VSIV Experimental Analysis of a Catenary Riser Model in the Modal Space

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Summary. Vortex Self-Induced Vibration (VSIV) is a highly nonlinear fluid-structure interaction that can occur in catenary risers when there is an imposed motion at the structure hang-off point. The fluid-structure coupling shows persistent response, *i.e.* there is no lateral vibration mitigation after a post-critical in-plane induced oscillatory flow. The present study aims at analyzing multi-modal response of a small-scale catenary riser model using Garlerkin's decomposition. The frequency ratio parameter, as the one used in linear oscillator resonance analysis, shows to be a strong control parameter altogether with the modal Keulegan-Carpenter number.

Vortex Self-Induced Vibration (VSIV) phenomenon

The Vortex Self-Induced Vibration (VSIV) belongs to the class of Flow Induced Vibration (FIV) phenomena in fluid-structure nonlinear dynamics study field. Generally, the VSIV occurs always on slender flexible structures, as risers and umbilical cables, that are launched in catenary-like configuration, so that an imposed movement at their top end, as those caused by gravitational waves, causes an oscillating movement at their configuration plane (henceforth called in-plane movement). As a result of such in-plane oscillations, vortex shedding is established and it induces lift forces that causes out of plane oscillating vibrations.

Some intermittent vibrations were firstly reported in experimental tests conducted within large-scale models of steel catenary risers (SCR) in Grant et al. [1], which later were further exploited by Le Cunff et al. [2] in their experimental campaigns with small scale SCR model. Initially, Le Cunff et al. [2] described the VSIV as Heave Induced Lateral Motion (HILM) and later experimental campaigns conducted by Fernandes et al. [3] broadened the scope of HILM renaming the phenomenon as VSIV. Fernandes et al. [3] also points out that the VSIV were observed in real riser structures of Petrobras P18 platform.

Over the last decade, the VSIV was observed and reported in small scale SCR models, as in Rateiro et al. [4] and Pesce et al. [5], in which multi-modal out of plane responses occurs due to in-plane movement caused by harmonic vertical displacements imposed at the top. Their experimental campaign shown that the structure dynamic response is highly nonlinear, coupling VSIV with internal resonance phenomenon and even parametric instabilities amid the multi-modal responses. VSIV was also reported in some recent papers Fu et al. [6].

The VSIV presents some idiosyncratic features: the synchronization amid in-plane and out-of plane oscillating movements is persistent, not occurring the structural and fluid oscillators decoupling as when the VIV reaches the post-critical regime; several lateral amplitude response peaks are observable and they are related to the cycle number control parameter, $N = f_b/f_n$ (f_b is the out of plane response frequency and f_n, the in-plane one), which always assumes integer values; the cycle number N values depends on the Keulegan-Carpenter number (KC), assuming larger values as the KC increases; and a jump phenomenon that decreases the N value as the in-plane movement velocity increases.

As a result of all features aforementioned, the out-of-plane response never fades away and can assume fairly large values of the structure diameter, $\mathcal{O}(D)$. Besides, the VSIV bares a close similarity to the responses observed in rigid cylinder subjected to oscillating flow, as shown in classical results obtained by Sarpkaya and Rabaji [7] and Sumer and Fredsøe [8]. This similarity is pointed out in several of VSIV idiosyncratic features, specially when regarding KC and N as strong control parameters to the cylinder persistent lateral response, which later in the present study will be complemented by the frequency ratio, $f^\star = f_b/f_N$ (f_N is the natural frequency of the considered out of plane mode).

VSIV acting upon a small scale flexible cylinder model experimental response: modal approach

Experimental set-up

The small-scale flexible cylinder experimental model used in the present analysis is the same one already thoroughly discussed in Rateiro et al. [4] and Pesce et al. [5]; see Figure 1a. The experimental tests were conducted at the Institute for Technological Research (IPT) towing tank and the 3D model Cartesian displacement response was directly measured using underwater optical target tracking cameras; see [4]–[5]. The estimated measurement precision isof the order $\mathcal{O}(1mm)$; see Salles and Pesce [9]. In addition the effective traction at hang-off point is also obtained using a load cell; Figure 1b.

Considering the displacement results at local reference frames comprised of the tangent and normal versors, $\vec{t}$ and $\vec{n}$, respectively, which spans the catenary plane and the orthogonal binormal versor, $\vec{b}$, Figure 1c shows the multi-modal binormal dynamic response, due to the in-plane movement caused by the hang-off imposed motion. Particularly, in this selected case, the second out of plane mode shows up as the dominant response mode.

Galerkin's decompostion and VSIV modal response

Galerkin's decomposition acts as a spacial filter, grouping the nonlinear dynamic responses into a small number of modal series. The chosen modal basis was determined using a discrete beam model and a finite element solver. Considering the dominant in-plane modal series as an input for the multi-modal response out-of-plane, it is possible to broaden the concept of the Keulegan-Carpenter parameter, considering it as a modal value.

