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Conference Paper · July 2017

DOI: 10.1115/OMAE2017-61543

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Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2017
June 25-30, 2017, Trondheim, Norway

OMAE2017-61543

EXPERIMENTAL STUDY ON THE VORTEX-INDUCED MOTIONS (VIM) OF A SEMI-SUBMERSIBLE FLOATER IN WAVES

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ABSTRACT

Recent studies suggest that the vortex-induced motions (VIM) of a semi-submersible found in model tests over-predicts the response in the field, which may lead to an over conservative design of the mooring and riser system. Within the Vortex Induced Motion Joint Industry Project (VIM JIP), run by MARIN and University of São Paulo (USP), possible reasons for this over-prediction are investigated using model tests and CFD [1–6]. A model test campaign was carried out at MARIN to test different candidates that might explain the observed differences. The results obtained with an air bearing setup regarding damping, mass ratio, draft variations and sinusoidal tow velocities, have been published elsewhere [6]. The present publication focuses on the influence of waves on the VIM response.

The model was a generic bare hull semi submersible with four rounded square columns at scale 56.5. A simplified mooring system consisting of four springs was designed to match the desired natural period in the sway and yaw direction. The model was towed at different velocities, corresponding to the range of reduced velocities where the highest response is expected. A VIM tow test campaign was carried out in calm water as a benchmark. The model was then tested at 7 different wave-current conditions, and the results are compared with the benchmark case.

The results suggest that two factors are important for VIM response in waves: the wave height, and the relation between wave and current direction. Comparing to calm water conditions, a reduction of 15% on the peak nominal response was found for a smaller sea state (H_S=2m,T_P=10s), however with a higher significant wave height (H_S=4m,T_P=10s) the peak nominal response was reduced by 30%. Depending on the combination of current-wave direction, the influence of the same sea state (H_S=4m,T_P=10s) on VIM response can be negligible (transverse seas) or result in a 30% reduction of the peak nominal response for collinear sea and current. This is a relevant finding since most research on the topic has focused on collinear conditions, and VIM tests in waves with transverse or oblique conditions are rare [7–9].

Comparing the calm water VIM response obtained with the air bearing setup, published in [6], with the soft mooring configuration reported here, the latter shows a generally smaller response, with a narrower lock in region. Nevertheless the peak response is found to be similar for both experimental setups.

INTRODUCTION

Background

Vortex induced motions (VIM) of a multi-column floater is a complex phenomenon, due to the coupling between the motion of the floater and the hydrodynamic forces it experiences. When the vortices are shed at a frequency close to the natural frequency of the floater a resonant behaviour occurs. The range where this resonance is observed is called the lock-in region, and is characterized by regular oscillatory motions of the floater. These motions are an important element in the fatigue analysis of risers and mooring lines [10, 11], and in some cases can

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account to up to 90% of the predicted SCRs fatigue damage [11].

In recent years, VIM has been investigated for deep draft semi-submersibles with several publications dedicated to the subject, see [12] for a review. The preferred method is to perform model tests, obtaining information regarding the magnitude of the VIM response for different combinations of current speed and heading. However, recent comparisons between VIM field measurements and standard model tests suggest that the latter is significantly over predicting the VIM magnitude observed in the field, as well as the range of current velocities in which it occurs [10, 13]. Therefore an overly conservative design of risers and mooring may be the result of using the typical model test procedure, with significant impact on costs.

Within the VIM JIP [1–6], initiated by MARIN and University of São Paulo (USP), several possible candidates to explain the difference between model tests and field observations have been investigated using model scale testing and CFD. These candidates include damping, mass ratio, Reynolds scale effects, unsteady current, and wave-VIM interaction. This publication addresses the influence of waves on VIM.

Wave-VIM Interaction of Offshore Floating Units

One of the first published open research into wave-VIM interaction was focused on a truss spar [7]. Three different sea states were tested, for different combinations of wave and current directions. For inline sea and current conditions a significant VIM reduction was found for the higher waves ($H_S \geq 7$m) when compared to current alone tests. For smaller (operational) seas, at $H_S = 3$m, similar VIM response to the current alone tests is reported, with the authors concluding that for larger sea states less VIM response can be expected. It has been observed that a lower VIM response occurs with collinear wave-current environment when compared to the same sea state in oblique conditions (current from 180 degrees and 135 degrees wave direction). However, for transverse sea-current conditions, some headings showed larger cross-flow motions than for current alone.

Similar behaviour has been observed for a mono column platform [14], where three regular waves were tested inline with current. The larger waves showed less VIM response, with the authors suggesting that heave motions might be an important factor in the VIM mitigation due to waves. In another study [9] for a mono column platform, the VIM response in transverse waves was larger than observed in current alone .

Wave-VIM Interaction of Semi-Submersibles

VIM reduction due to waves has been reported for a semi-submersible platform [8]. The authors suggest that the ratio between wave induced particle velocity and current velocity is an important parameter to assess wave-VIM interaction, since large wave induced velocities might disrupt the vortex shedding consistency, and therefore result in smaller VIM response. The same authors reported a smaller VIM response for collinear environment than for oblique conditions(current from 180 degrees and 135 degrees wave direction) [8]. This trend was also found for a spar [7] and a monocolumn platform [9].

For semi-submersibles, VIM is mainly of interest for fatigue analysis, while for hurricane conditions, where larger sea states occur, other factors become critical. Therefore some research was focused on the VIM response of a semi submersible in operational sea states ($H_S \leq 5$m) [15, 16]. Three different operational sea conditions were tested, with a minimal effect on VIM response when compared to calm water tests. However other authors have reported significant VIM reduction for a circular column semi-submersible, albeit based on very short tow tests ($\approx$5 VIM cycles measured) [17].

