Experimental Verification of the Whipping Phenomenon on Offshore Catenary Risers Caused by the Internal Flow Momentum

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Abstract. *A laboratory-scale model was designed to investigate the influence of the internal flow of two-phase oil and gas mixtures on the motion of slender risers hanging in catenary configuration used for offshore petroleum production in deepwaters. The behavior of the riser arises from an interplay of various dynamic phenomena: the long length and relative small diameter of the pipeline confers a cable-like elasticity to the system, which, under static loading, assumes a catenary shape; dynamic excitation caused by environmental conditions generates oscillations; the internal flow momentum may impose a natural whipping displacement – compounding sway and bending – adding to the concerns of stress and fatigue; the internal flow may display different two-phase patterns (bubbles, slugs, intermittent, annular or stratified mixtures) possessing completely different characteristics; also, the fluids' dynamic loading depends on the flow rates of both oil and gas phases. Although computer codes have been developed to simulate the motion of risers, there is much need for experimental validation. This research attempts to discern the effects of the internal flow, discriminating it from the other dynamic phenomena. Accelerometers and video acquisition were employed to verify the phenomenon and to determine the frequency spectrum of the oscillations.*

Keywords*: Catenary Riser Whipping, Offshore Petroleum Production, Internal Flow*

1. INTRODUCTION

Over the last decades, the petroleum industry went through significant changes. The exhaustion of onshore oil reserves and the rise of international prices of petroleum led to the exploration of new reservoirs under deep waters. Researches have been conducted to develop equipments and methods adjusted for these challenging conditions.

In this quest, the riser – a suspended pipe connecting the subsea wellhead to the surface production facilities atop the offshore platform – is a critical element of the system. In deep waters, the riser may be considered a slender body, due to its long length and relative small diameter, assuming a catenary shape. The riser is submitted to several environmental loads. The currents, waves and platform motions may impose a natural oscillatory 3D-displacement, which may cause failure due to fatigue of the material.

The present work attempts to assess the effects of the internal flow, discriminating it from the other dynamic phenomena. There is not much about this subject in the literature. The variation of the momentum of the produced petroleum fluids inside the riser originates a dynamic load on this system, which may induce a whipping movement of the suspended pipeline. Also, the gas-liquid flow may assume different configurations (bubbles, slugs, intermittent and annular patterns), each one possessing different properties, and requiring specific laboratory tests to properly characterize its behavior.

A laboratory-scaled model was designed to investigate the influence of the internal flow on the motion of the slender catenary riser. The riser model was manufactured from a flexible silicone tube, where air and water were used to generate the two-phase flow. The experimental apparatus was equipped with flow-meters, accelerometers, a video acquisition system and a load-cell. Tests were run to evaluate the dynamic response of the model when submitted to several flow rates corresponding to actual field conditions. Data sets were acquired for the pipe displacements, the frequency spectrum of oscillations, the sustaining force at the top and the flow rates of the two-phase patterns with the help of a data-logger system.

The results showed that there is a significant relationship between the flow rates of the liquid and gas, the two-phase patterns and the magnitude of the dynamic response of the riser model. It was verified that the internal flow may play a role on the structural loading of deepwater risers.

2. LITERATURE REVIEW

There are two kinds of risers, namely rigid risers and flexible risers. There are a variety of configurations for marine risers, such as free hanging catenary riser, top tensioned production riser and others. A widely used configuration for deep water is the free hanging catenary riser (Bai, 2001).

The steel catenary riser (SCR) is self compensated for the heave movement (vertical motion of the platform), *i.e.* the riser is lifted of or lowered on the seabed. This riser is also extremely sensitive to environmental loads. Even thought the riser is designed to resist to a high level of stresses, the combination of vessel motions, environmental loads and the effects of the internal flow may result in reduction of riser's service life. Besides that, mechanical properties of the riser and also the hydrostatic pressure due to the internal and external fluids present some effects on the riser (Kubota, 2003).

The riser response to environmental loads has been studied thoroughly during the years, and the methods for determining riser's behavior are well known. However, considering pipe's local curvature due to the catenary shape, the authors suspected that the momentum of the internal flow might induce an excitation along the riser's length. Based on previous works, it is clear that this phenomenon may not be neglect.

According to Gregory and Paidoussis (1966), certain critical values of the fluid velocity, inside a tube, may bring instability to the system and large amplitude oscillations will occur. Paidoussis (1970) proposed a physical model to determine the conditions of stability of vertical tubular cantilevers conveying fluid. It was found that the dynamic of this system depends on three dimensionless parameters, related to the inertial forces, to the bend stiffness module and to the flow conditions. Also, an experimental work was conducted in order to validate the theoretical model. The results showed good agreement between the theory and experiment.

Moe and Chucheeepsakul (1988) investigated the effects of a steady homogeneous flow inside a vertical riser, with constant top tension. The effect of the internal flow on natural frequency was considered moderate, with exception to the situations where the flow rates were high. For this case, the bending moment cannot be neglected. They also indicate that instabilities may occur in risers due to the internal flow, mainly for the case of time varying flows (intermittent).

