COMPARISONS BETWEEN FULL SCALE AND EXPERIMENTAL DATA FOR VORTEX SELF INDUCED VIBRATIONS ON CYLINDRICAL STRUCTURES

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ABSTRACT

The Vortex Induced Vibration (VIV) of cylindrical lines that may occur when the lines are submitted to currents has been extensively discussed in the past few years and its behavior has become well known. However, it is not so well known that the vibrations may occur in a current-less situation, induced by the lateral motion of the structure itself. The present work refers to the last as the Vortex Self-Induced Vibration, the VSIV. This occurrence has been made clear in measurements in full scale with the VIV bottle on a Steel Catenary Riser in the PETROBRAS 18 platform. These data was compared to experiments carried out at the LOC/COPPE/UFRJ (Laboratory of Waves and Currents of COPPE, the Graduate School of Federal University of Rio de Janeiro) by specifically designed tests. In these tests, a totally submerged horizontal cylinder was submitted to harmonic forced oscillations, being free to move in the transverse direction of the forced excitation. The VSIV then showed up, with the cylinder segment, describing vertical trajectories in two (vertical 8-shape), three, four, etc., almost circular trajectories (called the rings in the work). The tests were carried out with Keulegan-Carpenter equal to 10, 20 e 30 and for several amplitudes. The response of the cylinder was represented in non-dimensional parameters corresponding to the amplitude, the excitation and the response frequencies.

1. INTRODUCTION

As previously mentioned, the vibration self-induced by the motion of the structure, in contrast to the classical VIV, is not well defined in its behavior, especially if this vibration is due to the reminiscent wake caused by the forced lateral oscillation. The present work stimulated by this fact call these vibrations Vortex Self-Induced Vibrations–VSIV.

For the VSIV investigation, experiments were carried out with cylindrical structures forced to oscillate harmonically. The cylinder was free to move transversally to the direction of the forced excitation coupled to springs. This arrangement is different, therefore, from the experiments performed by Sumer and Fredsoe (1988), who studied the response of a cylinder in oscillatory regular flow. That is, in the latter case, the flow is oscillatory, but in this case, the totally submerged cylinder is forced to oscillate without any superimposed external flow.

Regarding to the response of a cylindrical structure under conditions of irregular oscillatory flow, some results were published by Kozakiewicz et al. (1994). These experiments were extremely useful to understand the phenomenon of VSIV on risers.

The phenomenon of VSIV also was observed in IPT (Institute of Technological Research) in 1996, while the work summarized in Fernandes et al. (1997) was carried out. On that occasion, tests were conducted with SCR (Steel Catenary Riser) models of the platform PETROBRAS 18 (P-18). The condition of forced lateral oscillations on the top of the SCR was carried out and it was observed that the model responded with significant transverse vibrations.

This phenomenon was also observed in 1998, in the tests conducted for a cooperative project (JIP) between several companies, with the direction of the Engineering PMB (1999). These tests were carried out on the Lake Pend Oreille in Idaho, with large scale models of risers submitted to oscillations on the top. The initial objective was to evaluate the behavior of VIV along the structure. Three configurations of risers were tested: Combined Vertical Axis Riser (CVAR), Lazy Wave Steel Catenary Riser (LWSCR) and Steel Catenary Riser (SCR).

More recently, Cunff et al. (2005) conducted experiments with small scale models of risers subjected to oscillations on the top. They called the observed vibrations Heave Induced Lateral Motion (HILM). The present work proposes another name (Fernandes et al. 2008), since the large transverse vibrations can also be excited by the lateral motion of the floating unit (Surge, Sway).

In the next sections, this paper describes the experiments carried out to establish the existence of VSIV. Moreover, shows the existence of the VSIV through full scale data obtained from the monitoring system of the P-18 Steel Catenary Risers.