An extensive study was carried out for a semi-submersible [18], with three regular and three irregular waves collinear with current for a 45 degrees floater heading, resulting in different effects on the VIM response. Contrary to previous studies on semi submersibles [8, 15, 16], a VIM reduction of approximately 20% was observed for operational irregular waves ($H_S \approx 5.2$m) and complete VIM suppression for small regular waves ($H_S \approx 4.4$m). An extended test program was then carried out to further study this discrepancy [19]. There it was proposed that the nature of the wave (regular vs. irregular) is not relevant to the VIM response, instead the wave influence on VIM response is related to the oscillatory nature of the inline flow. This effect can be quantified by the KC number, or for irregular waves, the equivalent KC_{irr} number, and velocity ratio α:

$$\text{KC}_{\text{irr}} = \frac{\sqrt{2}\sigma_U}{f_p D} \qquad , \qquad \alpha = \frac{\sigma_U}{\sigma_U + U_{\text{mean}}} \tag{1}$$

where σ_U is the root-mean-square value of the inline motion of the platform, f_p the peak frequency of the inline motion of the platform, and U_{mean} is the mean current velocity. The results of VIM response in waves can then be plotted in a KC_{irr} vs α plot, falling in the so called *viscous drag region* or *inertia region*. When the results fall within the inertia region the wave excitation dominates over the vortex shedding, therefore no VIM type response is observed. Conversely, for the viscous drag region, the vortex shedding phenomena dominates over the wave excitation, therefore VIM is still present, albeit possibly reduced, when compared to current alone conditions. This approach may allow to predict if VIM can still occur for a given combination of wave and sea conditions, however it has not been tested for other than collinear wave-current conditions.

In fact, a very limited number of studies have shown results for the wave-VIM interaction of other than collinear wave and current conditions for semi-submersibles.

EXPERIMENTAL SETUP

Basin

The VIM test campaign was conducted in MARIN's Depressurized Wave Basin (DWB), at atmospheric pressure. The DWB measures 240 x 18 x 8 m. An average steady state tow length of at least 120 m is available. This means that typically between 30 and 80 VIM oscillations are available per test. The area blockage ratio of the model is under 1%. The tests were carried out at a Reynolds number based on the column diameter between 10^4 and 10^5.

Hinged flap wave generators are positioned at two adjacent sides of the basin: along the length of the basin, at the -Y_{BF}

wall in Figure 2; and at the end of the basin, at the +X_{BF} wall in Figure 2. The system is equipped with compensation of wave reflection from the model. Opposite these wave generators, passive wave absorbers (beaches) are installed in order to avoid reflections from the basin walls.

Model Geometry

A symmetrical generic bare hull semi-submersible with four square rounded columns was tested at a scale of 56.5. The model is shown in Figure 1, and it is the same model as used in [6].

FIGURE 1: Finished model in the workshop.

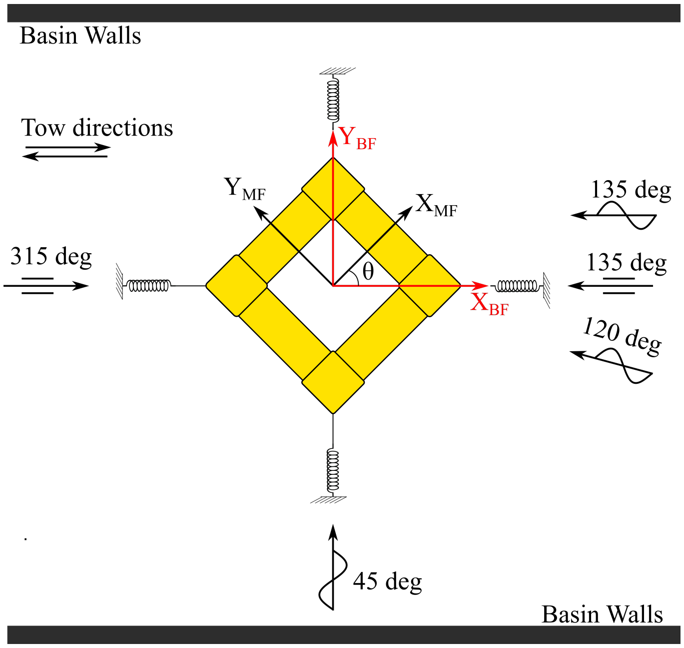


FIGURE 2: Top view sketch of the mooring system showing the definition of the coordinate system, current incidence (arrow with parallel lines), wave incidence (arrow with a sinusoid), and model heading θ.

Mooring Configuration

The model is connected to the carriage by four tensioned linear springs that provide the needed restoring force in the horizontal plane. The spring tension is measured by strain gauges and the model position is monitored by an optical tracking system. This setup is schematically presented in Figure 2. The model heading, θ, was kept at 45 degrees for all the tested conditions, since it was the condition where the highest VIM response was observed [6]. Free decay tests were performed to verify the mooring properties and natural periods of the model.

Reference Frame

Two coordinate systems are used throughout this paper, see Figure 2. A so called basin-fixed coordinate system (X_{BF},Y_{BF}), centered at the model CoG at rest, and moving with the carriage. This reference frame has the X_{BF} axis aligned with the basin longitudinal direction, therefore the possible towing directions are along $\pm X_{BF}$. The motions of the model are given in this reference frame, where motions along the X_{BF} axis are called inline motions, and motions along the Y_{BF} axis are called cross-flow motions.

The environmental conditions are defined with respect to a model fixed coordinate system (X_{MF},Y_{MF}), centered at the model CoG at rest, and aligned with the the model heading θ.

Environmental Conditions

Current: The current velocity was simulated by towing the model through the basin at the desired velocity. The model heading, θ, was set to be 45 degrees and kept fixed throughout the campaign, see Figure 2. Therefore when towing the model forward (in the +X_{BF} direction), the simulated current in the model-fixed reference frame is 135 degrees. Conversely, when towing backward, the simulated current in the model-fixed reference frame is 315 degrees.

Waves: The waves were selected to represent operational sea states, see Table 1. All waves were calibrated in the basin, for a duration of 1 hour full scale, prior to the start of the model tests, without the model present in the basin. The wave elevation was measured by means of resistance wire type wave probes, located at the neutral position of the model, with the carriage in the center of the basin. The wave makers are located in two adjacent sides of the basin: the long wave maker, which is located in -Y_{BF} wall and used to generate transverse seas (wave incidence 45 degrees); and the short wave maker, which is set at the end of the basin (+X_{BF} wall) and used to generate inline waves (wave incidence 135 degrees). Both wave makers are used to generate oblique sea states (wave incidence 120 degrees).

In the VIM tests the model is towed through the calibrated wave field, therefore it will not experience the calibrated wave spectra, but instead an encounter wave spectra, which is dependent on the tow direction and velocity. To correct for this factor, each wave would require a new calibration for each current velocity, which in practice is clearly unfeasible. At the highest tested current speed, a shift on the wave peak period under 10% is obtained, which is considered accurate enough to assess the influence of the presence of waves in the VIM response.

TABLE 1: Test matrix with the JONSWAP parameters of the tested sea states in full scale units.