Patel and Seyed (1989) presented the governing equations to flexible risers, allied with the equations for the excitation forces due to the internal flow. They show that the curvature and the flow intermittence, in a catenary flexible riser, induce forces due to variation of the momentum of the flow. They also assert that two-phase slug flow (intermittent) induces large fluctuating tensions to the pipe, causing an important cyclic fatigue loading.

Wu and Lou (1991) developed a mathematical model to a vertical riser motion. They aimed to examine the effects of the internal single-phase flow and the flexural rigidity in the dynamic behavior of the riser. The model was also subjected to the concomitant action of wave, current and platform offset. The rigidity becomes more important to the dynamic response of risers at high internal flow velocities.

Most of the times, petroleum production occurs as a multi-phase flow of oil, gas, water and also sediments. Usually, the main phases are oil and gas, although water is also present in many real cases.

Taitel & Dukler (1980) developed a mechanistic model to foresee the transitions among the several two-phase flow patterns in vertical pipes. They showed that it was necessary only two dimensionless groups to describe the transition between two regimes. Based on these parameters, a generalized map was made to assist the identification of the flow patterns. Their work presented a good agreement when compared with experimental data.

Beggs and Brill (1973) developed a method to predict the pressure gradient in horizontal and inclined rigid pipes. In their work, they showed that the liquid holdup (liquid content in a section of pipe, expressed in volumetric fraction of the section) as well as the flow patterns varies with the pipe inclination. Thus, the regimes observed in an inclined flow may be quite different from the ones in a horizontal flow.

Silva (2006) presented an experimental work where the oscillatory movement of the slender vertical riser was taken into account. He studied the two-phase flow patterns for vertical upward flow inside a flexible duct submitted to several flow and external loading conditions. He verified that no significant variation on the two-phase flow patterns, due to the oscillatory motion of the riser, occurred for frequencies less than 1 Hz, although the pipe movement had a distinct effect on the head loss.

3. METHODOLOGY

3.1. Scale Reduction

The study of the dynamics of the interaction of the fluid flow and the elastic behavior of the hanging pipe must be conducted in two fronts – experimental and theoretical. In the present paper, the experimental work is described. Practical factors dictated that a real-scale prototype could not be used; deepwater risers reach dimensions of the order of thousands of meters. Therefore, a laboratory-scale model was designed limited to the actual existing facilities. The Pi-Buckingham procedure (Fox & McDonald, 1998) was applied to determine the dimensionless parameters for the scale reduction, including geometric, structural, and flow variables.

Theoretically, if the values of the dimensionless parameters were kept equal for the model and the prototype, then complete geometric, cinematic and dynamic similarities should be maintained. Unfortunately, it is very difficult to reach exact similarity for complex phenomena such as the one studied here. One possible strategy is to enforce the equivalence of the most influential parameters discarding others. Although this may hinder the direct application of the lab-data to the field by a simple rule of proportionality, it provides theoretical insight into the physical phenomenon, if wisely done, and it supplies the numerical simulations with data to validate computer models.

Many risers are in operation today, but a real case under ultra-deep waters would imply a very high reduction of scale to fit inside the laboratory, which might have jeopardized the validity of the lab-work. A case for shallower waters had to be chosen retaining dimensions for which laboratory results would still be meaningful. The selected prototype (Figure 1) is at a water depth of 900 m, and the total height of the laboratory is 12.5 m, leading to a scale factor λ = 72. Geometric similarity requires that

$$L_{\text{model}} = \frac{L_{\text{prototype}}}{\lambda} , \tag{1}$$

where L is any dimension of the model and prototype. Dynamic similarity, regarding the inertia of the riser yields

$$m_{\text{model}} = \frac{m_{\text{prototype}}}{\lambda^2} , \tag{2}$$

where m is the linear mass of the pipe, while similarity regarding the structural elasticity leads to

$$EI_{\text{model}} = \frac{EI_{\text{prototype}}}{\lambda^5} , \tag{3}$$

where the bending stiffness EI is given by the Young's Modulus E and the moment of inertia I. Table 1 presents the main properties of the prototype and the corresponding values for the model.

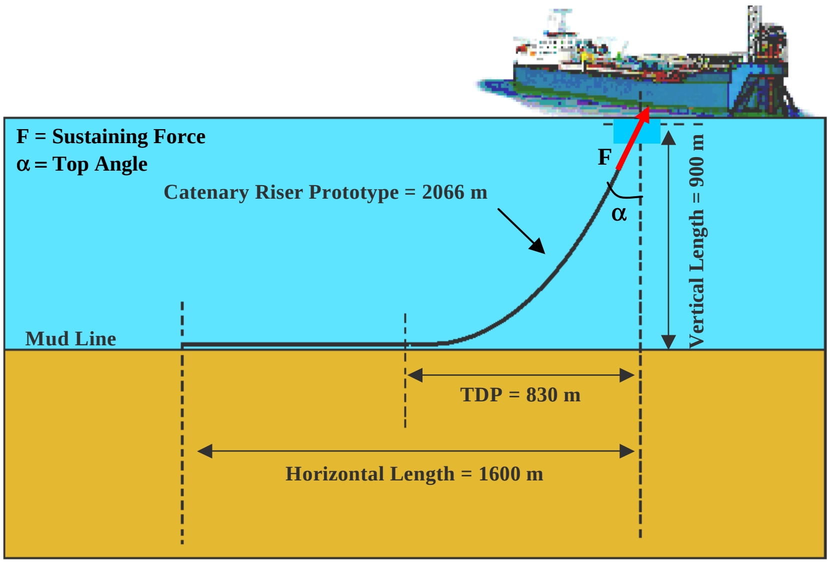

Figure 1. Prototype Properties.

