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Influence of flow-induced bend–twist coupling on the natural vibration responses of flexible hydrofoils

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ABSTRACT

For flexible hydrofoils, the natural flow-induced bending and twisting deformations are coupled if the center of lift is away from the elastic axis; this coupling may be influenced by viscous effects due to movement in the center of lift. The objective of this work is to investigate the role of flow-induced bend–twist coupling effects, as well as their dependence on the reduced velocity and solid-to-fluid added mass ratio. A secondary objective is to compare inviscid and viscous fluid–structure interaction (FSI) simulations of the natural flow-induced vibration responses of flexible cantilevered hydrofoils in water. The focus is on attached flow conditions in fully turbulent regimes at low angles of attack, where inviscid FSI method should be relatively accurate, and the foil response should be dominated by the foil's natural frequencies. The viscous FSI model is formulated by coupling a two-dimensional (2D) unsteady Reynolds-averaged Navier–Stokes (URANS) model with a two-degrees-of-freedom (2-DOF) model representing the spanwise tip bending and twisting deformations. The results show that the flow-induced bend–twist coupling terms are important for accurate prediction of the natural vibration frequencies and damping characteristics, particularly for the twisting motion, and their relative importance grows when the relative velocity increases and the solid-to-fluid added mass ratio decreases.

1. Introduction

Lightweight, flexible marine structures have generated increasing interest in recent years due to recent advances in three-dimensional (3D) printing technology, materials research, and manufacturing. Flexible marine hydrofoils and propellers can be tailored to deliver superior performance compared to their rigid counterparts in off-design operating conditions and in spatially and/or temporally varying flows (Motley and Young, 2011; Young, 2008; Zhanke and Young, 2009). The dynamic response and performance of lightweight, flexible marine structures can be significantly affected by flow-induced bend–twist coupling effects compared to aero/wind structures. This is because the density of water is three orders of magnitude higher than air, and the kinematic viscosity of water is an order of magnitude lower.

In general, the fluid forces acting on a solid body can be decomposed into inertial, damping, and disturbing force terms that are in phase with the body acceleration, velocity, and displacement, respectively (Garrick, 1946; Sears, 1941; Theodorsen, 1935; Weissinger, 1947). All three components of the fluid forces are directly proportional to the fluid density. If the center of pressure (CP) or center of lift is away from the elastic axis (EA), the lift force will induce a twisting moment, which leads to flow-induced bend–twist coupling terms that may be dependent on viscous effects. Viscous effects can affect the CP position by flow separation and vorticity generation/convection. Consequently, the system's natural vibration frequencies, damping characteristics, and dynamic

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Nomenclature

Dimensional terms

b	semi-chord length, $b = c/2$ (m)
c	chord length (m)
f	foil oscillation frequency, $f = \omega/(2\pi)$ (Hz)
f_h	first in-vacuum (or in-air) natural bending frequency, $f_h = \omega_h/(2\pi)$ (Hz)
f_θ	first in-vacuum (or in-air) natural twisting frequency, $f_\theta = \omega_\theta/(2\pi)$ (Hz)
f_h^*	first in-water natural bending frequency, $f_h^* = \omega_h^*/(2\pi)$ (Hz)
f_θ^*	first in-water natural twisting frequency, $f_\theta^* = \omega_\theta^*/(2\pi)$ (Hz)
f_n	undamped natural frequency, $f_n = \omega_n/(2\pi)$ (Hz)
$f(z)$	spanwise bending shape function (m)
$h(t)$	instantaneous bending deformation at the free tip, positive for upwards (m)
$\tilde{h}(z,t)$	spanwise bending deformation for each section z, positive for upwards (m)
m	structural mass per unit span (kg/m)
$\tilde{m}$	generalized structural mass (kg)
s	span length (m)
t	time (s)
z	spanwise coordinate (m)
$\tilde{I}_\theta$	generalized structural mass moment of inertia, $\tilde{I}_\theta = \tilde{m} r_\theta^2 b^2$ (kg m^2)
$\tilde{C}_{s,h}$	generalized structural bending damping value, $\tilde{C}_{s,h} = 2\tilde{m}\omega_h\zeta_{s,h}$ (kg/s)
$\tilde{C}_{s,\theta}$	generalized structural twisting damping value, $\tilde{C}_{s,\theta} = 2\tilde{I}_\theta\omega_\theta\zeta_{s,\theta}$ (kg m^2/s)
$\tilde{K}_{s,h}$	generalized structural bending stiffness value, $\tilde{K}_{s,h} = \tilde{m}\omega_h^2$ (N/m)
$\tilde{K}_{s,\theta}$	generalized structural twisting stiffness value, $\tilde{K}_{s,\theta} = \tilde{I}_\theta\omega_\theta^2$ (N m)
E_s	Young's modulus (Pa)
U	inflow velocity (m/s)
Δt	time-step size (s)
ρ_s	structural density (kg/m^3)
ρ_f	fluid density (kg/m^3)
ν_f	fluid kinematic viscosity (m^2/s)
ν_t	turbulent (eddy) kinematic viscosity (m^2/s)
τ	foil maximum thickness (m)