Condition	Wave properties				Current properties	
	T_P [s]	H_S [m]	γ [-]	Incidence [deg]	U_R [-]	Incidence [deg]
Calm water	-	-	-	-	5,6,7,8,9,10,12	135
Transverse seas	10	4	1	45	5,6,7,8	135
Inline following seas	10	4	1	135	5,6,7,8	315
Inline head seas	10	4	1	135	5,6,7,8	135
Oblique high following seas	10	4	3.3	120	5,6,7,8	315
Oblique high head seas	10	4	3.3	120	5,6,7,8	135
Oblique low following seas	10	2	3.3	120	5,6,7,8	315
Oblique low head seas	10	2	3.3	120	5,6,7,8	135

Test Matrix

The test matrix is shown in Table 1. The response in calm water was studied by running 7 different reduced velocities, with one repeat test carried out at the peak response (U_R=6). These tests are intended as a benchmark, to assess the influence of the presence of waves on VIM. The tests with waves are carried out for 4 different reduced velocities, covering the lock-in region, with one repeat test carried out at U_R=6. The repeat tests showed a maximum variation in the nominal response of approximately 5%. Therefore, differences between the tested conditions are only meaningful when the difference is larger than 5%.

ANALYSIS METHODS

VIM Parameters

The amplitude of the VIM response is made non dimensional with the projected column diameter, D. The commonly used parameter to quantify the VIM amplitude is the nominal A/D, also called nominal response, defined as:

$$\left(\frac{A}{D}\right)_{\text{Nom}} = \frac{\sqrt{2}\sigma_Y}{D} \tag{2}$$

Where Y is the motion in the cross-flow direction, and σ_Y its standard deviation. The yaw motion is here quantified by:

$$\sqrt{2}\sigma_{\text{Yaw}} \tag{3}$$

Where σ_{Yaw} is the standard deviation of the yaw motion. It is usual to represent these metrics for a range of reduced velocities, U_R, defined as:

$$U_R = \frac{UT_N}{D} \tag{4}$$

In which U is the current speed [m/s], T_N [s] is the natural period in the cross-flow direction and D [m] is the projected column diameter of the semi-submersible. Statistics of the signals are obtained after a steady regime is achieved. Typically between 30 and 80 VIM oscillations were used to derive the statistics.

Due to confidentiality the magnitude of the motions are omitted from this publication. However the qualitative comparison is sufficient to identify trends, which is the main focus of this paper. Unless stated otherwise, the scale of the same type of plots is kept the same. This allows a one to one comparison and highlights the trends discussed.

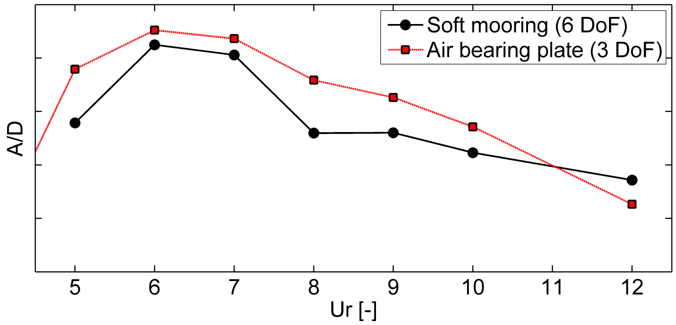
RESULTS

Different Experimental Setups

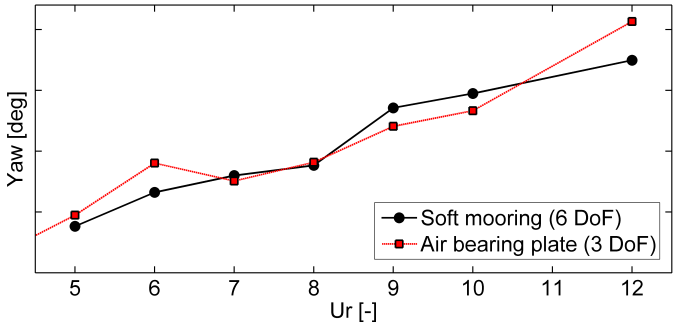
The experimental test campaign was divided in two phases. In the first one the model was tested with an air bearing plate setup, which allows motions only in the horizontal plane (surge, sway and yaw). Those results are reported in [6]. In the second phase the model was connected to the carriage in a soft mooring arrangement, as shown in Figure 2, and is therefore allowed to move in 6 DoF. Both experimental setups used the same model, with the same mass distribution, and are modeling the same horizontal stiffness. The natural periods in surge sway and yaw differ less than 3% between both cases, showing that both setups are equivalent. Therefore the main difference between both setups is the number of allowed degrees of freedom: 3 DoF (surge, sway and yaw) in the air bearing setup, and 6 DoF with the soft mooring arrangement.

The cross-flow and yaw response obtained in calm water conditions with both setups are shown in Figure 3. While similar response is found for yaw motions, some differences are observed for the cross-flow motions. The nominal cross-flow response is generally smaller (5% to 20%) with the soft mooring arrangement. Nevertheless, the peak nominal response is similar with both setups, the difference being within experimental repeatability ($\leq$5%). In addition, the lock in region seems to be narrower with the soft mooring setup.

A possible reason for this difference is that restricting the motions to the horizontal plane is favorable for the coherence of the vortices that drive the VIM. Therefore it is expected that with the air bearing setup stronger vortices are present, leading to a larger response. With the soft mooring setup, out of plane motions (heave, roll and pitch) will introduce a small disruption of the generated vortices, leading to a smaller response. This effect would be more noticeable at the limits of the lock-in region, e.g. U_R=5 or U_R=8, where small perturbations are sufficient to disrupt a resonant response. On the other hand, a smaller impact is expected at the lock-in region (U_R=6, U_R=7), where the resonant VIM motion is strong enough to overcome small perturbations.



(a) Cross-flow



(b) Yaw

FIGURE 3: Nominal response in calm water conditions, for both experimental setups.

Time Traces in Calm Water and Waves

A one hour segment (full scale time) of the measured time traces can be seen in Figure 5 for different reduced velocities tested in calm water. The time traces for U_R=6 are typical of the lock-in regime, where the vortex shedding period synchronizes with the natural period in the cross-flow direction. The resulting cross-flow motion shows a large oscillatory behaviour. Furthermore, as seen in Figure 9, this oscillatory motion has a single frequency close to the natural period of the floater. As the reduced velocity increases, the synchronization is disrupted, resulting in a less regular and smaller motion.