Table 1. Properties of the Prototype and the Model.

Properties	Prototype	Model
Total Lenght	2066 m	28.70 m
Horizontal Lenght	1600 m	22.22 m
Vertical Length	900 m	12.5 m
Touch Down Point - TDP	830 m	11.50 m
Internal Diameter	230 mm	3.2 mm
External Diameter	270 mm	3.7 mm
Linear Weigth	128.5 Kg/m	0.024 Kg/m
Bending Stiffness Module - EI	27.3×10^6 Nm²	14.1×10^{-3} Nm²
Axial Stiffness Module - EA	3.40×10^9 N	9.11×10^3 N

It would be next to impossible to establish realistic flow conditions for the thin diameters shown in Tab. 1. Therefore, the choice of the model diameter *D* was based on flow similarity (discussed in the following section), while Equations (1), (2) and (3) guided the values of *L*, *m* and *EI*, respectively.

3.2. Flow Patterns

During the design of the apparatus, two correlations were employed for predicting the two-phase flow patterns along the riser's length. Considering that the model consists of one horizontal section, lying on the floor, and one catenary shaped section, suspended from the ceiling, the two-phase flow will have distinct patterns along those regions.

Beggs and Brill's correlation (1986) was applied to the horizontal section. This correlation distinguishes three different groups of patterns: distributed (either bubble or mist), segregated (either stratified or annular) and intermittent (either plug or slug), depending on the flow rates of each phase. For the catenary section, where the flow is upward, the patterns were predicted using Taitel and Dukler's correlation (1980) for vertical flow. According to this correlation, the superficial velocities of both phases are the flow variables that govern the patterns. The superficial velocity is defined as the phase flow rate (Q_{phase}) divided by the total area of the pipe section (A_{pipe}),

$$V_{phase} = \frac{Q_{phase}}{A_{pipe}} . \qquad (4)$$

Throughout this article, V_{LS} and V_{GS} refer to the liquid and gas phase respectively. No reference was found in the literature for two-phase flows inside catenaries. Therefore Taitel and Dukler's data are employed as a mere reference for the expected flow behavior. The flow rates of water and air used in this experiment were determined from the prototype flow rates, equating the Froude number (Fr) and the input liquid content (ϕ) for prototype and model. This was intended to assure flow similarity. Although other dimensionless numbers (such as the Reynolds number) may also influence the flow behavior, it would be very difficult to correlate all these parameters in order to obtain complete flow similarity. Furthermore, according to Beggs and Brill (1973), the Froude number and input liquid content are the most significant variables for the determination of the two-phase flow holdup. The Froude number is defined as

$$Fr = \frac{V_{flow}}{\sqrt{gD}} , \qquad (5)$$

where V_{flow} is the volumetric-mean velocity of the two-phase mixture (Q_{flow}/A_{pipe}), *g* is the gravity acceleration and *D* is the diameter of the pipe. The input liquid content is defined as

$$\phi = \frac{Q_{liquid}}{Q_{flow}} . \qquad (5)$$

4. EXPERIMENTAL APPARATUS

4.1. Laboratory Setup

Figure 2 shows a sketch of the LabPetro's building at Unicamp where the experimental apparatus was located. The dimensions are indicated in the figure.

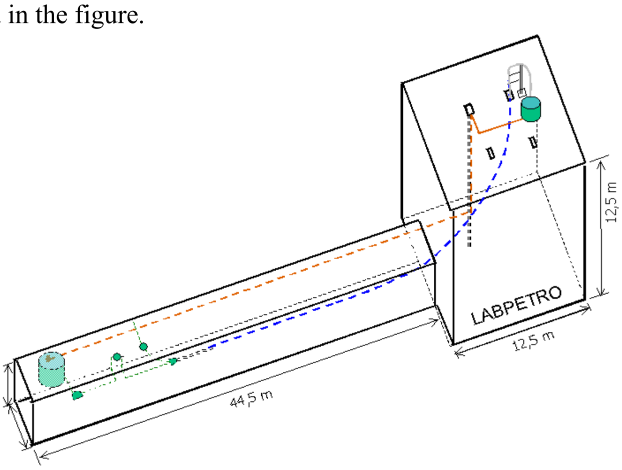

Figure 2. Sketch of Laboratory

4.2. Description of the Experimental System

Water is supplied by a tank with 1 m³ capacity installed on the terrace of the laboratory, feeding a pump on the ground floor that pressurizes the water before it passes through flow-meters (Fig. 3). The large range of liquid flow rates in the experiment required two flow-meters. One for lower flow rates, from 0.8 to 8.0 L/min, and another to higher rates, from 3.6 to 36.0 L/min. The flow is directed through only one of these meters. After this point the water enters the two-phase injector. A rotating compressor supplies pressurized air, which is introduced in the system through a restriction valve, connected to a manometer. The air flow rate is measured by a flow-meter, in the range of 0 to 67.0 L/min, before it is directed to the injector. The injector is composed of a mixer and a transparent outlet pipe for visualization. The fluids leave the injector as a two-phase flow. Downstream, the two-phase flow enters the catenary riser model.

