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On fatigue damage of long flexible cylinders due to the higher harmonic force components and chaotic vortex-induced vibrations

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ABSTRACT

Recent experimental data have revealed that vortex-induced vibrations of long flexible cylinders are characterized by time intervals of chaotic response, followed or preceded by periods of statistically stationary response. A chaotic response is characterized by a broad-band PSD, while the steady response can have large higher harmonic stress components. Regions of chaotic response and the steady regions with large higher harmonic stress components contain distinctly different response features and have significant implications on the fatigue analysis. To quantify the effect of the higher harmonic force components and chaotic oscillations on fatigue damage of long flexible structures, we generate stress time series such that we can include or remove the higher harmonics, and also use either a narrow-band or broad-band PSD. This approach enables us to conduct a systematic study on the influence of each of these phenomena on the resulting fatigue damage. We show a dramatic increase in fatigue damage for signals containing higher harmonics. On the other hand, for chaotic stress signals, the fatigue damage is increased moderately, relative to a stress signal with a narrow-band PSD with the same total power.

1. Introduction

Vortex-induced vibration (VIV) of a flexibly-mounted rigid cylinder placed in flow is a canonical problem in fluid-structure interactions. Many researchers have studied this phenomenon from various points of view and using various techniques, from purely experimental studies to purely numerical ones, with a cylinder free to oscillate in one direction only (1 degree of freedom) or in two directions (2 degrees of freedom). Bearman (1984), Sarpkaya (2004) and Williamson and Govardhan (2004) give a complete review of the VIV studies conducted on a flexibly-mounted cylinder.

The interest for these studies, besides the inherent fundamental understanding they provide, comes from various industrial applications, where vortex-induced vibration is observed. Examples range from risers used in the ocean oil platforms to the mooring lines used in the conceptual designs of the floating wind turbines, and cables used in cable-stayed bridges. In all of these examples, and many others, the structure is a flexible one with a large aspect ratio. This calls for studies on vortex-induced vibration of flexible structures placed in flow and, in fact, research on such systems has been on-going in the past few decades (Vandiver, 1993). Although vortex-induced vibration is of rather low amplitude (up to one cylinder diameter), it can lead to failure of the structure due to fatigue.

For a long time, these oscillations were considered only in the crossflow direction (motion perpendicular to the flow direction) and they were treated as purely harmonic oscillations with only one major frequency close to the Strouhal frequency, a dimensionless quantity representative of the frequency of vortex shedding. Recently, it has been shown (Williamson and Jauvtis, 2004; Vandiver et al., 2006; Dahl et al., 2007) that for both the rigid and flexible cylinders, inline oscillations cause drastic changes in the wake and the resulting fluid forces, including a significant 3rd and in some cases 5th harmonic components in the measured crossflow fluid force signals and even-harmonics in the inline force. The inclusion of these higher harmonic components of the stress in the fatigue analysis can increase the predicted damage by an order of magnitude (Modarres-Sadeghi et al., 2010). The phasing between the crossflow and inline oscillations has been shown to have a significant effect on the resulting oscillations. When the energy is transferred from the flow to the structure (lock-in region in a flexible cylinder), the phasing between the inline and crossflow is such that the cylinder moves upstream at the extremes of its orbital motion (Bourguet et al., 2011).

On the other hand, it has been shown (Modarres-Sadeghi et al., 2011) that the observed cylinder response is characterized by time

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intervals of chaotic, followed or preceded by periodic response. Furthermore, the periodic motion consists of cases with purely 1st harmonic oscillations, as well as cases where higher harmonic components have a strong contribution. While in a traditional view of such experiments, the chaotic responses as well as the higher harmonic components of the periodic signals are normally ignored, it is observed that these components have a non-negligible influence on the forces acting on the structure (Modarres-Sadeghi et al., 2010, 2011). We call the statistically stationary regions, mainly periodic, or Type-I signals and the regions with qualitatively chaotic characteristics (e.g., rather broad-banded PSDs), Type-II signals. If a Type-II signal is approximated through an "equivalent" Type-I signal, as is often the case in semi-empirical methods, fatigue calculations seriously under-predict the fatigue damage.

The objective of this paper is to separately assess the impact of the higher harmonic components as well as the Type-II responses on the resulting fatigue damage of the flexible cylinders. The major contribution of this approach will be a quantitative measure of the influence of the higher harmonic components and Type-II signals. In order to achieve this goal, we use statistical methods to generate stress time series based on the PSD plots similar to those of the experimental signals. Using this method, we can systematically alter the signal spectrum, from a purely 1st harmonic signal to a signal with sharp peaks both at the 1st and the 3rd harmonics, and to a signal with increasing frequency spreading toward a completely Type-II signal.

2. Experimental data

We have used the Norwegian Deepwater Programme (NDP) Riser High Mode VIV tests (Braaten and Lie, 2004) in order to come up with proper ranges of various parameters used in our study. The riser properties for those tests are given in Table 1. The tests were conducted both for a uniform flow case and for a linearly sheared flow profile (zero flow velocity at one end, and a maximum flow at the other end). In these tests, the maximum flow velocities were varied from 0.3 m/s to 2.2 m/s, in increments of 0.1 m/s, and measurements of the crossflow and inline strain and acceleration were taken at various points.

