FLOW INDUCED MOTIONS OF MULTI COLUMN FLOATERS

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ABSTRACT

Recent years have shown an increasing interest in low frequency response of offshore floaters in current. Spar VIM behavior and Semi Submersible flow induced behavior is known from calm water tow tests. Recent tow test projects have also shown low frequency TLP response in steady current. The motions from the model tests are used in the global analysis of the mooring systems and risers for these platforms. This paper discusses the dynamic behavior in current of multi column floaters and the associated complex flow patterns. Shielding between columns is addressed as well as the effect of mass ratio (i.e. floater mass divided by displacement). It is shown that lower mass ratios such as for conventional TLP’s may result in larger sway response than for deep draft semi submersibles. The motion behavior is discussed as well as the increase in total mean current loads due to transverse motions.

BACKGROUND

The vibration that is caused by a fluid flowing around a bluff body is known as flow-induced vibration. A tentative list of different types of flow-induced vibration includes [21]:

- Vortex Induced Vibrations (VIV)
- Galloping and Flutter
- Flow Interference
- Turbulence Induced Vibrations (Buffeting)
- Static Divergence
- Drag Crisis

The offshore industry has recognized the importance of this phenomenon to the design of fixed and floating structures in current for some time now. However, most of the effort in the offshore arena has so far been focused on vortex induced vibration, VIV, also referred to vortex induced motions (VIM).

Evaluation of vortex induced motion (VIM) in offshore floating structures has been largely been carried out for spars. Classic spar, truss spar and cell spar hulls are all known to exhibit VIV (VIM) [1], [2], [6], [7], [8], [9], [10], [12], [13], [14], [15], [16], [19], [27], [28], [29], [31], [32].

More recent work has indicated that in addition to spars, both semi-submersibles and TLPs are also known to exhibit flow induced motions [18], [24]. However, the motions of multi-column floaters are more complex and can involve more than one of the phenomenons listed before.

The motivation for the recent series of tow tests is confirm the behavior and to further investigate the significance of the response.

This work has shown low frequency response of Tension Leg Platforms (TLP) and deep draft semi-submersibles in steady current. The authors note that the included results provide trends for current induced motion of semi submersibles and TLPs. However, actual responses on a specific floater design may vary even due to small differences in the geometry.

Based upon this work and that of others it is apparent that current induced motion should address during the design process for the both riser and mooring fatigue. The response in these structures can have significant influence on the fatigue life of steel catenary risers (SCR).

INTRODUCTION

A bluff body immersed in a stream of fluid is susceptible to vortex resonance as well as galloping instabilities. A structure experiences vortex resonance (VIV or VIM) if its natural frequency coincides with the vortex-shedding frequency. Galloping is a form of self excited vibrations, where the body generates an aerodynamic force aiding the motion, which can build up into large-amplitude, low-frequency vibrations [22].
Several parameters are defined to help in understanding which process is being investigated and to assist in generalizing the results.

The Strouhal number \([5], [26]\]
\[St = \frac{Df_s}{U},\]
is the proportionality constant between the predominate frequency of vortex shedding
\[f_s = \frac{StU}{D}\]
and the free stream velocity \((U)\) divided by the maximum width normal to the free stream \((D)\). D, the maximum width normal to the free stream, is ordinarily used because this width tends to govern the width of the wake.

Strouhal (1878) determined the average Strouhal number for a circular cylinder to be 0.185. Later work by Rayleigh (1879) and others has shown this value to be 0.2.

Recent work by Sarioglu, M. and Yavuz, T, [25], for Reynolds number range \(1 \times 10^5 \rightarrow 2 \times 10^5\) determined Strouhal numbers between 0.12 and 0.16 for the square cylinder \((w=h = 1.0)\) having the same hydraulic diameter as that of the circular cylinder at 0 degree incidence.

In addition, for the rectangular cylinders the Strouhal number decreases with increasing width-to-height ratios.

A parameter called reduced velocity is normally defined as
\[U_r = \frac{U}{fD}\]

It is used to establish a relationship between flow velocity, amplitude of the response, and, the frequency of vibration of the structure, \(f\).