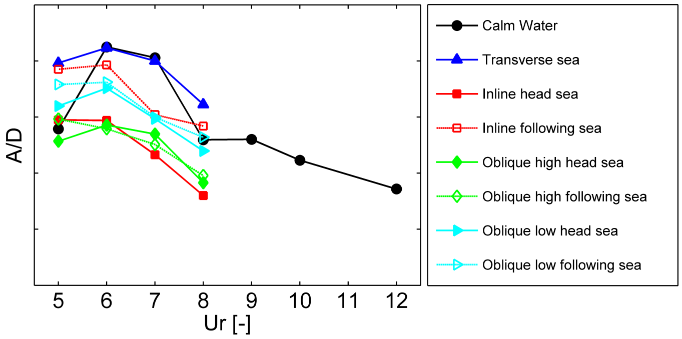
Since the yaw natural period is smaller than the cross-flow natural period, the yaw resonance occurs for higher U_R, where a larger vortex shedding frequency is found. Therefore the yaw motions found at U_R=12 are larger and more regular than those found at U_R=6. This trend has been observed in previous research [4, 18].

Figure 6 shows a one hour segment (full scale time) of the measured time traces for two different reduced velocities in inline head seas. VIM behaviour still occurs, i.e., the cross-flow motion exhibits a regular oscillatory motion, with a dominating frequency close to the natural frequency of the floater. However, when compared to calm water conditions, the response is less regular and with a smaller amplitude. Therefore VIM is till present with this sea state, but not as pronounced as in calm water conditions.

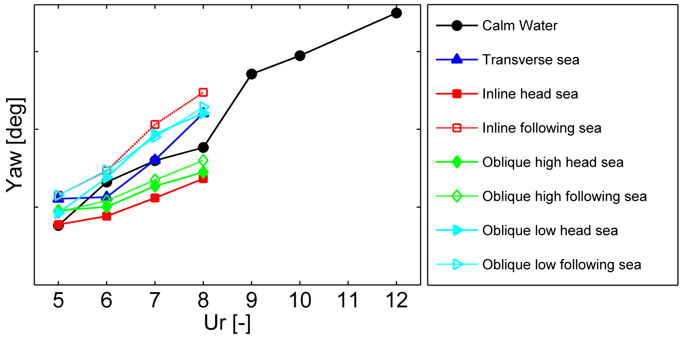
Nominal Response

An overview of the measured cross-flow and yaw response is given in Figure 4 for all the tested conditions. The typical VIM behaviour is observed for the calm water tests. The lock-in region occurs for $5 \leq U_R \leq 8$, with the peak response at U_R=6. For higher reduced velocities ($U_R \geq 8$) the response drops. The VIM response in waves shows different trends when compared to the calm water tests, depending on the wave considered.

The discussion of the measured nominal response in waves will be made separately: first the observed results at different wave incidence angles will be discussed; and then the effect of different wave heights will be presented.



(a) Cross-flow



(b) Yaw

FIGURE 4: Overview of the response measured for all the tested conditions.

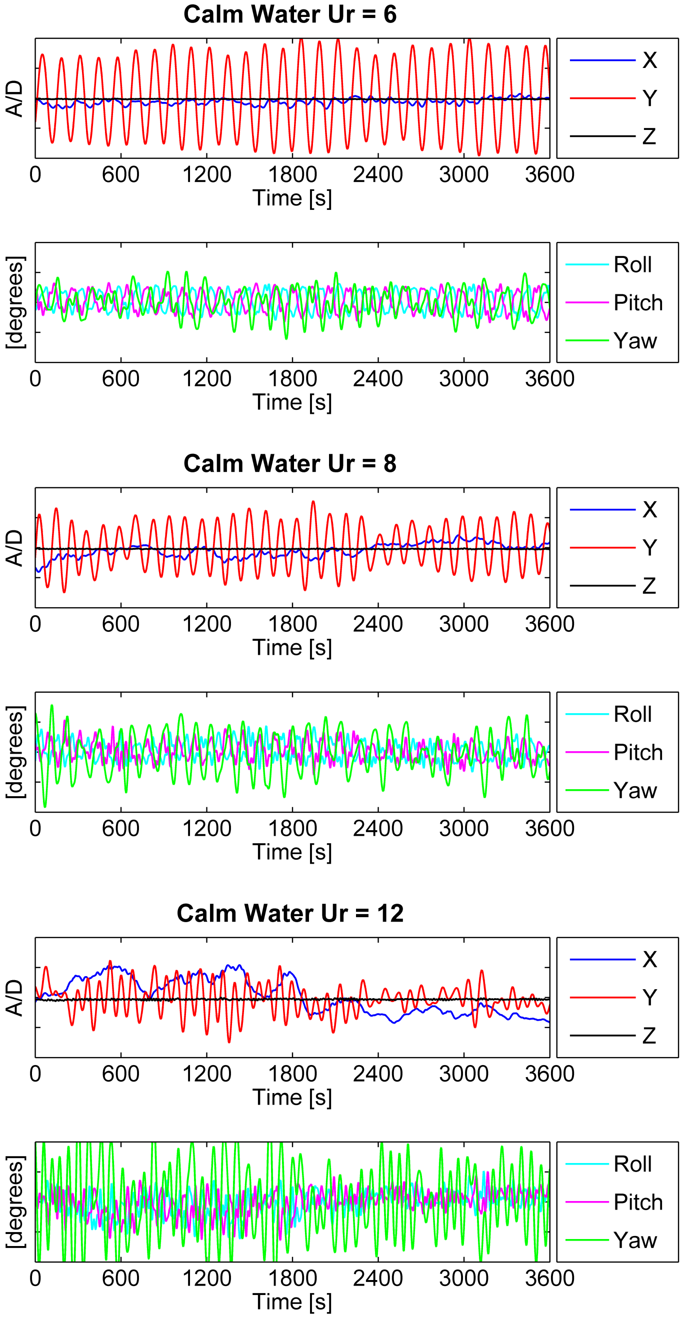


FIGURE 5: One hour (full scale) segment of the measured time traces for different reduced velocities in calm water conditions. The mean was removed from the signals for illustration purposes.

Effect of the wave incidence The same sea state (H_S=4m,T_P=10s, γ=1) was tested at different environmental conditions: transverse seas, where the waves are perpendicular to the current direction; inline following seas, where the waves and current have opposite directions; and inline head seas, where the waves and current are collinear. The measured response can be found in Figure 7 for these sea states.