2. RESULTS IN FULL SCALE

The amplitude and frequency data obtained from the bottle positioned on a Steel Catenary Riser of P18 will be presented graphically by the relations f_r / f_n, f_r / f_e e σ / D versus V_r, for *KC=10* (*Keulegan-Carpenter* Number), where f_r is the frequency of transverse vibration of the riser, f_n is the natural frequency, f_e is the excitation frequency, σ/D is the standard deviation of amplitude over diameter and V_r is the reduced velocity defined by equation (1). Once the riser is submitted to an irregular flow, f_e is the peak frequency of the displacement spectrum in line with the flow and f_r is the peak frequency of response on the transverse direction. Assuming $f_r = N f_e$, N (relative frequency) is the number of rings observed on the planar trajectories. The value of f_r / f_n is obtained for the closest natural frequency, assuming that the riser response for a considered measurement is close to only one of the natural frequencies.

The selected data of measurements on the flow direction have *KC* close to 10. The *KC* Number also was calculated considering the root mean square of velocity as presented on equation (2).

The figures (1) and (2) present results of these measurements obtained from the monitoring system. The results in terms of amplitude and frequency are presented on figures (3), (4) and (5).

$$V_R = \frac{\sqrt{2}\sigma_U}{f_n D} \qquad (1)$$

$$KC = \frac{\sqrt{2}\sigma_U T_w}{D} \qquad (2)$$

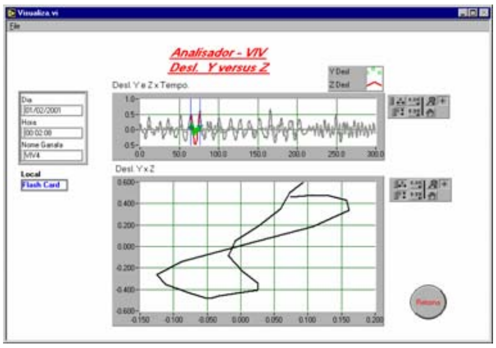


Figure 1: *Planar Trajectory for N=2 and KC=10.*

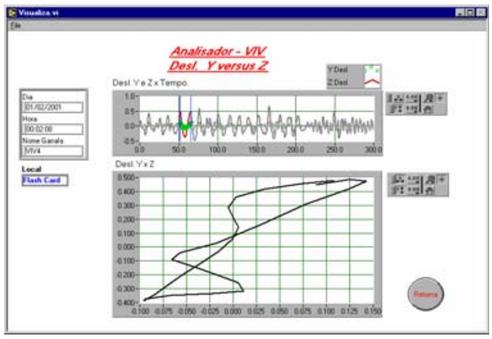


Figure 2: *Planar Trajectory for N=3 and KC=10.*

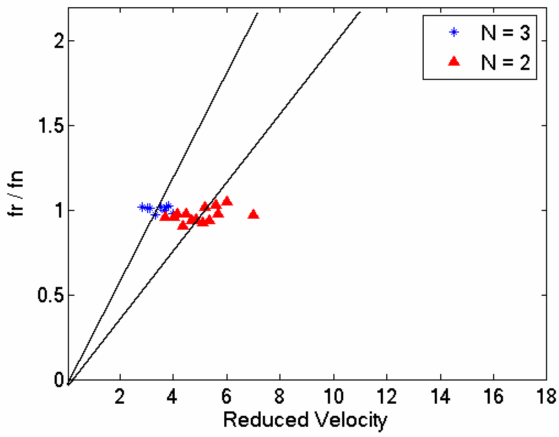


Figure 3: *Frequency Ratio of the SCR for KC=10.*

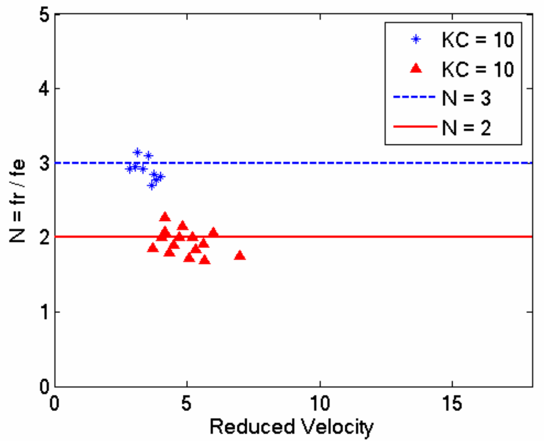


Figure 4: *Relative Frequency of the SCR for KC=10.*

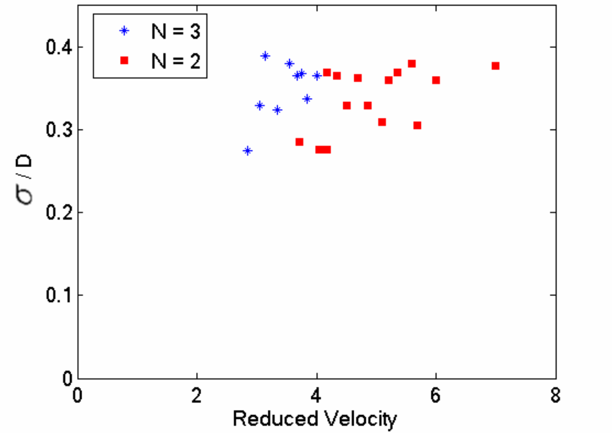


Figure 5: *Response Amplitude for KC=10.*

Some observations can be extracted from the monitoring data of the SCR.

The higher value of *KC* obtained for the SCR as a function of the RMS of velocity is approximately 10. For the irregular excitation and *KC=10*, the riser transversal vibration occurs for $f_r = 2f_e$ and $f_r = 3f_e$, presenting two and three rings, respectively. The maximum amplitude of transversal vibration for the SCR was approximately equal to one diameter.