Several materials have been investigated for the riser model and a flexible silicone tube was chosen. The selection of the material was based on the scale of $1{:}72^5$ between the flexural rigidity of the model and prototype, as mentioned before. A bending stiffness module of $16.04 \cdot 10^{-3}$ N·m² was adopted. The model, suspended from a steel frame on the terrace of the laboratory, assumes a catenary shape. The riser has a length of 28.70 m, its inner and external diameters are 19 mm and 25 mm, respectively. The model's weight per unit length is 0.254 kg/m.

Five cameras (Fig. 4) focusing the whole extension of the model are positioned to capture images, which are processed, afterwards, to yield the frequency and amplitude of the oscillations. Color marks are fixed along the length of the riser for the cameras to target. The video acquisition system has a maximum sampling rate of 30 fps (frames per second). The top of the riser model is held up by a load-cell, which provides the assessment of the top tension. The load-cell is connected to its frame support by a pin-joint designed to allow the variations of the top angle of the catenary under the dynamic loading.

The two-phase flow exits the riser model after the load-cell through a tube returning to the water tank, where the gas is vented to the atmosphere and the liquid is reinserted into the system. All the signals generated by the instruments are transmitted to the data acquisition system, where they are stored for later processing and analysis.

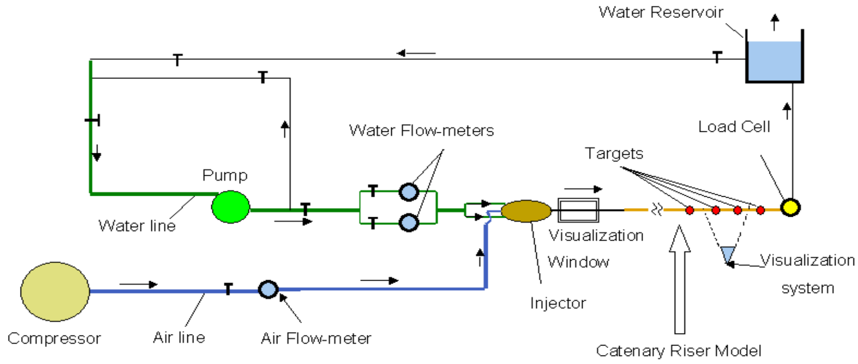

Figure 3. Circuit Diagram of Experimental

5. EXPERIMENTAL PROCEDURE

The shaded region on Fig. 5 represents the range of gas and liquid superficial velocities of interest in this experiment. The range was obtained from the prototype flow conditions by a scale reduction analysis, as presented before. The range encloses a large area of the map of Taitel & Dukler where the bubble, slug and intermittent (churn) patterns are foreseen.

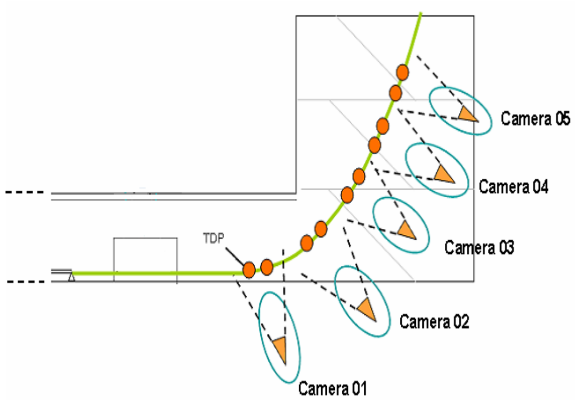

Figure 4. Cameras of the Video Acquisition System

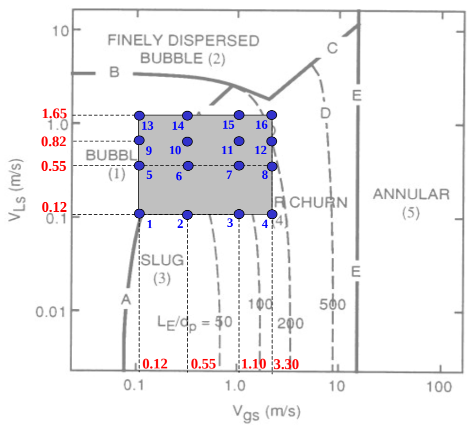

Figure 5. Range of Gas and Liquid Superficial Velocities on Taitel & Dukler Map

The sixteen circles inside the shaded area represent pairs of gas and liquid superficial velocities, selected for the experimental tests, covering all the region of interest.

