Proceedings of the ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2016
June 19-24, 2016, Busan, South Korea

OMAE2016-54746

INVESTIGATION ON REASONS FOR POSSIBLE DIFFERENCE BETWEEN VIM RESPONSE IN THE FIELD AND IN MODEL TESTS

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ABSTRACT

Floating offshore structures, such as production semi-submersibles and spars, can exhibit significant in-line and transverse oscillatory motions under current conditions. When caused by vortex shedding from the floater, such motions are generally called Vortex-Induced Motions (VIM). For semi-submersibles these motions could have a strong impact on the fatigue life of mooring and riser systems. Some field development studies indicate that the VIM induced fatigue damage for larger diameter Steel Catenary Risers (SCRs) can have a magnitude equal to or larger than the wave-induced fatigue damage.

The VIM phenomenon for multi-column floaters is characterized by complex interactions between the flow and the motions of the floater. Presently, model tests are the preferred method to predict the VIM response of a multi-column floater. However, several studies indicate that the observed VIM response in the field is less than what is observed in model test campaigns: typical model test results are very conservative. Using such test results in the development of mooring and riser design can easily result in very conservative designs which can have a significant impact on mooring and riser cost, or even affect SCR selection and/or feasibility.

The primary objective of the VIM JIP was to increase the physical insight into the VIM phenomenon. This knowledge is then used to address possible areas that could explain the differences between the results from model tests and field observations. To address these objectives, the JIP focused on model testing and CFD studies. A key segment of the JIP was the use of identical semi-submersible hull geometries for the numerical and experimental studies thereby facilitating the interpretation of the various response comparisons.

The JIP identified that a CFD model, at model-scale Reynolds number, can reasonably well reproduce the VIM response observed in model tests. However, to have confidence in the CFD results extensive numerical verification studies have to be carried out. The effect of external damping was investigated in model tests and in CFD calculations. Both the numerical and experimental results show that external damping significantly reduces the VIM response. Comparisons between CFD results at model- and full-scale Reynolds number indicate that Froude scaling is applicable, with minor scale effects identified on the amplitudes of the VIM motions. Changing the mass ratio of the floater has a small influence on the VIM response. Experimentally it was found that VIM response under inline or transverse waves is slightly smaller than without the presence of waves and is wave heading and wave height dependent. The presence of waves does not explain the observed differences between model test results and field observations. The effect of unsteady current on the VIM response is minimal.

Based on the results from the JIP it is concluded that increased external damping reduces the VIM response. The questions that remain are if the increased external damping is actually present in full-scale conditions and if the mooring and riser systems provide the required damping to reduce the VIM amplitudes.

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INTRODUCTION

The VIM phenomenon for multi-column floaters is characterized by complex interactions between the flow and the motions of the floater. During VIM, the formation and shedding of vortices from the columns occur in a synchronized manner as illustrated in Figure 1, taken from [11]. The shedding frequency and natural frequency of the floater are close to each other and adapt to each other in the so-called lock-in range. The amplitude of the VIM response is typically defined in terms of the nominal A/D value $(A/D)_{nom}$ for different reduced velocities UR which are defined by:

$$\left(A/D\right)_{nom} = \sqrt{2}\frac{\sigma_Y}{D}, \qquad UR = \frac{UT_n}{D} \tag{1}$$

where σ_Y is the standard deviation of the motion Y(t) in the direction perpendicular to the incoming current, D is the projected column diameter, U is the current velocity and T_n is the natural sway period of the floater.

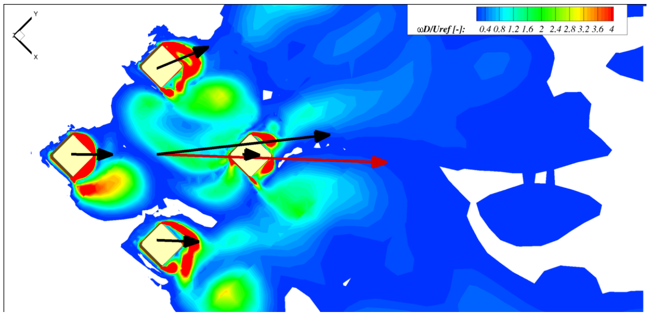


Figure 1: Illustration for the vorticity distribution around the four columns of a semi-submersible during VIM illustrating the vortices being shed from the columns. Presented is a flow solution of a CFD calculation at 45 degrees, taken from [11]. Flow is from left to right and the floater is moving upwards at the presented time instant. Presented with the black arrows are the forces on each column. The black arrow in the center shows the total force on the columns. The red arrow shows the total force on the complete semi-submersible including pontoons.