In this work a modified definition of \(U_r\) has been used. Instead of the response frequency we will use the calm water natural frequency, \(f_s\). Therefore,
\[U_r = \frac{U}{f_s D}\]

VIV or VIM is the unique case where the structural response frequency is equal to the vortex shedding frequency,
\[f = f_s\]
The response of a structure at or near the vortex shedding frequency is broad banded. However, when the two frequencies are very close a phenomenon can occur which is commonly referred to as lock-in. The process does not increase without bound as it is drag limited.

Galloping is different than VIV. First, it is a low frequency response. That is, the vortex shedding frequency is much larger than the structural response frequency,
\[f_s >> f\]

Second it is not self limiting. Galloping tends to increase with increasing velocity. The structure responds to the hydrodynamic force generated by an oscillating flow field. Small motion of the structure can cause the flow relative to the structure to oscillate. The hydrodynamic force generated by the oscillatory flow can cause the amplitude of motion to grow until limited by system nonlinearities.

Another important parameter influencing VIM response is the mass ratio \((m_r)\), \([3], [11], [17]\). It is especially important for TLPs. It is defined as the ratio of floater mass \((M)\) to the floater displacement \((\Delta)\) as shown below. The mass ratio is close to 1 for spars and semi-submersibles, while it is much less than 1 for TLPs.
\[m_r = \frac{M}{\Delta}\]

Vandiver’s work \([29, 30]\) on riser VIV found that the mass ratio of a submerged structure can affect the response in current. The physical background of the increased VIM response for low mass ratios lies in the fact that the added mass becomes more important. VIM is generally known as a coupled hydromechanics phenomenon. The response and exciting forces can not be separated from each other, since the exciting forces depend on the motion (and its history) of the structure. This is because the flow pattern and the related forces depend on the motion of the structure interactively. Furthermore, the added mass adapts itself to the motion and therefore the VIM does not only occur at one signal frequency but at a range of frequencies around the natural frequency in calm water. Because of its shape, the response curve is generally referred to as the bell curve.

The ability of the added mass to adapt itself to the motion becomes more pronounced if the added mass is larger with respect to the mass of the floater itself. This means that the expected response is larger at a wider frequency range for lower mass ratios. In this paper the increase in VIM response for lower mass ratios is discussed such as for TLPs compared to that of deep draft semi submersibles.

Yet another variable that affects flow induced response is the excitation length or the correlation length at which the vortices are shedding in phase. A critical excitation length is needed for VIM to occur.

The response of an elastically mounted cylinder in free stream or towed can be divided into three regions, sub-critical, critical, and post-critical. These occur at increasing velocities. At very small speeds (sub-critical), the transverse motion is very small and without significant periodicity. In the critical region, lock-in can occur, a harmonic transverse oscillation with nearly constant amplitude. Periodic transverse oscillation can also occur under post-critical condition. It is due to galloping phenomenon in this regime.

The flow induced response becomes much more complex for tube arrays or multiple cylinders as in case of semisubmersibles and TLPs. Depending on the flow direction.
relative to platform heading the arrangement of the columns can be visualized as in-line, staggered or offset.

Figure 1: Definition of column arrays

The flow past the leading column(s) has an effect on the flow around and between the columns. The modified flow can be categorized as proximity interference, wake interference or both [4]. Any interference or shielding will affect the response of multi-column floaters. A cylinder in the wake of another can be strongly influenced even at a distance of 20 diameters or more [21].

TOW TEST CONFIGURATION

To obtain more information on the effect of draft and mass ratio, towing tests were carried out to record the response. The model (scale 1:70) that was used for the tests consisted of sharp cornered building blocks that allowed for easy adjustment of the floater shape and weight distribution. Two main shapes were tested:

1. Four columns (14m x 14m) with two pontoons
2. Four columns (14m x 14m) with four pontoons

Figure 2: Building blocks model of a semi submersible

Table 1: Tested configurations

<table>
<thead>
<tr>
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<td>Displacement (t)</td>
<td>Mass Ratio</td>
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<td>Column height (m)</td>
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The results of configuration I and II were tested to compare the effect of mass ratio. Both configurations have exactly the same geometry. However, the second configuration has 32% less mass than the first. The lower mass ratio is typical for a TLP.

The configuration III was tested to investigate the effect of the correlation length of the columns by comparing it to configuration I. The third configuration was chosen such that the free span column height was 50% smaller than for configuration I.