Table 2 shows the superficial velocities and the corresponding flow rates for each one the sixteen analyzed cases. The cases were grouped by the liquid flow rate. In the same group, the water flow rate is maintained constant while the gas flow rate is increased.

The initial tests were intended to explore qualitatively the influence of several variables on the system behavior, resulting in an approximate classification of the intensity of the whipping motion. Also, the frequency band of the phenomenon was determined.

In the next stage, a quantitative analysis was performed. All selected cases were run to allow measurements of the pipe displacement and the sustaining force at the top as a function of time. For each case, the gas and liquid flow rates were adjusted and a quasi steady-state was achieved. Images of the riser model were captured in video. These images were stored in a computers for later processing. The two-phase flow pattern was observed and classified following the nomenclature cited before. The load-cell provided the instantaneous sustaining force. The raw data had been collected during an interval of 120 seconds at a rate of 5 Hz, but the first and last five seconds were discarded during the analysis of the data. The tests were repeated and the results were compared. They are shown in the next section.

Table 2 – Superficial Velocities and Flow Rates

Group	Case	Liquid Phase		Gas Phase	
		Flow Rate (L/min)	Superficial Velocity (m/s)	Flow Rate (L/min)	Superficial Velocity (m/s)
1	1	2.05	0.12	2.05	0.12
	2	2.05	0.12	9.41	0.55
	3	2.05	0.12	18.81	1.10
	4	2.05	0.12	56.43	3.30
2	5	9.41	0.55	2.05	0.12
	6	9.41	0.55	9.41	0.55
	7	9.41	0.55	18.81	1.10
	8	9.41	0.55	56.43	3.30
3	9	14.02	0.82	2.05	0.12
	10	14.02	0.82	9.41	0.55
	11	14.02	0.82	18.81	1.10
	12	14.02	0.82	56.43	3.30
4	13	28.22	1.65	2.05	0.12
	14	28.22	1.65	9.41	0.55
	15	28.22	1.65	18.81	1.10
	16	28.22	1.65	56.43	3.30

6. RESULTS AND DISCUSSION

The values of the displacements (δ), the frequency spectrum of oscillations, the two-phase flow pattern and the sustaining force at the top were acquired for the sixteen cases studied. The following discussion will focus on the results obtained for the group 2 (cases 5 to 8), as shown on Tab. 2. Similar results, not shown here for lack of space, were observed for the other twelve cases.

6.1 Riser’s Displacement

Figure 6 presents the graphics of displacement versus time obtained from camera 04. The vertical axis represents the amplitude of oscilation normalized by the riser model external diameter. The horizontal axis is the time interval in seconds. The displacements are referenced to the static equilibrium position of the catenary model fully filled with water (100% holdup).

It should be noticed that as the air flow rate is increased there is a significative growth on the averaged amplitude of the riser whipping motion. This behavior can be explained by the variation of momentum of two-phase flow inside the riser. Both the mass and the velocity of the mixture are varying in each section of the model, as a function of time. Moreover, due to the catenary configuration of the riser, the velocity of the flow is also repeatedly changing in direction. This intermittence of the flow momentum and direction causes a variable excitation within the pipe (along its length as a function of time) and, consequently, an oscillatory response of the riser. As the air flow rate (or air superficial velocity) increases, the magnitude of the intermittences also increases. The larger amplitudes of oscillations indicate that the excitation may be approaching the natural response of the system.