Presently, model tests are the preferred method to predict the VIM behavior of a multi-column floater, see for an overview [4]. However, several studies indicate that the observed VIM response in the field is less than the observed VIM response in model test campaigns, see for example [3], [12], [18]. As discussed by Ma et al. [12] the occurrence of VIM in the field seems to be much less than expected, within a narrower range of reduced velocities and with amplitudes much smaller than observed in model tests. Overly conservative design guidance for moorings and risers may be the result of only using standard model test information, with significant impact on costs.

MARIN and the University of São Paolo (USP) initiated the VIM JIP to investigate possible candidates for this reduction in VIM response in the field. The main objectives of the VIM JIP were to:

- Increase insight in physics and phenomenon behind VIM;
- Evaluate possible candidates for differences between model tests, CFD and field observations;
- Investigate most promising candidates in model tests and CFD calculations;
- Build confidence in CFD for VIM through dedicated verification and validation;
- Provide general conclusions and lessons learnt for VIM model tests and VIM CFD calculations.

To address these objectives, the JIP focused on model testing and CFD studies. Field data was not available to the JIP and it was believed that it would have been time-consuming and costly to investigate field data thoroughly to be able to draw clear conclusions on the possible reasons responsible for the reduction in the field. Based on studies already present in the literature, the following candidates were selected as possibly being responsible for the reduction in the field:

- Waves
- Scruton number: damping and mass ratio
- Reynolds scale effects
- Asymmetric and non-linear mooring configuration
- Unsteady and sheared currents

To improve the insight in the physics and phenomena behind VIM, design variations were tested at 1:100 scale at University of São Paolo to investigate the difference in VIM response between a semi-submersible with round columns and one with rounded-square columns [7]. Also at this smaller scale, the effect of roughness was investigated [5].

The same bare hull semi-submersible with rounded-square columns was tested at MARIN at 1:56.5 scale for CFD validation and for reference benchmark to compare against the results from the model tests incorporating one of the possible candidates for the reduction in field response. So, in this test campaign the floater was tested for different drafts, in waves, under varying tow conditions and with additional damping and different mass ratio applied, see [14], [15].

CFD calculations were carried out to investigate the applicability, accuracy and limitations of CFD for VIM predictions, see [11]. CFD results allow to obtain insight in the physics behind VIM in addition to model tests as detailed flow visualizations can be made. Also, the forces on each column with respect to the motions of the floater can be easily analyzed as illustrated in Figure 1. Furthermore, insight in Reynolds scale effects can be obtained by comparing the results from CFD at model- and full-scale Reynolds number.

In this paper an overview of the results obtained within the VIM JIP are discussed and compared with other findings in the literature. Some of the JIP findings have been and will be presented in [5], [7], [11], [14], [15].

Based on the results from the JIP it is concluded that additional damping, externally applied, reduces the VIM response. Therefore, a difference in damping levels between the model tests and in full-scale conditions in the field is a good candidate for the difference in VIM response.

HULL GEOMETRY EFFECTS ON VIM

Semi-submersibles with four rounded-square columns generally follow the same response curve as shown in many previous studies, see for example in [4], [6], [7], [14], [26]. The response is dependent on the exact geometry of the columns and pontoons of the floater, the number and type of appendages and on the current heading. The highest sway response is typically found for reduced velocities between 5 and 9, for a current heading between 30 and 45 degrees with respect to the column face and with nominal (A/D) values around 0.35 to 0.55. The highest yaw response is usually found for 0 degrees current heading with respect to the column face and is ranging from a few degrees up to even 10 degrees or higher and at higher reduced velocities. The yaw response is usually attributed to galloping behavior originating from the lift forces acting on the pontoons.