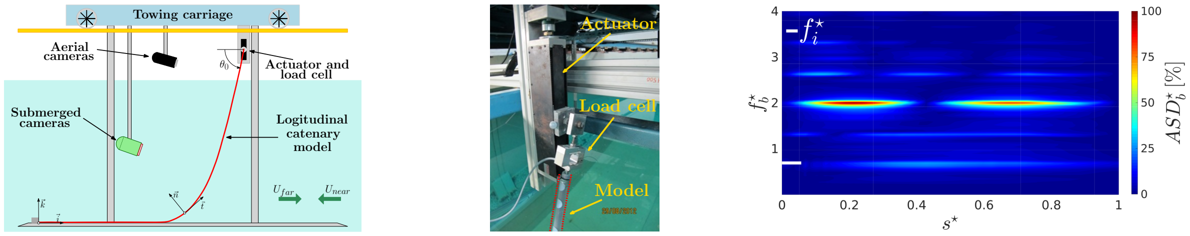

Figure 1: Flexible cylinder tests subjected to imposed movement at the top: a) experimental set-up; b) as-built model hang-off, displaying the actuator and a load cell; c) lateral amplitude spectrum of a selected case frequency response, showing multi-modal response, particularly with dominant second out of plane mode.

The frequency ratio amid dominant frequency response in-plane and the natural frequencies out-of-plane shows to be a strong control parameter, recovering a classical result of linear oscillators resonance response. The present study aims at analyzing the relation observed within all lateral modal peak-to-peak displacement, $2A_b^{(k)\star}$ for all in-plane modal frequency ratios; see illustrative results in Figures 2a–b. By working on the modal-space, grouping the results into small ranges of modal-KC numbers, strongly similar modal responses are revealed, enlarging the analysis contained in [2]–[6], made in the configuration space, and broading Sumer's & Fredsøe's [8] experimental results, obtained with a rigid cylinder mounted on linear springs in a given direction and forced to oscillate in the orthogonal direction. During the conference and in a full paper yet to come, much more results will be shown and discussed, as synchronisms, internal resonances and maps of typical orbits in the modal space.

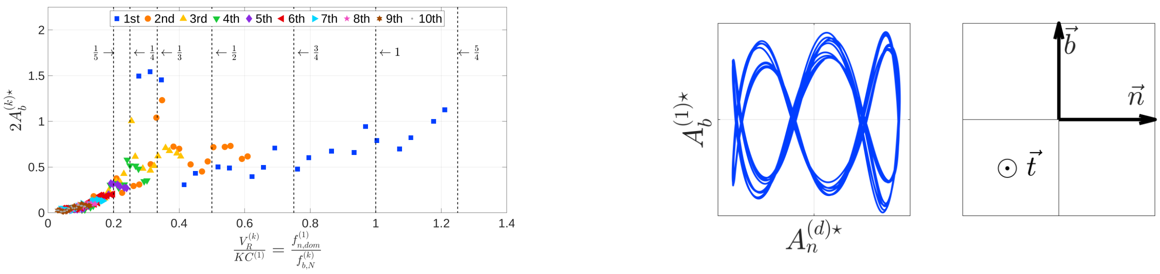

Figure 2: Modal space VSIV results for $30.2 \leq KC^{(d)} \leq 34$: a) Peak lateral modal displacement (each lateral mode is depicted as a different colored marker) as a function of frequency ratio parameter considering the first in-plane mode; b) Modal orbit of selected out-of-plane mode against dominat in-plane modal response.

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References

[1] Grant, R. G. and Litton, R. W. and Mamidipudi, P. (1999) Highly Compliant Rigid (HCR) Riser Model Tests and Analysis. Proc. Annual Offshore Tech. Conf. **2**.

[2] Le Cunff, C. and Biolley, F. and Damy, G. (2005) Experimental and Numerical Study of Heave-Induced Lateral Motion (HILM). OMAE **3**:757-765.

[3] Fernandes, A.C. and Mirzaeisefat, S. and Cascão, L.V. (2014) Fundamental behavior of Vortex Self Induced Vibration (VSIV). J. Applied Ocean Research **47**:183-191.

[4] Rateiro, F. and Gonçalves, R. T. and Pesce, C. P. and Fujarra, A. L. C. and Franzini, G. R. and Mendes, P. (2013) A Model Scale Experimental Investigation on Vortex-Self Induced Vibrations (VSIV) of Catenary Risers. Proc. OMAE **7**:183-191.

[5] Pesce, C. P. and Franzini, G. R. and Fujarra, A. L. C. and Gonçalves, R. T. and Salles, R. and Mendes, P. (2017) Further experimental investigations on vortex selfinduced vibrations (VSIV) with a small-scale catenary riser model. Proc. OMAE **2**.

[6] Fu, S. and Wang, J. and Baarholm, R. and Wu, J. and Larsen, C. M. (2014) Features of Vortex-Induced Vibration in Oscillatory Flow. JOMAE **136**:011801.

[7] Sarpkaya, T. and Rajabi, F. (1979) Dynamic Response Of Piles To Vortex Shedding In Oscillating Flows. Proc. Annual Offshore Tech. Conf. **1979-May**:2523-2528.

[8] Sumer, B. M. and Fredsoøe, J. (1988) Transverse Vibrations of an Elastically Mounted Cylinder Exposed to an Oscillating Flow. JOMAE **1988-11**:387.

[9] Salles, R. and Pesce, C. P. (2017) Experimental Assessments of the Added Mass of Flexible Cylinders in Water: The Role of Modal Shape Representation. Lectures Notes in Mech. Engi.: Proc. of 2017 DINAME **PartF6**:215-235.