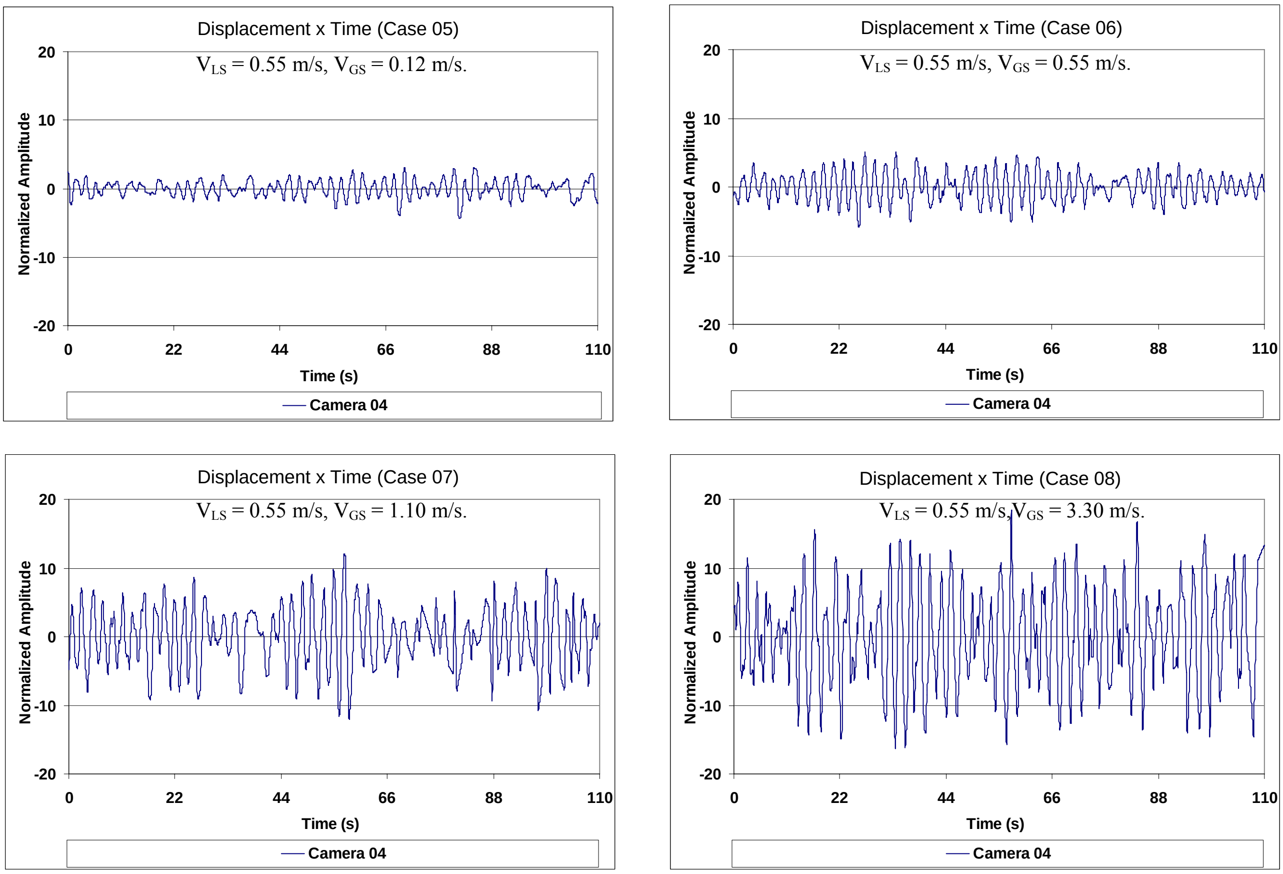

Figure 6. Graphics of Displacement Versus Time

6.2 Two-Phase Flow Patterns

For every case studied, the two-phase flow pattern was observed and the range of the magnitude of the whipping motion was classified using the ratio of the displacement to the pipe diamenter δ/D, as shown in Tab. 3.

Table 3 - Two-phase Flow Patterns and Magnitude of Whipping Motion

Group	Case	Two-Phase Flow Pattern	Magnitude of Whipping Motion (δ/D)
1	1	Slug	3 - 6
	2	Slug	3 - 6
	3	Slug / Intermittent	6 - 9
	4	Annular	0 - 3
2	5	Slug	0 - 3
	6	Slug	3 - 6
	7	Slug / Intermittent	6 - 9
	8	Intermittent / Annular	9 - 12
3	9	Slug	0 - 3
	10	Slug / Intermittent	0 - 3
	11	Slug / Intermittent	6 - 9
	12	Intermittent / Annular	12 - 15
4	13	Slug	0 - 3
	14	Slug	3 - 6
	15	Slug / Intermittent	6 - 9
	16	Intermittent / Annular	12 - 15

It was verified that the cases where the slug pattern was observed, in a general way, were associated to magnitudes of whipping in the range of 0 to 6 diameters. The cases classified as a transition between the slug and intermittent patterns presented, predominantly, magnitudes of whipping between 6 and 9 diameters. The higher magnitudes of whipping (9 – 15 diameters), cases 8, 12 and 16, correspond to the transition between intermittent and annular patterns. These may be critical operational conditions for the riser.

Care must be taken to analyze case 4. As discussed before, if the water flow rate is maintained constant and the air flow rate is increased, larger whipping motions are expected in the model. Since case 4 has the highest air flow rate inside group 1, greater intensities of whipping should be verified. However, it was observed that case 4 presents a low magnitude of whipping. This behavior can be explained considering that the flow has changed from intermittent to annular, due to a very high air superficial velocity. Thus, the flow behaves similarly to a single-phase air flow, almost homogeneous, where the whipping motion is very low, because of lower levels of intermittency.

6.3 Frequency Spectrum

The frequency spectrum of oscillations was determined from the raw data of displacements. The methodology of the Fast Fourier Transform (FFT) was employed for this purpose. This tool is used to transform a set of data from the time domain to the frequency domain. The FFT graphics for cases 5 to 8 are presented in Fig. 7. On the horizontal axis are the frequency values. The vertical axis is the magnitude of the FFT, which provides an idea of the weight of a determined frequency range on the total frequency spectrum.

It can be noticed that there is no significant frequency above 1.5 Hz. This is true for all cases tested. Furthermore, the dominant band of frequency is situated between 0.2 and 0.6 Hz, showing that this is the range of natural response of the riser model. It is also interesting to verify that the magnitude of the FFT increase from case 5 to 8. This behavior reflects the growth in the "energy" of the whipping motion caused by the increment in the air flow rate, as discussed previously.