The difference between the maximum amplitude of vibration between the full scale and the experimental data, as it can be observed on the next section, can be attributed to the differences on damping and mass ratio.

3. EXPERIMENTAL RESULTS

To investigate the VSIV in experiments, a test setup was developed consisting of a horizontal cylinder, submerged in a water channel, in which is applied a harmonic oscillation. The cylinder was sufficiently immersed in the fluid to avoid any effect of the free surface.

The experimental work was carried out on the Laboratory of waves and currents (LOC) at COPPE/UFRJ (Federal University of Rio de Janeiro). The channel is 32 m long, 1 m wide, 1 m deep and has a beach to avoid wave reflections.

The cylinder is 96 mm in length and was positioned horizontally in the channel. The distance between the cylinder extremities and the tank walls was approximately 2 mm.

The forced harmonic oscillation was conducted for different amplitudes and frequencies. The harmonic oscillator constructed for this purpose, consisted of an engine that turns an arm adjusted for the required amplitude transferring the desired amplitude and frequency for the motion of the cylinder. As mentioned before, this cylinder has a degree of freedom in the transverse direction to the forced oscillation, coupled to springs designed for the natural frequency of interest.

The properties of the two models tested are listed in table (1). A photo of the apparatus is shown in figure (6).

Table 1 – Properties of the Models

Properties	Nomenclature	Value
Length [m]	*L*	0.96
Diameter [m]	*D*	0.05 / 0.10
Mass in water [kg]	*M*	4.75 / 5.4
Damping in water *(D=0.1 m)*	ς	0.255
Damp. in water *(D=0.05 m)*	ς	0.282


Figure 6: *Experimental Setup.*

Two cylinders with diameters *D=5 cm* and *D=10 cm* were tested. For the cylinder with *D=5 cm*, the tests were carried out for *KC* (*Keulegan-Carpenter*) Numbers, presented in another form on equation (4), equal to 10, 20 and 30. This corresponds, respectively, to excitation amplitudes of 8 cm, 16 cm and 24 cm. For the cylinder with *D = 10 cm*, the tests were conducted only for *KC=10* that corresponds to a 16 cm amplitude of excitation.

