Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 199 (2017) 546–551

Procedia Engineering

www.elsevier.com/locate/procedia

X International Conference on Structural Dynamics, EURODYN 2017

Multivariate Analysis Of Vortex-Induced Vibrations In A Tensioned Cylinder Reveal Nonlinear Modal Interactions

Ersegun D. Gedikli[a], Jason M. Dahl[a], David Chelidze[b,*]

[a]*Department of Ocean Engineering, University of Rhode Island, Narragansett, RI, 02882, USA*
[b]*Department of Mechanical, Industrial and Systems Engineering, University of Rhode Island, Kingston, RI, 02881, USA*

Abstract

The modal structure of a tension-dominated flexible cylinder undergoing vortex-induced vibrations in a uniform current is investigated through multivariate analysis. Experiments are performed in a recirculating flow channel where a flexible cylinder is mounted across the flow channel and subjected to a uniform current. The cylinder response is measured using motion tracking with two high speed cameras, allowing for the measurement of both in-line and cross-flow motions of the cylinder. The recorded motion of the cylinder is analyzed in its measured phase space using smooth orthogonal decomposition (SOD) and proper orthogonal decomposition (POD). Both decompositions show that most of the motion energy is captured in a six-dimensional subspace; however, the corresponding modal structures are different between the decompositions. While SOD-based modes are persistent regardless of whether the flow speed is increasing or decreasing, the POD modes do not maintain this consistency. For example, the dominant (i.e., most energetic) POD mode changes shape depending on whether the flow speed is undergoing an increase or decrease. This inconsistency leads to a variability in the modal energy that is affected by hysteresis if the POD method is used. Modal frequency response curves show the corresponding variance of the modal response versus the reduced flow velocity. SOD-based plots show hardening spring behavior in the first mode oscillations, which are dominant at low reduced velocities and have negligible amplitude at high reduced velocities. Second mode oscillations are negligible at low reduced velocities but undergo subcritical Hopf bifurcation at higher reduced velocities. The associated hysteresis behaviors are observed over the same range of reduced velocity values for both modes. POD analysis also detects this behavior, but it is less pronounced and leaks into higher-order modes.

Peer-review under responsibility of the organizing committee of EURODYN 2017.

Keywords: Vortex-induced vibrations; Hopf bifurcation; Smooth orthogonal decomposition; Proper orthogonal decomposition

1. Introduction

Vortex-induced vibrations (VIV) are a self-limiting fluid-structure interaction caused by vortex shedding in the wake of a flexible structure. The coupling of the flexible structure's wake with the motion of the structure can lead to a wide band motion response and large amplitude motions that can contribute to fatigue damage in many engineering applications (e.g. bridges, marine cables, risers, transmission lines, heat exchangers, etc.). A significant volume of work has been devoted to understanding this problem, particularly through simplifications studying the interaction of single-degree-of-freedom, elastically-mounted rigid cylinder subjected to a cross-flow as discussed in a variety of

* Corresponding author. Tel.: +1-401-874-2356 ; fax: +1-401-874-2355.
E-mail address: chelidze@uri.edu

1877-7058
Peer-review under responsibility of the organizing committee of EURODYN 2017.
10.1016/j.proeng.2017.09.159

Nomenclature

A_x	In-line amplitude response	IL	In-line
A_y	Cross-flow amplitude response	m^*	Mass ratio
AR	Aspect ratio	Re	Reynolds number
CF	Cross-flow	T	Tension
D	Cylinder diameter	U	Nominal flow speed
f_n	First natural frequency of the cylinder in air	Vr_n	Nominal reduced velocity

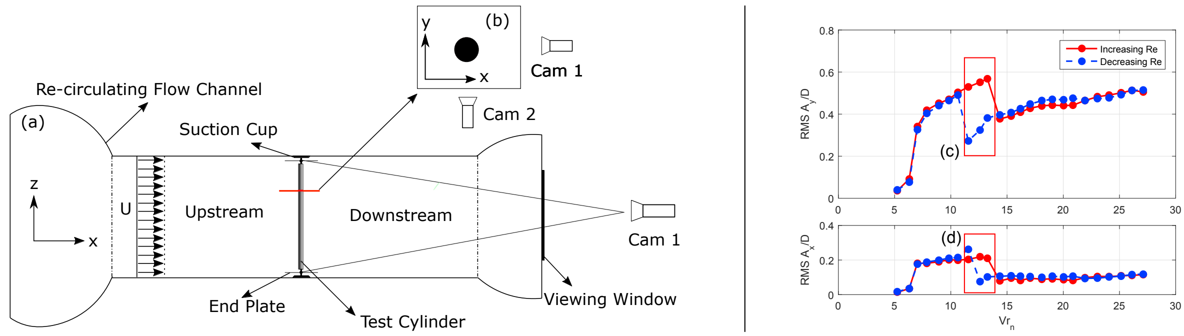

Fig. 1. Left image: Schematic of the experimental setup; (a) Top view. Camera 1 is located in front of the flow channel; (b) Side view of cylinder cross-section. Camera 2 is located underneath the flow channel. Flow is from left the right. Right image: Priori RMSE Amplitude response for increasing and decreasing Reynolds number values. Red boxes show different amplitude responses obtained (c) in CF and (d) in IL respectively.

reviews [1–3]. Sarpkaya[1] discusses the significant complexities of the problem in continuous systems, highlighting the large number of factors that contribute to this fluid-structure interaction in a continuous system.

Recent studies have illustrated the significance of studying combined IL and CF motion of continuous structures, due to the presence of large high-harmonic forces associated with figure eight type motion of a continuous structure's cross-section [4,5], which can significantly contribute to fatigue damage in structures. While a large number of studies on continuous, flexible structures have characterized the multimode response of flexible structures undergoing VIV in field experiments [6–9] and laboratory scale experiments [10–13], the analysis of the structural mode response has often been limited to a linear Fourier analysis of the system. While a Fourier analysis of structural modes in this highly nonlinear phenomenon can give a base estimate of the dominant response shapes and a characterization of the multiple frequency response of the system, these methods are not capable of characterizing the general underlying nonlinear behavior of the system. This is particularly important where the interaction of specific modes in the IL and CF direction may result in a different overall nonlinear behavior of the structure.

The present study aims to characterize the nonlinear response of a low-mode and low-mass ratio flexible cylinder, particularly when highly nonlinear behaviors (e.g., hysteresis) appear in the overall response of the system. A tensioned, flexible cylinder placed in a uniform free stream is used as the test apparatus, while multivariate analysis is used to characterize the underlying nonlinear behavior of the continuous system. The multi-mode dynamic response of the cylinder is analyzed in its phase space using smooth orthogonal decomposition (SOD) as described in [14] and compared with traditional proper orthogonal decomposition (POD) to illustrate the importance of using empirical modes in characterizing the nonlinear response of the system. Since the fluid-structure interaction in VIV is inherently nonlinear, there is no physical basis to argue that the modal response of the cylinder must consist of sinusoidal Fourier modes. These multivariate data analysis methods allow for the determination of the empirical spatial mode shapes associated with the energy in the system, with the first mode being the most energetic and so on. Applying both decomposition methods reveals that most of the motion energy is captured in a six-dimensional subspace of the phase space. More interestingly, SOD-based decomposition clearly identifies the hardening spring type behavior and subcritical Hopf bifurcation in first and second mode oscillations, respectively; whereas POD analysis also detects this behavior, but it is less pronounced and leaks into higher-order modes.