At the 1:100 scale the effect of column design on the VIM response was investigated by testing a semi-submersible floater with round columns and with rounded-square columns [7]. In the tests both semi-submersible floaters had the same pontoon geometry, mass ratio and mooring system, only the columns were replaced. Overall, it was found that the semi-submersible with round columns has larger VIM response for all headings than the floater with rounded-square columns.

One of the recurring questions in VIM model testing is whether roughness should be applied on the models. This question was addressed in the JIP at the 1:100 scale. The floaters with round and rounded-square columns were tested both with different levels of roughness, i.e. bare hull, low level and high level of roughness [5]. For the floater with rounded-square columns the VIM response was very similar for all three roughness levels. However, applying roughness for the floater with circular columns had an effect on the VIM response. With a low level of roughness the VIM response slightly increases compared with the results for the bare hull. With a high level of roughness the response was slightly lower than in the tests with the bare hull. The most probable reason for this is that the separation regions, which are not well defined on circular structures, are affected due to the roughness. For rounded-square columns these separation regions are more or less well defined on the edges of the columns. Note that the Reynolds number in the VIM lock-in region, based on the column diameter, was around 10^4, which is well below the transitional regime.

The effect of draft changes was investigated at the 1:56.5 scale, see [14]. The rounded-square semi-submersible was placed under an air-bearing plate restricting the floater at a certain draft. Keeping the same mass ratio the effect of draft changes could easily be investigated. Similar to the results observed in [6] and [26] it was found that the VIM response increases with larger draft. This is likely due to a larger exposed column length, also called correlation length, which intensifies the strength of the vortices. Furthermore, the VIM response significantly decreases for smaller draft.

The effect of appurtenances has not been investigated within the JIP. Commonly, in VIM model tests for multi-column semi-submersibles the larger appurtenances are included and smaller structures are omitted. Appurtenances seem to slightly reduce the amplitude of the VIM response of a floater with rounded-square columns, see [17], [19], probably due to an increased amount of hydrodynamic damping. They may also influence the VIM response slightly for different headings due to asymmetric appurtenances. Note that for a floater with circular columns, similar to spars, appurtenances may affect the location of flow separation and thus they may significantly influence the VIM response.

Rijken et al. [19] investigated the effect of asymmetric mooring to include the effect of the combined SCRs resulting in a different surge and sway stiffness. However, they did not observe an effect on the VIM response, thus this aspect was not pursued further within the VIM JIP.

Although the draft, column shape and (to a lesser extent) the roughness of the hull of the semi-submersible have a significant effect on the VIM response, these geometric features of the floater are not causing a different VIM behavior in the field when compared to model test results as the model tests are generally carried out with the correct hull geometry. In the field the roughness of the hull may be larger than in the model tests due to marine growth, but as discussed above and in [5] the reduction in VIM response in the model tests with large roughness level is not large enough to explain the difference compared with the field observations.

COMPUTATIONAL FLUID DYNAMICS FOR VIM

In recent years Computational Fluid Dynamics (CFD) has progressed impressively to predict the VIM response of semi-submersible floaters in terms of accuracy, efficiency and accessibility. Examples of CFD results for multi-column semi-submersible VIM response can be found in [1], [9], [10], [16], [24], [25], [28], [29].

Generally, it can be concluded that at model-scale Reynolds number the CFD results match the experimental results in terms of VIM amplitudes and periods provided that numerical verification and validation studies have been carefully carried out. Particular care should be given to using fine enough grid resolution at the semi-submersible hull surface, in the boundary layers near the hull and in the region around and in the wake of the columns. Good examples are shown by Kim et al. [10] and Wu et al.[28]. These verification and validation studies require a considerable effort, hardware, time and money, but are essential to be able to trust the CFD results for VIM predictions.

Based on the success of those results, CFD starts to become incorporated in the design process of semi-submersible floaters as discussed in [25], [28], [29]. Furthermore, CFD can be used to investigate and evaluate special aspects such as design variations of the floater and the influence of damping on VIM.