Configuration IV was a 2 pontoon version of configuration I. This was tested to investigate the effect of different geometries. The two pontoons can generate lift forces that change sign for varying yaw angle. These lift effects are known to cause instabilities in floater motions in current, such as the fishtailing behavior of tankers in tandem offloading situations.

Test Setup with air bearings

A test setup using air bearings was developed to be able to model the different vertical pretensions and allow the model to freely respond to the incoming flow. The model was equipped with 3 ultra low friction air bearings that slide along a horizontal plate that is mounted to the carriage (see Figure 7). Prior to the model test the surge/sway/yaw damping due to the friction of the air bearing was investigated and found to be less than 1% of critical damping.

The vertical pretension for the semisubmersibles is a result from the weight of the mooring lines and risers. For the TLP the downward force is introduced by the pretension in the tension legs and risers.

The vertical pretension was applied to the model by pushing it down into the water, without restricting the horizontal motions. The horizontal restoring is provided by two soft springs in the tow direction.

Figure 3: Sketch of the test setup

Test Program

To investigate the effect of flow induced motion behavior a reduced velocity ($U_r$) range between 4 and 40 was tested for all 4 configurations. The tested $U_r$, towing velocities and projected diameter, D, can be found in Table 4.

Tow directions

The test program included main tow directions, 0 and 45 degrees and all measurements were referenced to a basin fixed coordinate system.
RESULTS

Natural periods

The natural periods of the system in calm water are given below. The X and Y natural periods were taken in the basin fixed reference system. Therefore, the natural periods in the 45 deg towing direction were slightly different due to small differences in the added mass with respect to the 0 deg tow direction. The presented $U_r$ for every configuration are based on the Y natural periods in calm water.

Table 2: Natural periods for 0 deg towing direction

<table>
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<tr>
<th>Config</th>
<th>$T_x$ [s]</th>
<th>$T_y$ [s]</th>
<th>$T_{yaw}$ [s]</th>
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Table 3: Natural periods for 45 deg towing direction

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<tr>
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Drag

Figure 8 $C_v$ vs $\left( \frac{A}{D} \right)$ and Figure 9 – Drag force vs. tow speed for 45 degree platform heading present results similar to that found by Rijken, et al [24] showing an increase of the total drag on the platform with increasing tow velocity with a dependency on both forward speed as well as the amplitude of oscillation.

Flow Induced Vibration

The results from the towing tests are analyzed by taking the statistics from the time traces as follows.

nominal response: $\left( \frac{A}{D} \right)_{nominal} = \sqrt{2} \times \sigma(Y(t)) / D$

where $\sigma$ = standard deviation of $Y(t)$

maximum response: $\left( \frac{A}{D} \right)_{maximum} = \max(Y(t)) - \min(Y(t)) / D$

At $U_r$ of 7 for the 45 deg tow direction we observed much more regular response:

Figure 6: Y response for Config 1 (45 deg tow angle, $U_r =7$).

Table 4 shows the observed transverse motion (Y) periods and the vortex shedding periods for Strouhal numbers of 0.14, 0.16 and 0.2. It also shows that the platform motion period varies considerably with towing speed. This can be attributed to the increase in added mass. The shift in period away from the vortex shedding frequency indicates that the response is not VIV but more likely due to galloping or a combination of vortex shedding and galloping. The change in response frequency and monotonic increase in response with velocity is attributed to variation in added mass and lift coefficient and a visibly modified flow between and around the cylinders which can be categorized as proximity interference, wake interference.

Test results are presented in Figures 10, 11, 12 and 13 for platform transverse and torsional response, all 4 configurations and the 2 tow headings. The response at 45 degree tow...
direction has larger transverse response which is again consistent with what Rijken, et al [24].

In the 45 degree towing angle the vortex shedding period is close to the observed motion period for \( U_r = 6, 7 \) and \( 8 \) which indicates that the shedding vortices are the most likely driver for the motion for these velocities. The peak response is found at a \( U_r \) between 5 and 8.