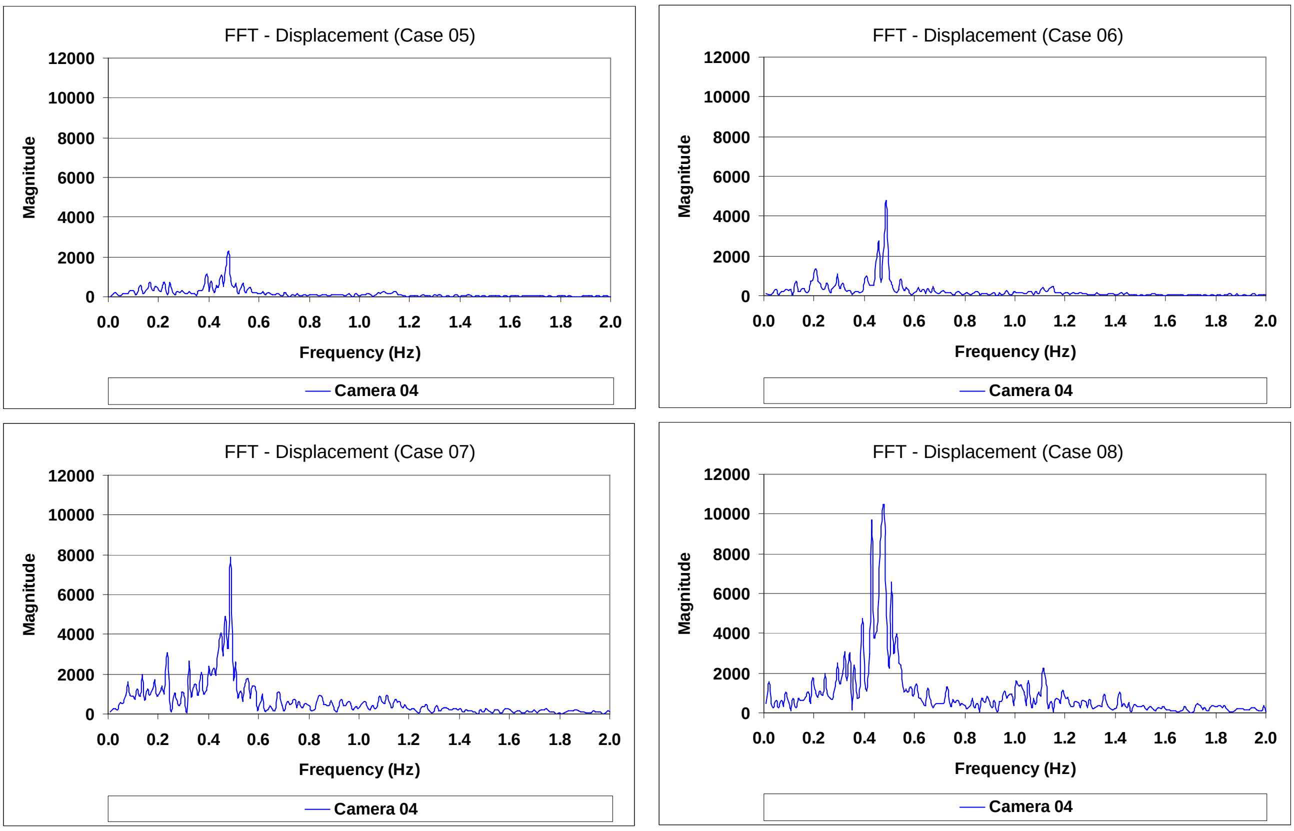

Figure 7. Frequency Spectrum Graphics

6.4 Sustaining Force at the Top

The magnitude of the sustaining force at the top of the riser model through the time was measured with a load cell. The results for case 5 to 8 are shown in Figure 8. On the vertical axis are the sustaining force values while on the horizontal axis is the time interval in seconds. The variation of the sustaining force and its mean value are plotted.

Recalling that the air flow rate is increasing from case 5 to 8, it should be noticed that there is a decrease of the mean of the sustaining force in this direction. This behavior is due to the reduction of the two-phase mean density inside the riser model, caused by the larger fraction of air volume in the pipe. Notice that the mean sustaining force is always limited between the values of the static sustaining force when the pipe is fully filled with water (120 N) and when it is completely dry (60 N).

On the other hand, it is observed that the amplitude of oscillations of the sustaining force increases as the air flow rate is augmented. This is in agreement with the results obtained for the displacement and the same analysis can be applied.