For each one of the *KC* numbers, the Reduced Velocity (V_r) range varies from 0 to 16 through variations on the excitation frequency in accordance with equation (3).

$$V_r = \frac{2\pi f_e A_e}{f_n D} \tag{3}$$

Where, f_n is the natural frequency in water, f_e is the excitation frequency and A_e is the amplitude of the excitation. The *KC* Number is evaluated by the following expression.

$$KC = \frac{2\pi A_e}{D} \tag{4}$$

Through dimensional analysis the other non-dimensional groups significant and related to the tests (Silva, 2006) are f_r / f_n, f_r / f_e, σ / D and *2A/D* that are presented for each Reduced Velocity (V_r). In the previous relations, f_r is the response frequency in the transverse direction, σ is the standard deviation of the vibration in the transverse direction and *2A/D* is the double amplitude of vibration, also, in the transverse direction.

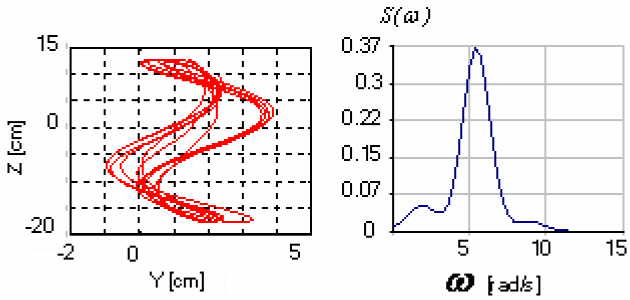
Combining the equations (3) and (4), the equation (5) can be obtained.

$$\frac{f_r}{f_n} = \frac{N}{KC} V_r \tag{5}$$

Where *N* is the relative frequency defined on the equation (6) and represents the number of transversal oscillations per cycle. The number *N* controls the number of rings formed by the combined trajectory of the forced oscillation and the VSIV, as already presented on the full scale results. For constant *KC* and *N*, equation (5) is a set of straight lines for the relation $f_r / f_n \text{ x} V_r$.

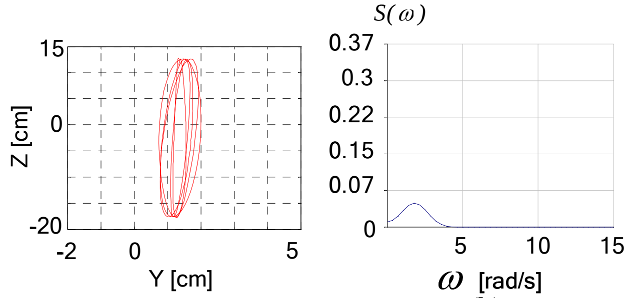
$$N = \frac{f_r}{f_e} \tag{6}$$

In order to exemplify the tests results, figure (7) presents the trajectory on the plane and the density of energy spectrum of the cylinder motion on the transverse direction for a test that matches *KC=20* and $V_r = 7.5$. The figures (8), (9) and (10) present these trajectories restricting some frequency ranges in order to see the influence of each range on the shape of the trajectory. The frequency band considered for each result was obtained by filtering the time series of displacements.



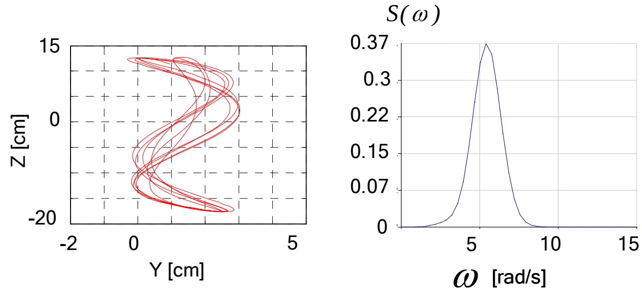
(a) *(b)*

Figure 7: *(a) Trajectory on plane. (b) Transversal Response Spectrum (KC=20 and* $V_r = 7.5$*).*



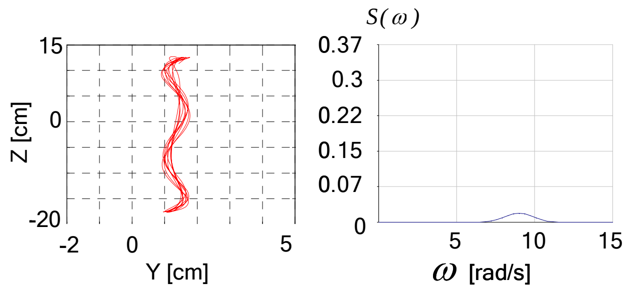
(a) *(b)*

Figure 8: *(a) Trajectory for the low band. (b) Transv. Resp. Spectrum (KC=20 and* $V_r = 7.5$*).*