The measured cross-flow response in transverse seas at lock-in (U_R=6, U_R=7) is the same as observed in calm water conditions. However a larger response in transverse seas is found at U_R=5 and U_R=8. This is consistent with previous model test observations on a spar [7] and a mono-column platform [9].

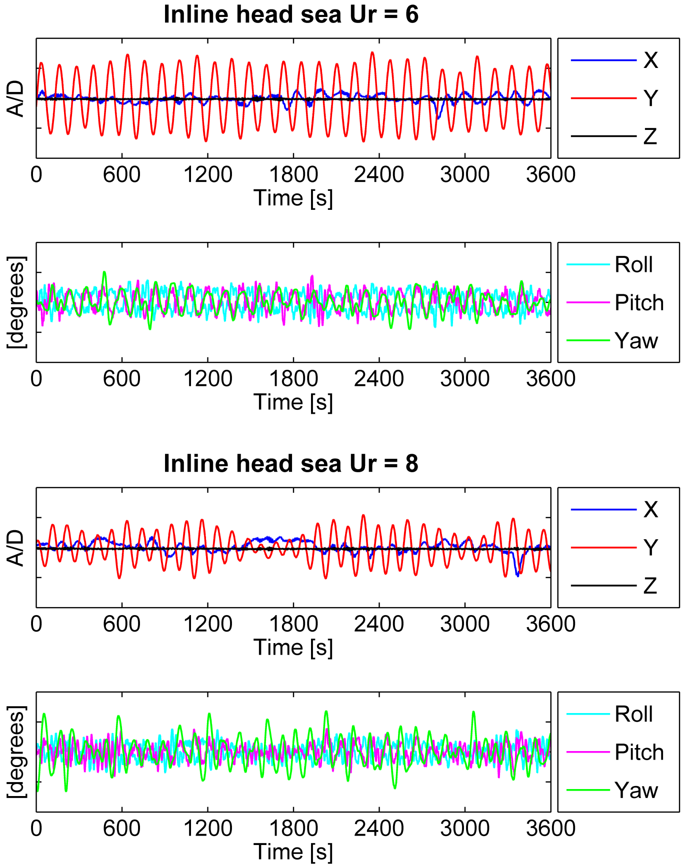
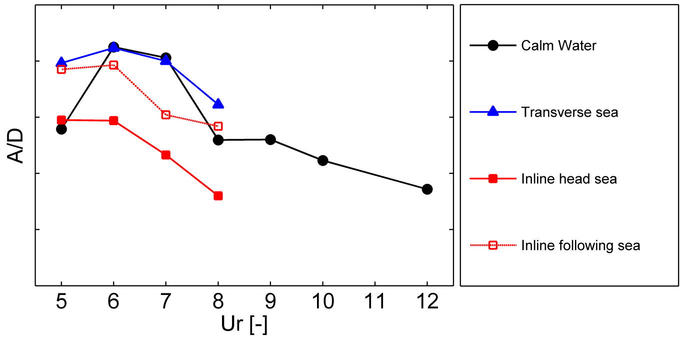


FIGURE 6: One hour (full scale) segment of the measured time traces for different reduced velocities with inline head seas. The mean was removed from the signals for illustration purposes.

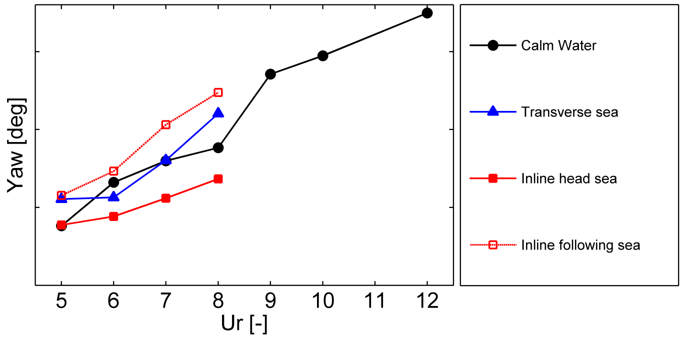
In the presence of the inline following seas, the VIM response is smaller than in calm water conditions, with the peak response showing a 15% reduction. However, for the inline head seas, the peak response is instead reduced by 30%. For oblique high sea conditions (H_S=4m,T_P=10s, γ=3.3) a 30% smaller VIM peak response is obtained when compared with the calm water conditions. However in this case not only the wave direction is changed, but also the peak enhancement factor.

These results suggest that the VIM-waves interaction is dependent on the wave incidence. Comparing to the calm water VIM response, the same sea state can have a negligible impact (transverse seas) or reduce the peak response by 30% (collinear sea-current), depending on the wave incidence.

It is interesting to observe that for the inline conditions, both the cross-flow and yaw motions are significantly smaller in head seas (current and waves coming from the same direction) than in following seas (current and wave direction with opposite directions). However for oblique sea states, both head and following seas show similar response. The cause for this difference could be in the peak period of the wave encounter spectra, which is dependent on the towing direction and speed. While for following seas the model is towed with the waves, thus reducing the wave encounter frequency, for the head seas the model is towed against the waves, resulting in a larger wave encounter frequency. More investigation is required to clarify this issue, possibly by testing the same sea state with different wave peak periods.



(a) Cross-flow



(b) Yaw

FIGURE 7: Response measured for different wave incidence angles.

Effect of the wave height The same sea state was tested at different wave heights: oblique high seas, with H_S=4m; and oblique low seas, where H_S=2m. The response can be found in Figure 8.

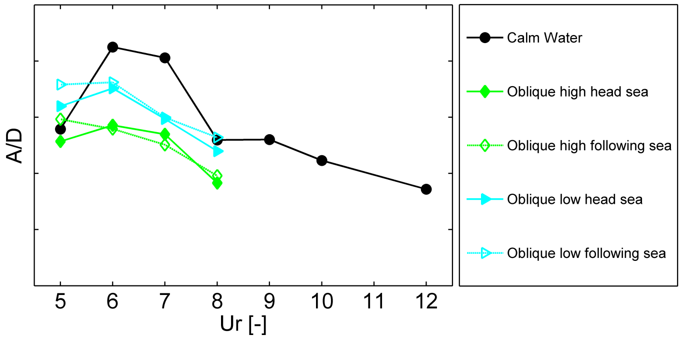
The variation found in the response between oblique head seas and oblique following seas is within experimental repeatability ($\leq$5%), and is therefore negligible. This occurs for both oblique high seas and oblique low seas.