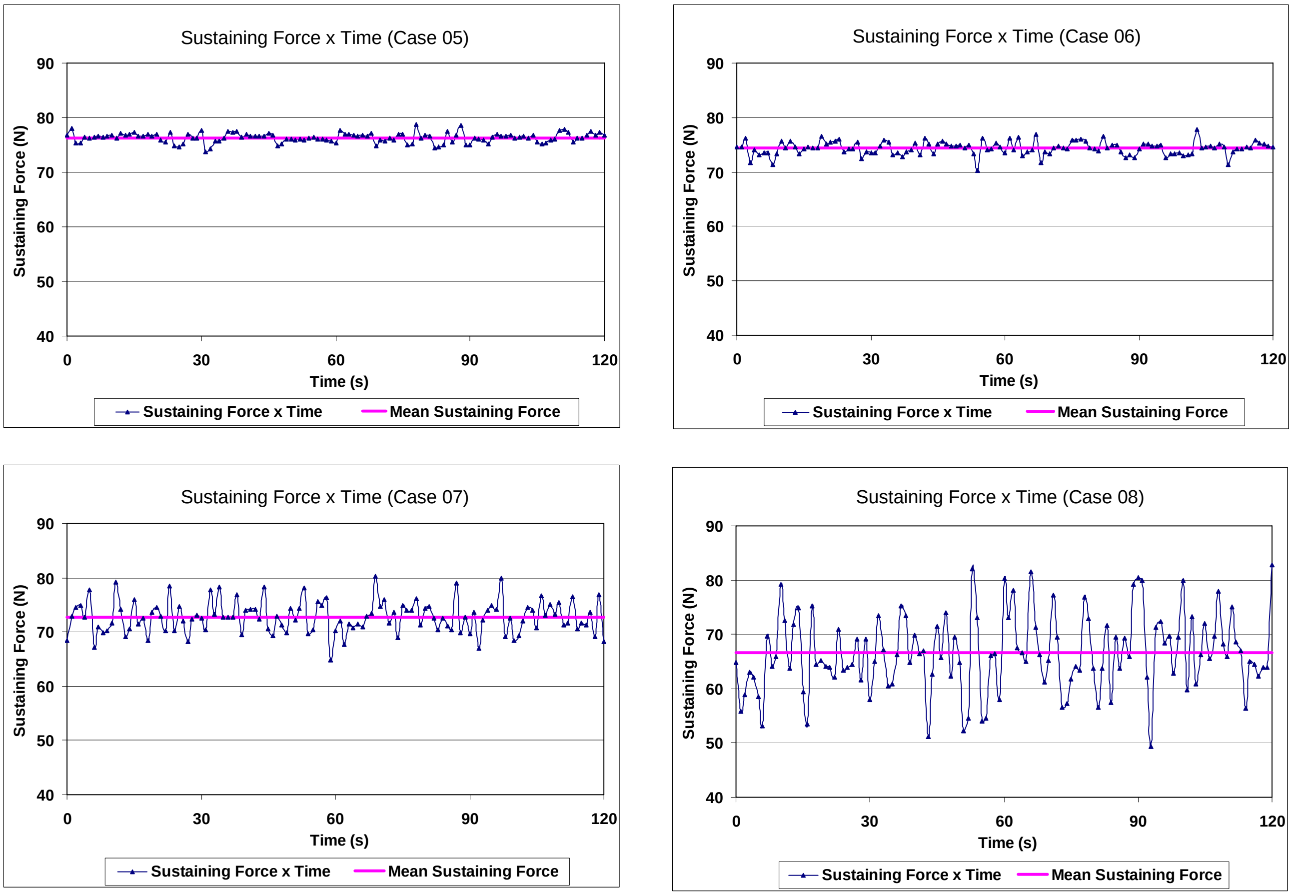

Figure 8. Graphics of Sustaining Force Versus Time

7. CONCLUSIONS

This research presented an innovative a study of the influence of the internal flow on the structural loading of the catenary slender riser. A laboratory-scaled model was designed for this purpose. The main geometric, structural and flow parameters were correlated between the model and the prototype attempting to achieve physical similarity for this phenomenon.

Sixteen cases representing pairs of air and water flow rates were chosen in the range of interest for this experiment. Several tests were run to evaluate the dynamic response of the model when submitted to this flow conditions. Data sets were acquired for the displacements, the two-phase flow pattern, the frequency spectrum of oscillations and the sustaining force at the top.

The results showed that there is a significant relationship between the flow rates of the liquid and gas, the two-phase patterns and the magnitude of dynamic response of the riser model. If the liquid flow rate is fixed and the air flow rate is increased, it was observed that both the magnitude of whipping motion and the variation of the sustaining force at the top also increase. The frequency spectrum of the phenomenon shows that the dominant response frequency in the model is situated between 0.2 and 0.6 Hz. The natural frequencies of the model must be evaluated to provide a better understanding of the riser response. Efforts are being conducted in order to measure the eigen-frequencies for the cases when the model is empty and fully filled with water. These values will be compared with analytical results and published in future papers.

The amplitudes of the displacements reached up to 15 times the external model diameter. Dangerous conditions were observed and indicate that the effect of the internal flow may play a role on the structural dynamics of the slender catenary riser. Further investigation is under way to determine the frequencies of the excitation imposed by the internal flow.

In this study, the effect of internal flow was investigated discriminating it from the other dynamic phenomena. The importance of considering this effect on the design of catenary risers for deepwater production was verified by this initial study. It will be the starting point for future researches about the phenomenon.

8. ACKNOWLEDGEMENTS

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