(a) *(b)*

Figure 9: *(a) Trajectory for the central band. (b) Transversal Resp. Spectrum (KC=20 and* $V_r = 7.5$*).*



(a) *(b)*

Figure 10: *(a) Trajectory for the high band. (b) Transv. Resp. Spectrum (KC=20 and* $V_r = 7.5$*).*

The complete set of results can be obtained from Silva, (2006). In the rest of the section, the main results in terms of $f_r / f_n \text{x} V_r$, $f_r / f_e \text{x} V_r$, σ / D x V_r and *2A/D x* V_r .will be presented.

3.1 Results for the cylinder with *D=5* cm and *KC=10*

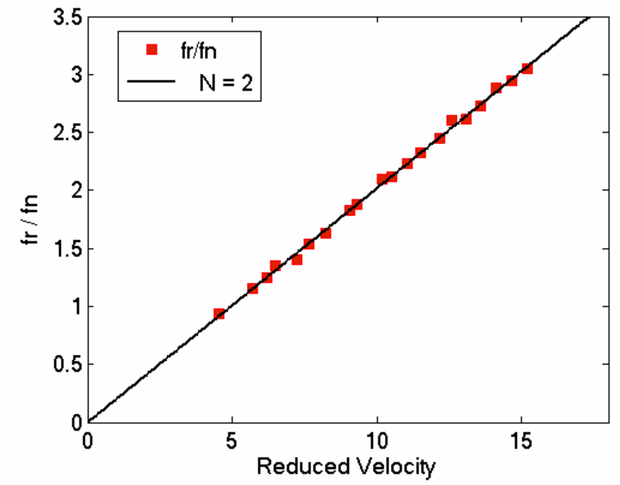


Figure 11: *Frequency Ratio for KC=10.*

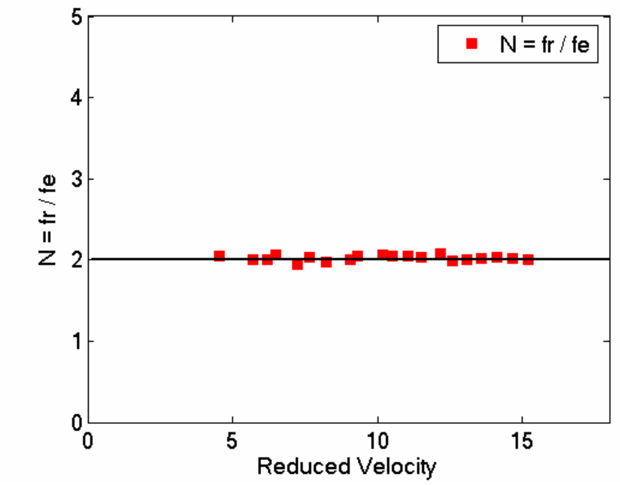


Figure 12: *Relative Frequency for KC=10.*

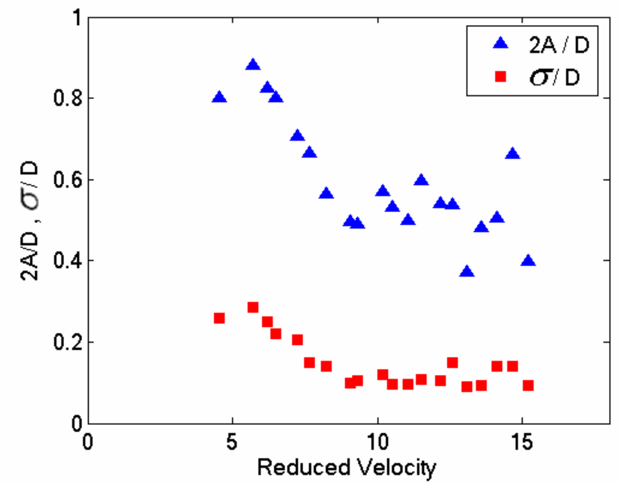


Figure 13: *Response Amplitude for KC=10.*

3.2 Results for the cylinder with *D=10* cm and *KC=10*

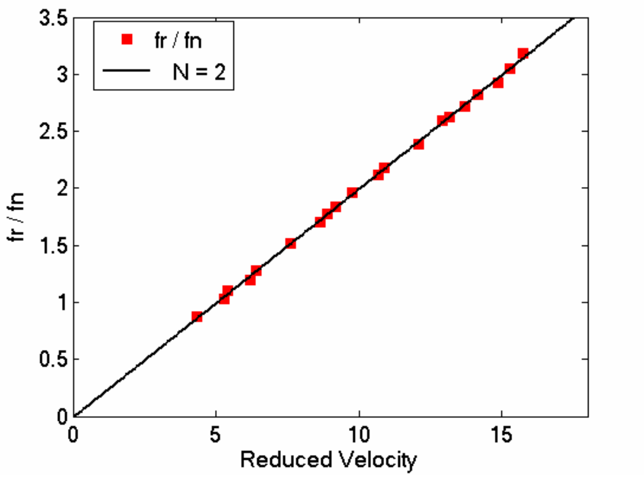


Figure 14: *Frequency Ratio for KC=10.*

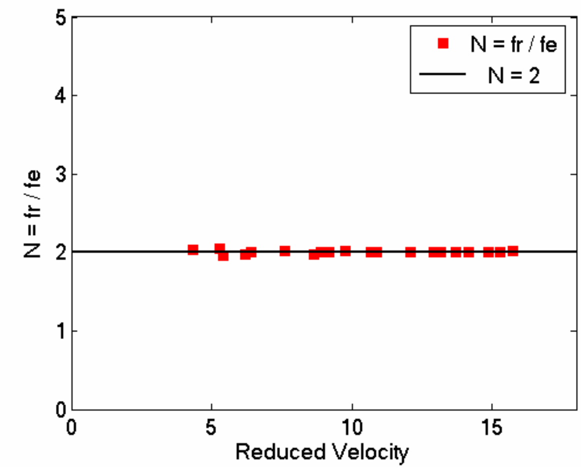


