Journal of Fluids and Structures 26 (2010) 602–610

JOURNAL OF FLUIDS AND STRUCTURES

www.elsevier.com/locate/jfs

Vibration frequency and lock-in bandwidth of tensioned, flexible cylinders experiencing vortex shedding

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Received 8 October 2008; accepted 15 February 2010
Available online 20 March 2010

Abstract

In-water vortex-induced vibration (VIV) tests of top-tensioned, flexible cylindrical structures were conducted at Shell Westhollow Technology Center current tank. These tests revealed that the top tension and structural stiffness (both lateral and axial) can have a significant impact on vibration frequencies. During lock-in between the vortex-shedding frequency and the structure's natural frequency, the increase of the vibration frequency with flow speeds is strongly related to the rise of the axial tension. After an initial abrupt rise, the vibration frequency of a bending-stiffness-dominated structure only increased slightly during lock-in. Alternative explanations are provided on why the vibration frequency does not rise significantly but there can still exist a broad lock-in band, and why a more massive structure has a narrower lock-in bandwidth.

Keywords: Vortex-shedding; Vibration frequency; Flexible cylinder; Lock-in band; Tension; Stiffness

1. Introduction

VIV of subsea pipelines and marine risers, used in offshore oil and gas exploration and production, are a practical concern in design. If not properly protected from VIV, these structures may fail due to oscillating stress-caused fatigue, at frequencies often higher than those resulting from ocean waves, in a very short period of time.

VIV has been a subject of intensive research. These efforts have been focused mostly on the effects of fluid-related parameters, such as Reynolds number (Lienhard, 1966), flow profile (Vandiver et al., 1996), mass ratio (Sarpkaya, 1979; Vandiver, 1993; Govardhan and Williamson, 2002), hydrodynamic damping (Griffin et al., 1975), and surface roughness (Allen and Henning, 2001; Achenbach, 1971). Investigations into structural effects on VIV of a flexible cylinder, most prominently the tension, lateral and axial stiffness, are scarce. A systematic study of these parameters, to the authors' knowledge, does not exist. Huse et al. (1998) studied experimentally a flexible riser model with top tension and concluded that the dynamic axial stresses due to VIV should be considered in design. Vandiver (1993) investigated the dynamic effects of VIV on finite and infinitely long structures and developed parameters that govern such response behavior. Gharib (1999) studied experimentally the spring constants of a spring mounted rigid cylinder. Sparks (2001) performed studies to examine riser VIV and provided simplified analytical solutions for such vibrations, which

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0889-9746/$ - see front matter
doi:10.1016/j.jfluidstructs.2010.02.002

Nomenclature

D	cylinder outside diameter	I	area moment of inertia
E	Young's modulus	L	cylinder length
f_1	in-water natural frequency of a cylinder in its first bending mode, in Hz	m	mass per unit length of a cylinder
		T	tension
		V	water speed
		V_r	reduced velocity, given by V/f_1D

compared well with finite element-based models. Lee and Allen (2009) questioned the theoretical basis of the Griffin plot for VIV motion prediction, since it does not account for the effects of structural stiffness.

Vibration frequencies and lock-in bandwidth are both important pieces of information for VIV design. The vibration frequency is directly related to the fatigue damage from VIV. A structure vibrating at a higher frequency will fail in a shorter time. The lock-in bandwidth is used by designers to determine the potentially harmful current speeds. A broader band signals a wider range of critical speeds. It is widely held that during lock-in the added mass decreases with the flow speed, and that makes the natural frequency and thus the vibration frequency rise. This is the reason why there exists a broader lock-in zone for lighter structures since the added mass effects are more pronounced to these cylinders than to the heavier ones (Vandiver, 1993).

In-water, VIV tests of a number of top-tensioned, flexible cylindrical structures were conducted at Shell Westhollow Technology Center current tank. Two such structures, with outside diameters of 2.5 and 4.5 in. (1 in. = 2.54 cm), were selected to investigate the effects of the top tension, lateral and axial stiffness on VIV responses, in particular the vibration frequency and lock-in bandwidth. These tests revealed some facts which are in contradiction to our common beliefs, and new insights are gained by carefully studying the test data. In the following sections, the test facility and setup are first described, and test results are then presented and discussed, followed by conclusions and recommendations.

2. Test description

2.1. Current tank facility

The Shell Westhollow current tank steel test structure is built to circulate (fresh) water at current speeds of 0–2.13 m/s. A ship's propeller driven by a hydraulic power package circulates the water. Two honeycomb sections (straighteners) are used to minimize turbulence and fluid rotational effects, and a shear screen can be used to produce sheared velocity profiles when desired. A 15.24 m deep, 0.91 m inside diameter steel caisson is located in the test-section to allow for test cylinders as long as about 18 m. The excitation region of the test-section is 3.66 m deep by 1.07 m wide and is produced by a fixed steel insert with baffles that change the cross-sectional dimensions of the flow from 2.13 m deep by 1.83 m wide to 3.66 m deep by 1.07 m wide, and then back to 2.13 m deep by 1.83 m wide beyond the test-section. A plan view and an elevation view of the tank test-section are displayed in Fig. 1.

2.2. Test set-up and test parameters

The two test cylinders were both Acrylonitrile Butadiene Styrene (ABS) tubes (see Table 1 for their properties), with the same length, 3.72 m. The cylinders were terminated at lower and upper ends by universal joints (Fig. 2). These ball joints were designed such that they allowed motion in all directions except torsional motion. A biaxial accelerometer was mounted inside the pipe at the center of the cylinders. A bending load cell, made by our own staff, was mounted beneath the lower ball joint to monitor loads in the in-line and cross-flow directions.

Similarly, a bending load cell was mounted above the upper ball joint inside a sleeve. A tension load cell was placed on top of a spring that was linked at the top of the bending load cell. A rod was connected at the top of the tension load cell. A tension was applied at the top for all test cases. The lower end was constrained such that all translational movements were restricted. At the upper end, the pipe was allowed to move vertically (resisted only by the spring), but not laterally. The center-to-center distance between the ball joints was approximately 3.73 m. The top end (ball joint) was not submerged (about 0.3 m above the still waterline).

Also listed in Table 1 are test speed range and speed increment for each cylinder. The mass ratio is the mass of the pipe, including that of the contents, divided by the mass of the displaced water. The in-water natural frequencies are also provided. The first natural frequencies were obtained from the pluck tests in which an initial displacement was