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Effect of damping on variable added mass and lift of circular cylinders in vortex-induced vibrations

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ABSTRACT

Extensive VIV data, collected by the MRELab of the University of Michigan, are analyzed to investigate the effect of damping on added mass and lift. Systematic change of damping and stiffness is enabled by the *Vck* system, which simulates the mechanical oscillator without including the hydrodynamic load in the closed control loop. The data acquired are in the TrSL3 flow regime, for Reynolds number $25{,}000 < Re < 130{,}000$, mass ratio $m^* = 1.93$, damping ratio ζ in the range $0.0158 < \zeta < 0.1758$, and spring stiffness k in the range $400\ \mathrm{N/m} < k < 1800\ \mathrm{N/m}$. To find the effect of damping on added mass and lift, three powerful techniques are used: (a) The damping coefficient c^* introduced by Vandiver in 2012 to replace the mass-damping parameter. (b) The variable added mass method introduced by Vikestad et al. in 2000 modeling VIV as a resonance phenomenon with variable natural frequency due to variable added-mass. (c) The data collected by the *Vck* system, which eliminates all nonlinear system damping occurring naturally due to friction before adding mathematically accurate linear viscous damping. The main findings of this study are: (1) With variable added mass, the oscillation frequency is about equal to the mean of the damped natural frequency and the phase between force and displacement is about 90°, consistent with resonance in the VIV lock-in range for the damping-ratio values tested. (2) In the entire upper branch range, the time-averaged variable added mass coefficient increases with increasing damping. Before and after the upper branch, increased damping results in decreased added mass. (3) The maximum non-dimensional amplitude, over the entire lock-in range occurring at the end of the upper branch, depends linearly on $c^* (A^* = \gamma c^* + \delta)$ with correlation coefficient $R^2 \cong 0.99$.

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1. Introduction

The phenomenon of Vortex-Induced Vibrations (VIV) has fascinated researchers for centuries, because of its catastrophic consequences on numerous engineering applications. Understanding and modeling VIV is still an active area of research. VIV is a subgroup of motions within Fluid–Structure Interaction (FSI), which also includes galloping, flutter, and buffeting. VIV occurs when a bluff elastic body, in this case a cylinder on end-springs, experiences von-Kármán-type vortex shedding and is excited primarily in the direction transverse to the flow exhibiting large amplitude response not just at its natural frequency in still water but over a wide range of frequencies and corresponding flow velocities. In-line oscillations also occur when that second degree of freedom motion is allowed. There are several characteristics unique to VIV that other FSI do not exhibit.

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Nomenclature

A	Amplitude of oscillation (Average max 60 peaks) (m)
A_{max}	Maximum amplitude of oscillation A over a dataset (m)
A^*	Non-dimensional amplitude of oscillation (A/D)
A^*_{max}	Maximum non-dimensional amplitude of oscillation (A^*) over a dataset
c	Damping coefficient (N s/m)
c_c	Critical damping coefficient, $2m_{osc}\sqrt{k/m_{osc}}$ (N s/m)
c^*	Vandiver damping parameter, $2c\omega_{osc}/\rho U^2 L$
C_a	Added mass coefficient
C_d	Drag coefficient
C_L	Lift coefficient
D	Cylinder diameter (m)
F	Forcing function (N); Force per unit length (N/m)
F_o	Forcing amplitude (N)
f	Frequency parameter (Hz)
f_n	Natural frequency with added mass in water (Hz)
f_{osc}	Frequency of oscillation (Hz)
f_s	Frequency of vortex shedding for stationary cylinder (Hz)
f_{vac}	Natural frequency in vacuum (Hz)
k	Spring stiffness coefficient (N/m)
KC	Keulegan–Carpenter number, $U_m(T/D)$
L	Cylinder length (m)
m	mass (kg)
m_a	Added mass (kg)
m_d	Displaced fluid mass (kg)
m_{osc}	Mass of cylinder and moving parts (kg)
m^*	Mass ratio m_{osc}/m_d
n	Number of oscillatory periods
R	Correlation coefficient
Re	Reynolds number using the diameter as the characteristic length
S_c	Scruton number, a mass-damping parameter
S_G	Skop-Griffin parameter, a mass-damping parameter
St	Strouhal number, $f_s D/U$
T	Period between upward zero-crossings of displacement (s)
t	Time variable (s)
U	Free-stream velocity (m/s)
U^*	Reduced velocity $= U/(f_{vac}D)$
U^*_n	Reduced velocity $= U/(f_n D)$
Vck	Virtual damping–spring system
V_{cyl}	Cylinder volume (m^3)
x	Cylinder displacement perpendicular to the flow (m)
$\dot{x}$	Cylinder velocity perpendicular to the flow (m/s)
$\ddot{x}$	Cylinder acceleration perpendicular to the flow (m/s^2)
x_o	Cylinder amplitude (m)
x_{rms}	Root-mean-square cylinder displacement (m)
α	Line-fit coefficient determined from experimental data
β	Line-fit coefficient determined from experimental data
γ	Line-fit coefficient determined from experimental data
δ	Line-fit coefficient determined from experimental data
ζ	Damping ratio, c/c_c
ρ	Fluid density (kg/m^3)
φ	Phase shift (rad or degrees)
ω or ω_o	Frequency (rad/s)
ω_{osc}	Frequency of oscillation (rad/s)

VIV has been shown to occur from Reynolds numbers of about 40 up to 10^{10}, with the exception of the flow transition inside the vortex ($150 < Re < 400$) and inside the boundary layer ($3 * 10^5 < Re < 5 * 10^5$). The lift coefficient has been shown