Non-dimensional terms

a	non-dimensional distance from mid-chord to elastic axis, positive for elastic axis after mid-chord (–)
d	non-dimensional distance from elastic axis to three-quarter-chord ($3c/4$), $d = a - 0.5$ (–)
e	non-dimensional distance from elastic axis to aerodynamic center, positive for AC upstream of the elastic axis, $e = a + 0.5$ (–)
k	reduced frequency: the ratio between structural oscillation frequency and fluid convection frequency, $k = \omega b/U$ (–)
$g(z)$	spanwise twisting shape function (deg)
r_θ	non-dimensional radius of gyration about the elastic axis, $r_\theta = \sqrt{\tilde{I}_\theta/(\tilde{m}b^2)}$ (–)
x_θ	non-dimensional distance from elastic axis to center of gravity, positive for center of gravity aft of elastic axis, $x_\theta = \tilde{S}_\theta/(\tilde{m}b)$ (–)
λ	eigenvalue (–)
α_o	geometric angle of attack, positive for clockwise with respect to the incoming flow (deg)
α_{Lo}	angle of attack at which the lift force is zero, positive for clockwise about the elastic axis (deg)
α_{eff}	effective angle of attack, positive for clockwise about the elastic axis, $\alpha_{\mathrm{eff}} = (\alpha_o - \alpha_{Lo}) - \theta$ (deg)
ν_s	structural Poisson ratio (–)
μ	relative mass ratio: the ratio between structural inertial force and fluid inertial force for bending motion, $\mu = m/(\pi\rho_f b^2)$ (–)
Ω	structural bending to twisting frequency ratio: the ratio between first in-air natural bending frequency and first in-air natural twisting frequency, $\Omega = f_h/f_\theta$ (–)
$\theta(t)$	spanwise twisting deformation at the free tip, positive for counter-clockwise about the elastic axis (deg)
$\tilde{\theta}(z,t)$	spanwise twisting deformation at section z, positive for counter-clockwise about the elastic axis (deg)
ζ_T	total damping coefficient (–)
$\zeta_{s,h}$	structural bending damping coefficient (–)
$\zeta_{s,\theta}$	structural twisting damping coefficient (–)
$\zeta_{f,h}$	fluid bending damping coefficient (–)
$\zeta_{f,\theta}$	fluid twisting damping coefficient (–)
$\zeta_{T,h}$	total bending damping coefficient (–)
$\zeta_{T,\theta}$	total twisting damping coefficient (–)
$C(k)$	Theodorsen's circulation function (–)
$C_{M,AC}$	moment coefficient about the aerodynamic center, positive for counter-clockwise about the elastic axis (EA) (–)
C_P	pressure coefficient, $C_p = (p - p_o)/\left(\frac{1}{2}\rho_f U^2\right) = (p - p_o)/\left(\frac{1}{2}\rho_f \overline{U}^2\omega_\theta^2 b^2\right)$ (–)
Re	Reynolds number: the ratio between fluid inertial force and fluid viscous force, $Re = Uc/\nu_f$ (–)
$\overline{f}$	non-dimensional frequency, $\overline{f} = f/f_\theta$ (–)
$\overline{f_h}$	non-dimensional natural bending frequency, $\overline{f_h} = f_h^*/f_\theta$ (–)
$\overline{f_\theta}$	non-dimensional natural twisting frequency, $\overline{f_\theta} = f_\theta^*/f_\theta$ (–)
$\overline{p}$	non-dimensional total pressure, $\overline{p} = p/\left(\rho_f\omega_\theta^2 b^2\right)$ (–)
$\overline{t}$	non-dimensional time, $\overline{t} = t\omega_\theta$ (–)
$\overline{\mathbf{u}}_f$	non-dimensional local fluid velocity (–)
$\overline{\nu}_t$	non-dimensional turbulent (eddy) kinematic viscosity (–)
$\overline{\varpi}$	non-dimensional vorticity, $\overline{\varpi} = \omega b/U$ (–)
$\overline{z}$	non-dimensional spanwise coordinate, $\overline{z} = z/s$ (–)
$\overline{U}$	reduced velocity: the ratio between fluid convection frequency and structural first in-air natural twisting frequency, $\overline{U} = U/(\omega_\theta b)$ (–)