Within the VIM JIP extensive verification and validation studies were carried out to investigate the applicability of CFD to predict VIM response [11]. A good comparison, within 8%, between CFD results at model-scale Reynolds number and model test results was found for the semi-submersible with rounded-square columns as illustrated in Figure 2.

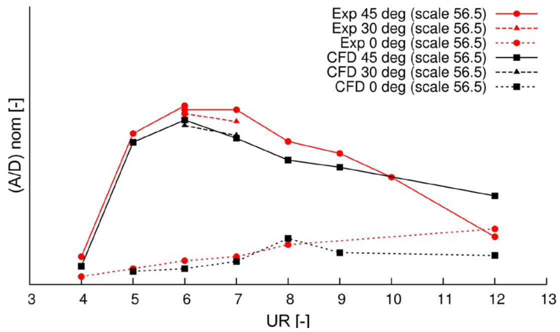


Figure 2: Calculated and measured model-scale results for VIM response of semi-submersible with rounded-square columns. Results taken from [11].

INFLUENCE OF WAVES

It is plausible to assume that waves and wave-induced velocities can disorganize or decrease the coherence of the vortices being shed from the columns, resulting in smaller lift forces on the columns and thus that the effects of waves can decrease the VIM response. The effects of waves on the VIM of multi-column semi-submersibles were investigated in for example [6], [8], [13], [16]. In Appendix A a short overview is presented on the results found in these studies. Summarized it can be concluded that in larger waves (100 year or Hurricane waves) the VIM response significantly reduces or even disappears. However, during loop-current events in the field the waves are small or absent. Martin and Rijken [13] focused on the effect of operational sea-states on VIM with Hs below 5m and found a minimal effect of these waves on the VIM response. They only carried out a few tests so no solid conclusions could be drawn.

Therefore, the effect of waves on VIM motions was investigated further within the VIM JIP. Different irregular waves were tested in MARIN's Depressurized Wave Basin as will be presented in [15] as well. These wave conditions included in-line, transverse and oblique waves with respect to the current with low Hs. A range of reduced velocities was tested for all wave conditions. From these VIM tests in waves it was observed that:

- 10-30% reduction of VIM occurs for inline and oblique waves;
- No VIM reduction is observed for transverse waves;
- Lower VIM occurs in higher waves;
- Larger VIM reduction is observed when going against the waves than going with the waves.

From these observations we conclude that waves do have an influence on the VIM response, although for transverse waves the sway response did not decrease. For small waves as found in operational seas the reduction in VIM response is small. Based on these observations we state that the presence of waves are not the main reason for the observed differences between field observations and model test results as during loop-current events in the field the waves are small or absent.

INFLUENCE OF SCRUTON NUMBER: DAMPING AND MASS RATIO

Using the Scruton number, defined by $Sc = \pi/2\, m^* \zeta$, with m* the mass ratio and ζ the damping ratio with respect to the critical damping, regions with VIV for cylinders can be identified, i.e. when Sc > 0.1 the VIV response reduces, see Williamson [27]. A similar Scruton number for VIM of multi-column semi-submersibles does not exist, but it can be assumed that the same principles apply for the effect of mass ratio and damping to the VIM response of multi-column floaters. When we consider a free-floating semi-submersible with mass ratio 1 and when we assume that the damping in the VIM model tests only consist of hydrodynamic damping and that the associated damping ratio is around 5%, the Scruton number then is 0.08. This suggests that if the same principles apply as for the VIV of a cylinder, the VIM response of the semi-submersible could be reduced by either increasing the mass ratio or increasing the damping levels. Both aspects have been investigated in the VIM JIP.

Influence of external damping

The influence of external damping on the VIM response of multi-column semi-submersibles was previously investigated by a number of studies, see for instance [1], [3], [13], [17], [23], [28]. This external damping may originate from the risers and mooring, which are generally not modeled in the model tests. Other aspects may contribute as well, such as the damping from wind. Each of the studies mentioned above used a different method to introduce damping and are further discussed in Appendix B. Summarized, the results indicate that external damping may reduce the VIM response, but as the methods to introduce damping are different, slightly different trends were observed.