The experimental VIV response can be quite complex. The scalogram shown in Fig. 1(a) belongs to a case where multiple-frequency response is observed. Besides the wide-spread frequency content at each instant of time, the frequency content varies over time as well. Large 3rd harmonic components with rather broad frequency spectrum are also observed. Simultaneous presence of the 1st and the 3rd frequencies corresponds to the figure-8-type orbital motions of the flexible cylinder at different points along its length as shown in Fig. 1(b).

Fig. 2(a) shows a typical PSD plot of a signal from the NDP tests (shear bare 2360 crossflow sensor 4), where the signal consists of a 1st harmonic component at around 3.4 Hz (closest to the Strouhal frequency), together with some higher harmonic components at around 10.2 Hz (3rd harmonic). Each peak is spread over a range of frequencies – e.g., the 3rd harmonic component has its maximum amplitude at 10.2 Hz, and is spread over the range of frequencies from 9–12 Hz. This is an example of a Type-II signal. Fig. 2(b) shows another case (shear bare 2350 crossflow sensor 4) in which the frequency contents are single peaks located at the 1st and the 3rd harmonic frequencies. This is an example of a Type-I signal.

Before conducting any stress-signal construction, we use the measured strain signals to calculate the relative power stored in each of the strain signal harmonics. Fig. 3 shows the ratio of power stored in each harmonic component of the signal based on the spatial average PSD plots, for the linearly sheared and uniform flow cases. Obviously at some measurement points, the higher harmonic components could be larger (before averaging) than what is shown in this figure. It is observed that for the sheared cases, on average around 20% of the total power belongs to the 3rd harmonic component, while for the uniform flow cases, up to 40% of the power is due to the 3rd harmonic component.

Table 1
Cylinder properties in the NDP data.

Length between pinned ends	38 m
Outer diameter	0.027 m
Wall thickness	0.003 m
Young's modulus	36.2×10^9 N/m^2
Mass per unit length (air filled)	0.761 kg/m
Mass per unit length (water filled)	0.933 kg/m
Weight in water	2.79 N/m

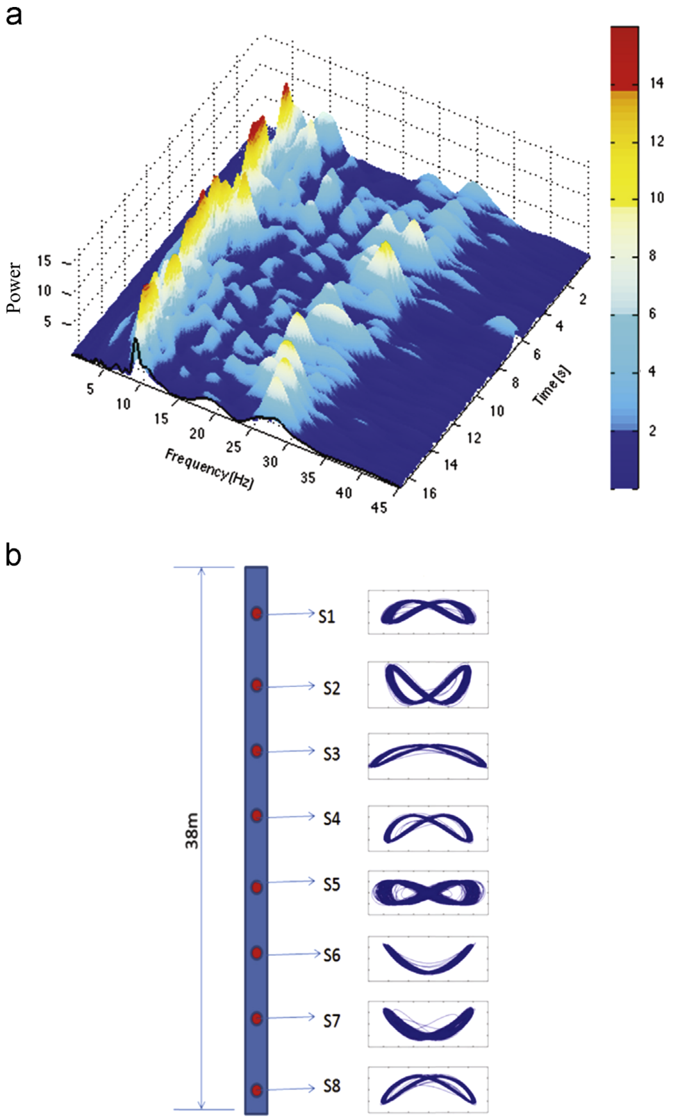

Fig. 1. (a) A sample scalogram of the NDP experimental data for a case with linearly sheared flow profile and with a maximum flow velocity of 0.8 m/s (case 2360), together with (b) sample orbital motions measured at 8 locations along the length of the riser.