Figure 15: *Relative Frequency for KC=10.*

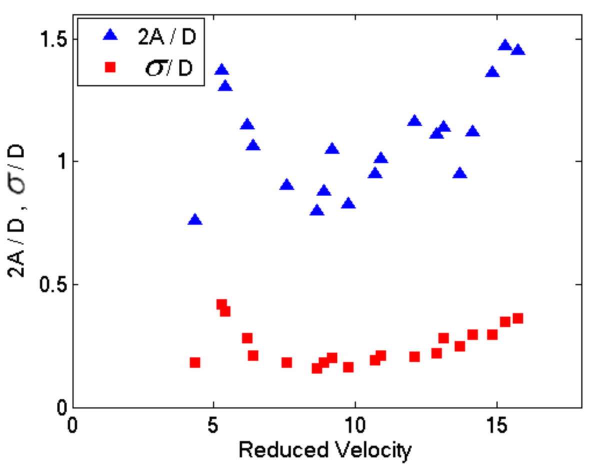


Figure 16: *Response Amplitude for KC=10.*

3.3 Results for the cylinder with *D=5* cm and *KC=20*

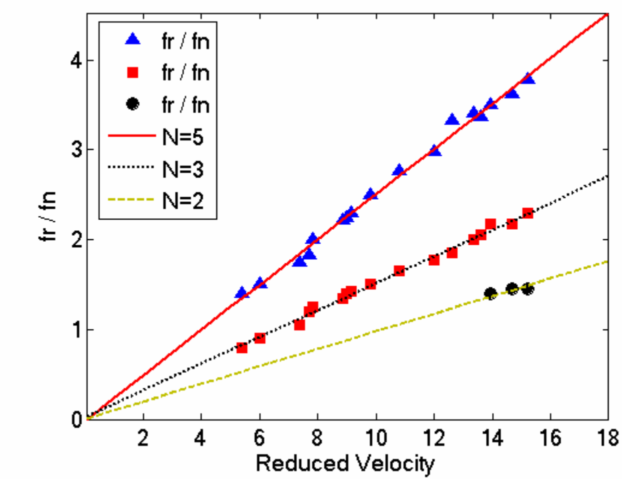


Figure 17: *Frequency Ratio for KC=20.*

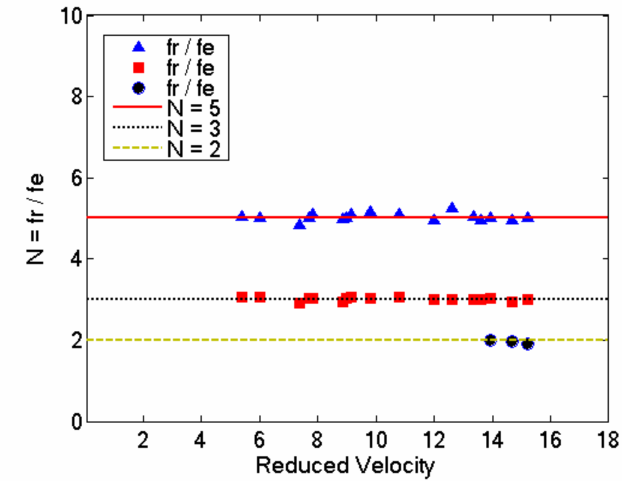


Figure 18: *Relative Frequency for KC=20.*

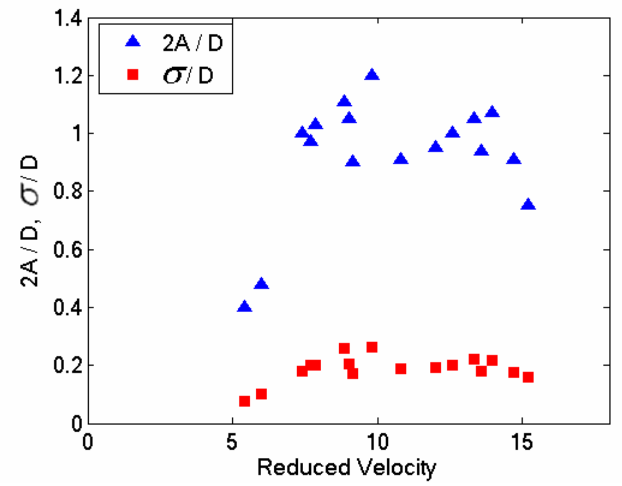


Figure 19: *Response Amplitude for KC=20.*

3.4 Results for the cylinder with D=*5* cm and *KC=30*

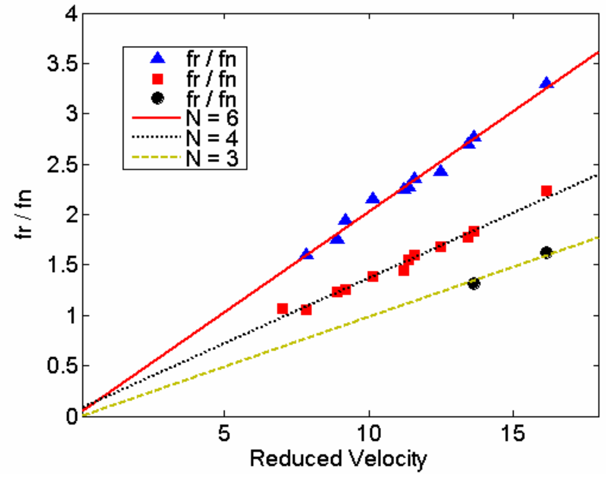


Figure 20: *Frequency Ratio for KC=30.*

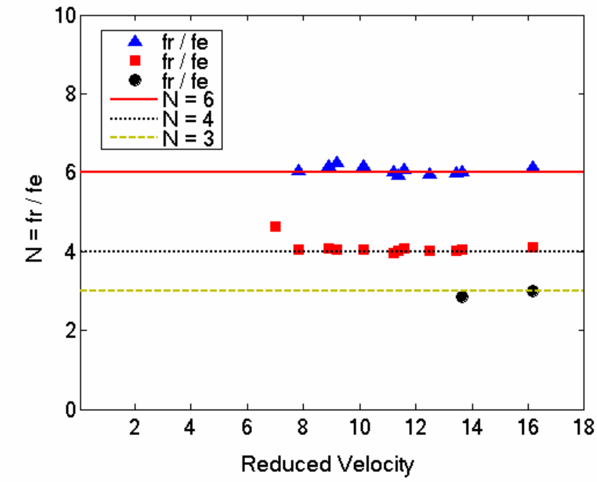


Figure 21: *Relative Frequency for KC=30*

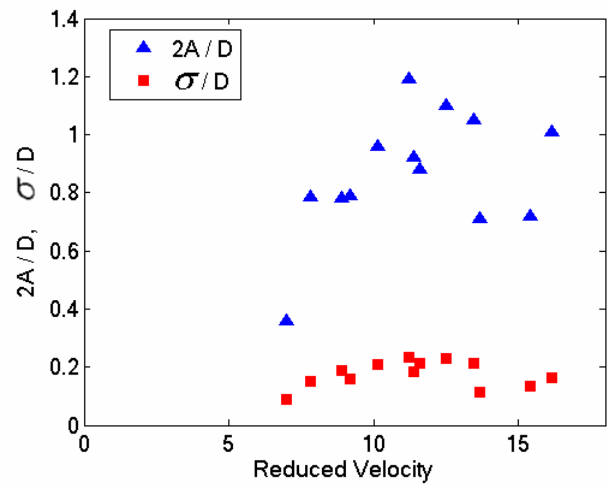


Figure 22: *Response Amplitude for KC=30.*

Related to the previous results, some important observations should be pointed. Firstly, for *KC=10,* the relative frequency N is kept equal 2 for all the values of V_r. For *KC=20*, N