In the oblique low sea conditions (H_S=2m) a reduction of 15% in the cross-flow peak response is found when compared to the calm water results. However with oblique high sea conditions (H_S=4m), the cross-flow peak response is further reduced to 30% when compared to calm water conditions. These results support previous research that observed less VIM response with higher waves [7, 8, 14, 16, 18].

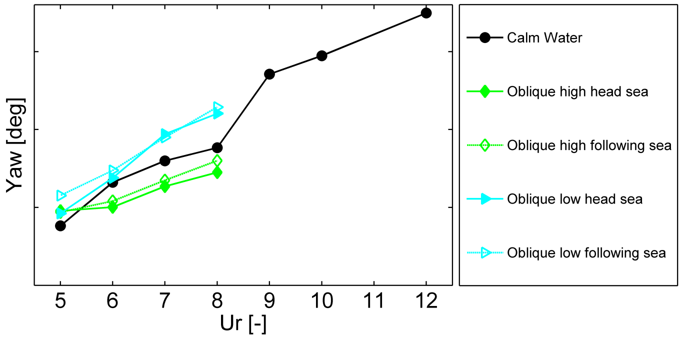
Frequency Analysis of the Motions

Figure 9 shows the power spectral density (PSD) for the horizontal plane motions with calm water and inline head seas. Other waves show qualitatively similar results, and were therefore omitted. In calm water conditions the inline motions show small energy for all frequencies, with a peak occurring at twice the natural period in the cross-flow direction.

For the cross-flow motion the largest energy is found for $5 \leq U_R \leq 8$ at the cross-flow natural frequency. The yaw motion shows energy at the cross-flow natural frequency, shifting to the yaw natural frequency for the highest reduced velocities. In the presence of waves there is small difference in the PSD for all motions when compared to the calm water conditions.



(a) Cross-flow



(b) Yaw

FIGURE 8: Response measured for different significant wave heights (H_S).

The inline motions, where the highest difference occurs, show an increase in energy at the lower frequencies, however their magnitude is still negligible when compared to the cross-flow and yaw motions. It should be noted that for all the tested waves, no energy is present at the wave peak frequency. This observation is consistent with the results presented in [18, 19]. Those authors report a relation between the energy distribution of the inline motion and the presence of VIM in waves: when no VIM was observed, most energy was found at the wave excitation peak frequency; conversely when VIM was still found despite the presence of waves, then the inline motion was dominated by energy at the VIM frequencies.

Individual Transverse Cycle Analysis

The amplitude of the cross-flow motion and respective zero crossing period for each measured cycle is plotted in Figure 10 for all the tested reduced velocities.

The largest amplitudes are found for periods close to the natural cross-flow period, where a more consistent response is found. As the reduced velocity increases, both the average zero crossing period and amplitude decreases and a larger scatter in both parameters is observed, suggesting a less regular response. In calm water conditions the zero crossing periods approach the natural cross-flow period for reduced velocities between 6 and 7, however when waves are present this range shifts to reduced velocities between 5 and 6. This observation is consistent with the generally larger nominal response found for the tests in waves for U_R=5, as can be seen in Figure 4.

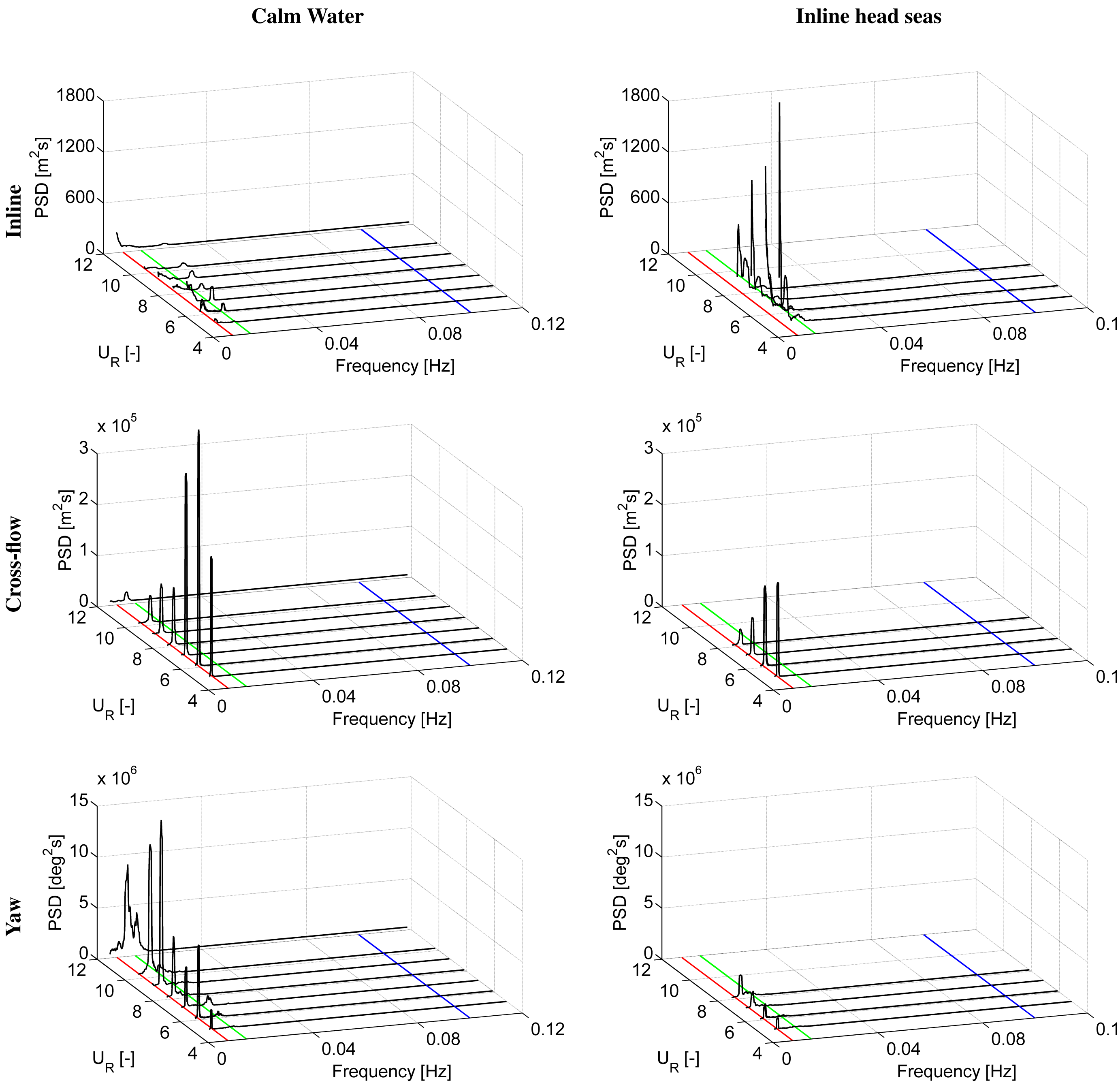


FIGURE 9: PSD for the motions in the inline direction (top), transverse direction (middle) and yaw motion (bottom) for calm water conditions (left) and inline head waves (right). The red line represents the cross-flow natural frequency, the green line the yaw natural frequency, and the blue line the wave peak frequency.

