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A new modeling approach for transversely oscillating square-section cylinders

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ABSTRACT

This paper proposes a new generalized semi-empirical model to simulate fluid–structure interaction forces experienced by a transversely oscillating square-section cylinder by a more comprehensive approach. The total fluctuating transverse aerodynamic forces determined by this new modeling approach are composed of three main unsteady excitation modules. The first component relates to the conventional fluid inertia effect; the second component represents the varying incidence angle effect, including the wavelength-changing effect of downstream wake undulation by introducing a circulation lag function; and the last one denotes the excitation effect due to the strong resonant interaction between wake undulation and Kármán vortex shedding. In addition, the new model establishment process follows the "simple-to-use" principle, so it can be applicable even when few experimental data are available. Good agreements are observed between the predictions by this model and unsteady force coefficient results taken from harmonically forced vibration experiments. Moreover, the new model developed in this study can not only simulate the interaction effects between the vortex-induced vibration (VIV) and galloping, but also retain the predictive capability for the cases of pure vortex resonance and pure galloping phenomena. Finally, some significant findings are also presented in the context of the aeroelastic instability phenomena.

1. Introduction

The flow-induced oscillations of a bluff body, usually involving complex phenomena of fluid–structure interactions, have been considered as one of the most complicated but most challenging problems in fluid mechanics (Bearman, 1985). The aero- or hydrodynamic excitations for oscillations of a bluff cylinder are primarily related to the unsteady boundary layer flow separation and reattachment around the body, and theoretical models such as those for the unseparated flows past streamlined shapes are not yet available for bluff bodies.

For simplicity, the present study focuses on two-dimensional transverse oscillations of a long body of square section immersed in uniform wind flow normal to one of its faces. Under this circumstance, the aeroelastic oscillation is often presented as that of a rigid body in cross flow, with discrete mass, a linear spring support and viscous-type damping. Thus,

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Nomenclature

Aj	Constant coefficients of polynomial approximation, $j = 1, 3, 5 \ldots$
a, b, c	Empirical parameters (for Corless and Parkinson's model, and the first model proposed by this paper)
$C(k)$	Complex Theodorsen's circulation function, $= F(k) + iG(k)$
C_D	Drag coefficient
C_{IN-L}	Unsteady force coefficient relates to incidence effect including the influence of circulation lag
C_K	Unsteady force coefficient due to Kármán vortex excitation
C_L	Lift coefficient
C_{mo}	Potential flow inertia coefficient
C_{QS}	Quasi-steady force coefficient
Cy	Total fluctuating transverse force coefficient
C_{Y0}	Amplitude of the transverse force coefficient fluctuation for the stationary cylinder, bandpass filtered around the Strouhal frequency
$\hat{C}_y(f_O)$	Amplitude of the fluctuating transverse force coefficient synchronized with the body oscillation
$\hat{C}_{yI}(f_O)$	Amplitude of the fluctuating force coefficient component in phase with the cylinder displacement
$\hat{C}_{yO}(f_O)$	Amplitude of the fluctuating force coefficient component 90° out of phase with the cylinder displacement
D	Length of side of the square section
f	Constant related to Magnus effect (for Tamura and Shimada's model, and the second model proposed by this paper)
f_N	Natural frequency of free undamped oscillation of system
f_K	Kármán vortex shedding frequency behind a stationary cylinder
f_O	Oscillation frequency of the cylinder
h	Width of wake oscillator (for Tamura and Shimada's model, and the second model proposed by this paper)
h^*	Dimensionless width of wake oscillator, $= h/D$
k	Reduced frequency with respect to half length of the streamwise dimension
K	Reduced frequency with respect to full length of the streamwise dimension
l	Half length of wake oscillator (for Tamura and Shimada's model, and the second model proposed by this paper)
l^*	Dimensionless half length of wake oscillator, $= l/D$
l_t	Length between the center of rotation and the center of gravity of wake oscillator
L	Streamwise dimension of cross-section
m	Mass of oscillating system per unit length
m^*	Dimensionless mass parameter, $= \rho D^2/(2m)$
St	Strouhal number, $= f_K V/D$
Sc	Scruton number, $= (4\pi m\xi)/(\rho D^2)$
U_{fK}	Critical reduced wind velocity of Kármán vortex resonance, $= 1/St$
$U_{\omega K}$	$U_{fK}/(2\pi) = 1/(2\pi St)$
U_{fN}	Reduced wind velocity with respect to the system natural frequency, $= V/(f_N D)$
$U_{\omega N}$	$V/(\omega_N D) = U_{fN}/(2\pi)$
U_{fO}	Reduced wind velocity with respect to the cylinder oscillation frequency, $= V/(f_O D)$
$U_{\omega O}$	$= V/(\omega_O D) = U_{fO}/(2\pi)$
U_{fQ}	Critical reduced wind velocity of galloping instability calculated with the quasi-steady theory, $= 4\pi\xi/(m^* A_1)$
V	Approaching flow velocity
V_{rel}	Relative wind velocity, $= \sqrt{V^2 + (y')^2}$
y	Cylinder transverse displacement
$\hat{y}$	Cylinder transverse oscillation amplitude
y'	Oscillation velocity, $= \partial y/\partial t$
Y	Dimensionless oscillation displacement of the cylinder, $= y/D$
$\hat{Y}$	Cylinder dimensionless oscillation amplitude, $= \hat{y}/D$
$\dot{Y}$	Reduced oscillation velocity with respect to τ_N, $= \partial Y/\partial \tau_N$
$\mathring{Y}$	Reduced oscillation velocity with respect to τ_O, $= \partial Y/\partial \tau_O$
α	Angular displacement of wake oscillator (for Tamura and Shimada's model, and the second model proposed by this paper)
β	Relative wind incidence angle, $= \arctan(y'/V)$
χ	Empirical parameter, $= D/l_t = 1/(1+l^*)$ (for Tamura and Shimada's model, and the second model proposed by this paper)