Figure 11 also shows that the nominal sway response for the 0 deg current angle is limited to an A/D value between 0.25 and 0.3 at \( U_r \) 8. (Please note that the reference diameter is a factor 1.41 smaller than for the 45 degree tests). However, the response is not reducing for higher \( U_r \) as is the case for the 45 degree tow direction. The vortex shedding frequencies are not close to the motion periods, therefore the motions are not driven by shedding vortices, but they are driven by lift effects on the hull.

Figure 12 shows that the galloping (at \( U_r >10 \)) seems to be more pronounced for the 2 pontoon semi submersible. It is likely that this because the 2 pontoons are directed into the undisturbed flow and not shielded by the foremost transverse pontoon. Therefore 2 pontoons can generate larger lift forces and consequently the response at the higher \( U_r \) is the largest for configuration 4 in 0 and 45 deg current angles.

The conventional semisubmersible, configuration III, shows much less flow induced transverse and yaw response when compared to configurations I, II and IV. This may be a result of the smaller column height. This would be consistent with reduced length of the column resulting in a smaller forcing length.

Figure 15 shows the response spectra for the 45 deg tow tests versus \( U_r \). The largest response can be found around \( U_r \) 6 and \( U_r \) 7. In Figure 16 for the 0 deg tow direction the response is less narrow banded and response is observed at a wider frequency range, especially at lower frequencies and higher \( U_r \).

**Mass Ratio**

Furthermore, the lower mass ratio of the TLP results in a higher maximum response at a wider \( U_r \) range. This is because the TLP added mass represents a larger part of the total mass that is moving and therefore the changing added mass effect results in relatively larger response at a wider \( U_r \) range (i.e. the added mass adaptation effect is stronger). Based on these results it is recommended to model the mass ratio correctly for a towing test with a TLP.

**Yaw**

The measured yaw motion for the 45 deg tow direction is small (< 1 deg). However, the yaw response for the 0 deg towing direction is considerable. The maximum measured yaw amplitude was 6.79 deg for the 2 pontoon configuration at a \( U_r \) of 40. Figure 13 shows the analysis of the yaw signal for configuration I. The behavior is very complex, especially at the higher \( U_r \). There are motion response peaks at the same frequencies as for the transverse (Y) motion. Furthermore, there is energy close to the natural period for yaw in calm water. A complex coupling between Y and yaw may be affecting the platform response.

Yaw motion of multi-column floaters induced due to steady current could due to galloping phenomenon as the data in Figure 13 suggests. This figure shows that the yaw amplitude is not self limiting but rather increases almost monotonically with tow speed, a characteristic of galloping induced response. The yaw motion is likely the result of moments generated due to disturbances in oscillating flow field induced by motion of the floater. Further research is required to better understand this behavior.

**CONCLUSIONS**

The largest motions were observed for the 45 deg towing direction. At this heading an increasing drag coefficient was found due to the motions. These findings were similar as from previous papers, although the observed Y response is smaller than in [24].

The effect of mass ratio for floater VIM is consistent with that of VIV on risers. A lower mass ratio causes a wider range of response that is slightly higher.

The correlation length of the column is important for the amount of response. With 50% of the column height of the deep draft floater, almost no flow induced motions could be observed.

At higher \( U_r \) a combination between galloping and VIM occurs. The motion behavior seems to be less regular compared to VIM response only. Larger yaw motions were observed for the galloping in high currents.

Further work should include variations such as column corner shape (sharp vs. rounded) and column spacing. Also further work is required on the yaw motions in 0 deg towing angle.

Finally, the authors note that the included results provide trends for flow induced vibrations for semisubmersibles. Actual responses on a specific floater design may vary due to small differences in the geometry. It is recommended during design process that testing and analysis be conducted to address the possibility of any flow induced vibration and its effect on the riser and mooring fatigue.
REFERENCES


Table 4 Y Motion periods and responses for configuration 1

<table>
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<th>Ur angle</th>
<th>Vtow [m/s]</th>
<th>D [m]</th>
<th>Y motion period [s]</th>
<th>Y response Max [A/D]</th>
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NOTE: The presented $U_r$ are based on the Y natural periods in calm water.
Figure 8
Drag vs Vtow for the 45 deg tow direction

Figure 9
Drag vs A/D for the 45 deg tow direction
NOTE: The presented $U_r$ are based on the Y natural periods in calm water.
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