CONCLUSION

The importance of a semi-submersible VIM to the fatigue life of risers and mooring lines is well know. Common prediction methods of VIM are based on towing tests at model scale, often without the presence of waves. In recent years, comparison between field data and standard model test data suggests that model test predictions are overly conservative, which might lead to over designed risers and mooring systems with significant impacts on costs.

The VIM JIP was started to investigate several candidates for the differences observed between model tests and field data. One of such candidates was the interaction between waves and VIM, since the standard model test campaign does not include runs in waves. For the 7 different sea state-current combinations tested, VIM was still observed, i.e., a resonant response was still observed, albeit generally less pronounced than in calm water conditions. The results suggest that two factors are relevant in wave-VIM interaction: the wave height, and the wave incidence angle.

Comparing two operational conditions where only the significant wave height was varied (H_S=4m and H_S=2m) highlighted the impact of the wave height in the VIM response. The higher wave showed a 30% reduction at peak response, while the smaller wave showed only a 15% reduction.

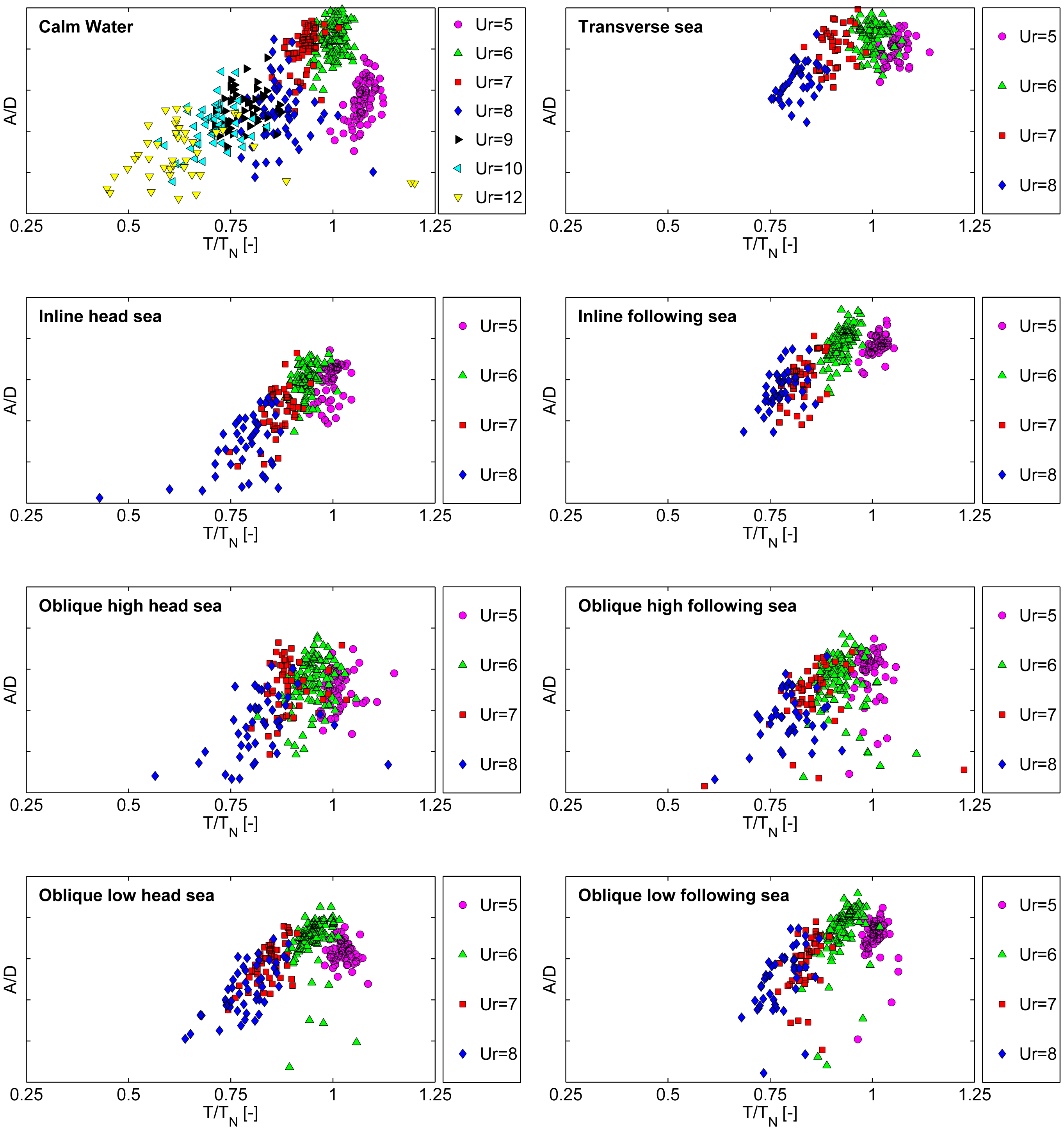


FIGURE 10: Distribution of the cross-flow amplitudes versus zero crossing periods.

For the same wave (H_S=4m,T_P=10s) tested with opposite direction of the current, collinear with the current, or transverse to the current direction, a reduction of 15%, 30%, or no influence in the peak response was observed, respectively. This is especially interesting since most VIM research in waves has been done for collinear conditions, and VIM tests in waves with transverse and/or oblique conditions are rare [7–9].

A more extensive test scope with additional variations of wave frequencies and directions is necessary to further clarify the role of wave and current directions in the VIM response, and whether a similar prediction method to the one proposed in [18] can be extended to other than collinear conditions.

Based on the results obtained in the model test campaign, reported here and in [6], it seems plausible that, under the right environmental conditions, waves can partially contribute to the difference observed between field data and standard model test predictions.

