficient
$C_L^{FW,t}$	theoretically predicted C_L in FW flow
$C_L^{SC,t}$	theoretically predicted C_L in SC flow
C_M	moment coefficient about the foil EA
$C_M^{FW,t}$	Theoretically predicted C_M in FW flow
$C_M^{SC,t}$	theoretically predicted C_M in SC flow
$\tilde{C}_h$	hydrofoil damping constant for spanwise bending
$\tilde{C}_\theta$	hydrofoil damping constant for spanwise twisting (torsion)
CP	center of pressure
c	hydrofoil chord length
$\tilde{D}$	net drag force on the hydrofoil
D'	2-D (per unit span) net drag force on the hydrofoil
DOF	degree of freedom
E_s	Young's modulus of the hydrofoil
EA	elastic axis
e	nondimensional distance (as a fraction of c) from the EA to the CP
$e^{FW,t}$	theoretically predicted e in FW flow
$e^{SC,t}$	theoretically predicted e in SC flow
FSI	fluid–structure interaction
FW	fully-wetted
f	normalized bending deformation shape function of the 3-D hydrofoil
f_c	cavity shedding frequency
f_h^a	hydrofoil's first bending natural frequency in air
f_h^w	hydrofoil's first bending natural frequency in water
f_θ^a	hydrofoil's first torsion natural frequency in air
f_θ^w	hydrofoil's first torsion natural frequency in water
g	normalized twisting deformation shape function of the 3-D hydrofoil
$\tilde{h}$	hydrofoil's bending displacement at EA
h	time-dependent part of the hydrofoil bending displacement at the free-tip and at the EA
$h^{FW,t}$	theoretically predicted h in FW flow
$h^{SC,t}$	theoretically predicted h in SC flow
$\tilde{I}_\theta$	hydrofoil's 3-D generalized moment of inertia along the EA
$\tilde{K}_h$	hydrofoil spanwise bending stiffness
$\tilde{K}_\theta$	hydrofoil spanwise torsion stiffness
$\tilde{K}_\theta^{Div}$	critical $\tilde{K}_\theta$ at which the foil undergoes static divergence
$\tilde{K}_\theta^{Sc,Div}$	$\tilde{K}_\theta^{Div}$ at SC conditions
$\tilde{L}$	net lift force on the hydrofoil
L'	2-D (per unit span) net lift force on the hydrofoil
LE	leading edge
LHC	Loose Hybrid Coupled
$\tilde{m}$	hydrofoil's 3-D generalized mass
n	exponent used in the empirical relation between $\mu*_t$ and μ_t
p_o	static pressure at the outlet
p_v	saturated vapor pressure
Re	Reynolds number
SC	Supercavitating
s	hydrofoil span length
s_{ff}	$= \int_0^s f(z)^2 dz$
s_{gg}	$= \int_0^s g(z)^2 dz$
$\tilde{T}$	net fluid-induced moment about the hydrofoil EA
T'	2-D fluid-induced moment (per unit span) about the hydrofoil EA
TE	trailing edge
TEV	trailing edge vortex
URANS	unsteady Reynolds Averaged Navier–Stokes equations
U_0	uniform inflow speed along **X**
U_0^{Div}	critical U_0 at which the foil undergoes static divergence
u	local velocity of the liquid/vapor mixture along the **X** direction
VOF	volume of the fluid method
(X,Y)	coordinate axis centered at the EA of the undeformed hydrofoil
(x_θ,y_θ)	nondimensional distance (as a fraction of b) from the EA to foil center of mass position along **X** and **Y**.
y^+	$=\rho_l u_\tau y/\mu_l$, where u_τ is the estimated friction velocity, y is the thickness of the first cell adjacent to the foil
z	span length parameter, ($=0$ at the hydrofoil fixed end, $=s$ at the hydrofoil tip)
α_0	hydrofoil initial angle of attack
α_{eff}	hydrofoil effective angle of attack
α_{L0}	hydrofoil's angle of attack at which lift force is zero (Camber angle)
Δt	time-step size
ΔX	local mesh width size
ζ_h	damping factor for hydrofoil bending in air
ζ_θ	damping factor for hydrofoil torsion in air
$\tilde{\theta}$	hydrofoil's twist-angle displacement along the EA
θ	time-dependent part of the hydrofoil twist-angle displacement along the EA at the free-tip
$\theta^{FW,t}$	theoretically predicted θ in FW flow
$\theta^{SC,t}$	theoretically predicted θ in SC flow
μ_l	dynamic viscosity of the liquid
μ_v	dynamic viscosity of the vapor
μ_t	turbulent eddy viscosity of the liquid/vapor mixture adjusted for the presence of cavitation
μ_t^*	turbulent eddy viscosity of the liquid/vapor mixture
ν_s	Poisson's ratio of the hydrofoil material
ρ_l	density of the liquid
ρ_s	density of the hydrofoil material
ρ_v	density of the vapor
σ	cavitation number
ϕ	local volume fraction of the vapor phase ($=1$ pure vapor, $=0$ pure liquid)