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Revealing the effects of damping on the flow-induced vibration of flexible cylinders

J. Kim Vandiver*, Leixin Ma, Zhibiao Rao

Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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ABSTRACT

This study reveals how damping shapes the global vortex-induced vibration (VIV) response of flexible cylinders. Global behavior may vary from full-length standing waves to traveling waves on infinite cylinders. Structural damping rules the standing wave case whereas radiation damping regulates VIV response on very long cylinders. A single scalar equation expresses the balance of power flowing through the structure. In that equation, A_{rms}, which is the root-mean-square response in the VIV excitation region, is shown to be an excellent indicator of global response because of its relation to power flow. Under steady-state conditions, the net power flow must be zero, which directly leads to three independent dimensionless damping parameters, namely α, β_R, and c^*. β_R indicates when radiation damping is important, α reveals the relative importance of structural versus radiation damping, and c^* locates the global VIV behavior on the spectrum of lightly to strongly damped systems. Structural, hydrodynamic, and wave radiation damping are all taken into account. Plots of A^*_{rms} versus c^* show the global effects of damping on response. Uncontrolled factors often reveal themselves as graphical anomalies, leading to new insights on VIV. Data from experiments and numerical simulations are presented to support the conclusions.

1. Introduction

Introducing flow-induced vibration to a newcomer is most often accomplished with reference to a few key dimensionless parameters. Strouhal number, Reynolds number, mass ratio, and reduced velocity immediately come to mind when explaining how the vortex-induced vibration (VIV) world works. Remarkably, there has been limited success in finding useful dimensionless parameters involving damping. In the 1950s, Scruton introduced what is today called the mass-damping parameter, $m^*\zeta_s$, which revealed a remarkably high correlation with peak response amplitude of smoke stack models in wind tunnels [1]. Unfortunately, $m^*\zeta_s$ is based on structural damping only and is of no use for long flexible cylinders, because it does not account for hydrodynamic or radiation damping. Currently, there are no dimensionless damping parameters that are able to place global structural response on a spectrum of lightly to heavily damped systems. The primary goal of this study is to define a set of dimensionless parameters, which show the role of damping in the regulation of the VIV of flexible cylinders.

* Corresponding author. Department of Mechanical Engineering Massachusetts Institute of Technology, Room 10-110, Cambridge, MA 02139, USA.
E-mail address: kimv@mit.edu (J.K. Vandiver).

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Nomenclature

A^*	Non-dimensional local peak amplitude
$A_{1,rms}$	Root-mean-square (RMS) amplitude for outbound wave
$A_{2,rms}$	RMS amplitude for returning wave
A_{rms}	Spatial and temporal RMS of $y(x,t)$ in excitation region
A^*_{rms}	Non-dimensionless value of A_{rms} in excitation region
$c(x)$	Damping coefficient, damping/length
c_a	Added mass coefficient
c_e	Equivalent damping coefficient
c_h	Hydrodynamic damping coefficient
c_{out}	Damping coefficient in power-out region
c_s	Structural damping coefficient
c^*	Dimensionless damping parameter for spring-mounted cylinder
c^*_e	Dimensionless equivalent damping parameter
c^*_u	Dimensionless damping parameter for dominant structural damping cases
c^*_Z	Dimensionless damping parameter for dominant radiation damping cases
$C_L(x,t)$	Lift coefficient
$C_{L,rms}$	RMS value of $C_L(x,t)$ in power-in region
$C_y(x,t)$	Force coefficient
C_{y0}	Peak value of $C_y(x,t)$
$C_{y,rms}$	RMS value of $C_y(x,t)$ in power-in region
D	Cylinder diameter
EI	Bending stiffness
f_v	VIV response frequency in Hz
$f(x,t)$	Force per unit length
k	Wave number
L	Pipe length
L_{in}	Length of power-in region
L_{out}	Length of one power-out region
$m(x)$	Mass/length with added mass
$m_{fairing}$	Mass/length ($kg \cdot m^{-1}$) fairing only in air
m_s	Mass/length ($kg \cdot m^{-1}$) in air without fairing
$m^*\zeta_s$	Mass-damping parameter
n_{out}	Number of half waves in one power-out region
$P(x)$	Tension
r_1	Amplitude ratio $A_{rms}/A_{1,rms}$
S_t	Strouhal number
T	Oscillation period of pipe
U	Flow speed
U^2_{rms}	Average mean square flow velocity in excitation region
V_g	Energy velocity/group velocity of wave
V_r	Reduced velocity
V_ϕ	Phase velocity of wave
x	Axial coordinate along pipe
$y(x,t)$	Time series displacement
y_{rms}	RMS of $y(x,t)$
Z_R	Impedance of a tensioned cable/beam
ζ_{out}	Damping ratio in power-out region
ζ_s	Structural damping ratio
α	Structural damping parameter
β_R	Wave attenuation parameter
λ	Wave length
ρ	Density of fluid
ω	Response frequency in rad/s
ω_n	Natural frequency for mode n in rad/s