Comparing the calm water VIM response obtained with the air bearing setup, where the model is restricted to 3 DoF published in [6], with the 6 DoF setup here reported, the later shows a generally smaller response, with a narrower lock in region. Nevertheless the peak response is found to be similar for both setups. The reduction found for the 6 DoF setup is attributed to the disruption of the vortex coherence caused by the heave, roll and pitch motions, which are restricted for the air bearing setup.

ACKNOWLEDGEMENTS

This study was carried out within VIM JIP. The authors are grateful to the participants for useful discussion and permission to publish this paper. The participants of the VIM JIP are: Aker Solutions, ConocoPhilips, Granherne, GVA, KBR, MARIN, Petrobras, SBM Offshore, and USP.

António Maximiano gratefully acknowledges WavEC-Offshore Renewables financial support to attend the conference.

REFERENCES

[1] Koop, A., Rijken, O., Vaz, G., Maximiano, A., and Rosetti, G., 2016. "CFD Investigation on Scale and Damping Effects for Vortex Induced Motions of Semi-Submersible Floater". In Proceedings of the Offshore Technology Conference (OTC), OTC-26977-MS, May.

[2] Koop, A., Wilde, J., Fujarra, A., Rijken, O., Linder, S., Lenblad, J., Haug, N., and Phadke, A., 2016. "Investigation on Reasons for Possible Differences Between VIM Response in the Field and in Model Tests". In 35^{th} International Conference on Ocean, Offshore and Arctic Engineering (OMAE), OMAE2016-54746, June.

[3] Fujarra, A., Gonçalves, R., Rosetti, G., Silva, H., and Koop, A., 2015. "Roughness Effects on the VIM Response of Deep-Draft Semi-Submersible Platforms". In Proceedings of the Twenty-fifth International Offshore and Polar Engineering Conference (ISOPE), June.

[4] Gonçalves, R., Fujarra, A., Rosetti, G., Kogishi, A., and Koop, A., 2015. "Effects of Column Designs on the VIM response of Deep-Draft Semi-Submersible Platforms". In Proceedings of the Twenty-fifth International Offshore and Polar Engineering Conference (ISOPE), June.

[5] Rosetti, G., Gonçalves, R., Fujarra, A., and Koop, A., 2016. "CFD Calculations of the Vortex-Induced Motions of a Circular-Column Semi-Submersible". In 35^{th} International Conference on Ocean, Offshore and Arctic Engineering (OMAE), OMAE2016-54987, June.

[6] Maximiano, A., Koop, A., Wilde, J., and Gonçalves, R., 2016. "Experimental Study on the Sensitivity of Vortex-Induced Motions (VIM) of a Semi-Submersible Floater to Damping and Mass Ratio". In Proceedings of the Twenty-sixth International Offshore and Polar Engineering Conference (ISOPE), June.

[7] Finnigan, T., Irani, M., and Van Dijk, R., 2005. "Truss Spar VIM in Waves and Currents". In 24^{th} International Conference on Ocean, Offshore and Arctic Engineering (OMAE), OMAE2005-67054, June.

[8] Hong, Y., Choi, Y., Lee, J., and Kim, Y., 2008. "Vortex-Induced Motion of a Deep-Draft Semi-Submersible in Current and Waves". In Proceedings of the Eighteenth International Offshore and Polar Engineering Conference (ISOPE), July.

[9] Saito, M., Masanobu, S., Taniguchi, T., Otsubo, K., Asanuma, T., and Maeda, K., 2012. "Experimental Evaluation of VIM on MPSO in Combined Environmental Conditions for Waves and Current". In 31^{st} International Conference on Ocean, Offshore and Arctic Engineering (OMAE), OMAE2012-83283, July.

[10] Ma, W., Wu, G., Thompson, H., Prislin, I., and S., M., 2013. "Vortex Induced Motions of a Column Stabilized Floater". In Deep Offshore Technology International Conference (D.O.T), May.

[11] Jun, Z., Poll, P., Antony, A., Das, S., Padmanabhan, R., Vinayan, V., and Parambath, A., 2014. "VIM Model Testing and VIM induced Fatigue of a Dry Tree Paired-Column Semisubmersible Platform". In Proceedings of the Offshore Technology Conference (OTC), OTC-25427-MS, May.

[12] Fujarra, A., Rosetti, G., Wilde, J., and Gonçalves, R., 2012. "State-of-Art on Vortex-Induced Motion: A Comprehensive Survey After More Than One Decade Of Experimental Investigation". In 31^{st} International Conference on Ocean, Offshore and Arctic Engineering (OMAE), OMAE2012-83561, July.

[13] Rijken, O., and Leverette, S., 2009. "Field Measurements of Vortex Induced Motions of a Deep Draft Semisubmersible". In 28^{th} International Conference on Ocean, Offshore and Arctic Engineering (OMAE), OMAE2009-79803, June.

[14] Gonçalves, R., Fujarra, A., Rosetti, G., and Nishimoto, K., 2010. "Mitigation of Vortex-Induced Motion (VIM) on a Monocolumn Platform: Forces and Movements". *ASME J. Offshore Mech. Arct. Eng*, ***132***(4), pp. 041102–041118.

[15] Rijken, O., and Leverette, S., 2008. "Experimental Study into Vortex Induced Motion Response of Semi Submersibles with Square Columns". In 27^{th} International Conference on Ocean, Offshore and Arctic Engineering (OMAE), OMAE2008-57396, June.

[16] Martin, B., and Rijken, O., 2012. "Experimental Analysis of Surface Geometry, External Damping and Waves on Semi-Submersible Vortex Induced Motions". In 31^{st} International Conference on Ocean, Offshore and Arctic Engineering (OMAE), OMAE2012-83689, July.

[17] Pontaza, J., Baar, J., and Liu, N., 2015. "Vortex-Induced Motions of a Model Scale Column Stabilized Floater with Round Columns in Calm Water and Random Waves". In 34^{th} International Conference on Ocean, Offshore and Arctic Engineering (OMAE), OMAE2015-42407, June.

[18] Gonçalves, R., Rosetti, F., Fujarra, A., and Oliveira, A., 2013. "Experimental Study on Vortex-Induced Motions of a Semi-Submersible Platform with Four Square Columns, Part II: Effects of Surface Waves, External Damping and Draft Condition ". *Ocean Engineering*, ***62***, pp. 10 – 24.

[19] Gonçalves, R., 2016. *Comportamento de plataformas de petróleo sob a ação do fenômeno de VIM e incidência simultânea de ondas*. University of São Paulo. Pos-doc Report (In Portuguese).