is equal 3 and 5, for all the values of V_r. For $V_r \geq 14$, N also is equal 2. For *KC=30*, N is equal 4 and 6, and for $V_r \geq 14$, N is equal 3.

For $N = 2$, it can be observed, from the charts of trajectory, two rings and when *N=3*, it can be observed three rings, and so on.

For *KC=10,* it can be observed that the relation f_r / f_n follows equation (3), for *N=2*. For *KC=20* f_r / f_n also follows equation (3), for *N=2*, *N=3* and *N=5*. As well as for *KC=30,* with *N=3*, *N=4* and *N=6*.

The VSIV amplitude for the model with *D=10 cm* and *KC=10* is higher than that for the cylinder with *D=5 cm* and *KC=10,* once the second one has higher damping and mass ratio.

The VSIV presents a combination of harmonic frequencies in the response. It can be observed from the spectrum presented on figure (7) and from the response frequency results.

Consistently, for *KC=20,* the dominant response frequency is $f_r = 3 f_e$, once in the charts of trajectory it can be observed that the tendency of three rings is stronger than the other ones.

For *KC=10*, the VSIV starts to occur for $V_r = 4.5$, for *KC=20,* it starts for $V_r = 5.5$, and for *KC=30* it starts for $V_r = 6.5$.

4. CONCLUSIONS

It can be concluded from the tests and the full scale measurements that the VSIV may lead to large amplitudes. It may imply large damage to cylindrical structures applied on offshore industry like risers.

The large amplitude of vibration on the full scale measurements can be attributed to the vertical forced oscillation.

The VSIV showed to be very different from the better-known VIV, especially when comparing the shapes of the amplitude charts.

The present work focused on kinematics. Future works intend to investigate the dynamics of the structure and the flow visualization of the VSIV.

5. ACKNOWLEDGMENTS

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