In the VIM JIP the effect of external damping was investigated both in the model tests and in the CFD calculations. In the model tests the same active damping system of [23] was used to introduce external damping. It was found that when applying external damping a significant reduction of VIM amplitude is observed. When 20% of external (linear) damping is applied the VIM response is reduced by more than a factor two, see also [14]. In the CFD calculations the effect of damping was investigated by carrying out calculations at model- and full-scale Reynolds number for 45 degrees current heading for the reduced velocity with the largest response. It was observed that at both Reynolds numbers the VIM response quickly reduces for increased damping levels, very similar to the trend observed in the model test results, see also [11].

It should be noted that in the VIM JIP investigations linear damping was applied both in the CFD and in the model tests. However, it is not known if this is the correct damping model to represent the damping of risers and mooring. The effect on the VIM response should be investigated for other damping models such as Coulomb damping, quadratic damping or a combination of these types.

Further investigation is recommended to assess the actual damping levels from riser and mooring configurations which occur at prototype semisubmersibles, so that the correct VIM response can be considered in the design phase. The damping levels of risers and mooring can be calculated analytically in time-domain as discussed in [3], [12], [22] as well. The question for the time-domain calculations is how to estimate the correct drag and added mass coefficients of the riser members including shielding effects for different riser layouts.

The damping estimate for the complete system will depend on the riser and mooring configuration, number of risers, water depth, current conditions (including profile and orientation), sea states, and shielding effects between riser members and between hull and risers. A conservative approach could be to estimate the minimum damping level based on a minimum number of risers combined with a low level of current, but within the expected VIM range. For fatigue estimates it could be essential to evaluate the difference in damping with minimum number of risers as well as with maximum number of risers and the corresponding VIM amplitudes. An alternative approach could also be to base the damping level on estimates from in–place model tests with risers and mooring lines incorporated, but for deep water conditions the issue with truncation of lines and risers will then make the damping estimate more uncertain.

Based on the results in the VIM JIP, we conclude that external damping is an important candidate for the reduction in VIM response in the field compared with model test results. We recommend to investigate a range of external damping levels during standard VIM model tests to provide the sensitivity of the VIM response to external damping for the particular floater being tested.

Influence of mass ratio

The mass ratio of a free floating semi-submersible is equal to 1, the mass ratio can be smaller when the floater is constrained in the vertical direction, e.g. for a Tension Leg Platform (TLP). Rijken [20] argues that mass ratios higher than 1 can be achieved for floating semi-submersibles when considering the horizontal motions of the floater and the total mass participating in these horizontal motions, namely the mass and added mass of the hull together with the mass and added mass of the risers and mooring. The effect of mass ratio on the VIM response has been investigated in a limited number of studies by means of CFD calculations [20] and model tests [26]. In those studies it was found that the mass ratio has a limited influence on the VIM response, but only a small amount of data is available.

In the VIM JIP the effect of the mass ratio was investigated through the mass distribution and using the active control system, which was also used to investigate the effect of damping, see also [14]. In these model tests, it was found that with smaller mass ratio (i.e. $m^* \sim 0.85$) a slightly larger VIM response was obtained. For higher mass ratio in transverse direction (m^* up to 1.5) a small reduction in VIM response was observed.

Based on these results we conclude that the mass ratio has a small effect on the VIM response. However, the small reduction observed for the high mass ratio situation does not explain a large reduction in VIM response as observed in the field.

INFLUENCE OF REYNOLDS NUMBER

Model tests to assess the VIM response of multi-column floaters are typically carried out at model-scales between 1:40 and 1:60 using Froude scaling. The Reynolds number in the model-tests cannot be the same as at prototype scale, where the Reynolds number is defined by

$$\mathrm{Re} = \frac{UD}{\nu}, \tag{2}$$

with U the current velocity, D the projected column diameter and ν the kinematic viscosity of water. The Reynolds number in the model tests is usually between 10^4 and 10^5, whereas it is a factor $\lambda^{3/2}$ larger at prototype scale with λ the scale factor. For a circular cylinder the model-scale Reynolds numbers are below the transitional regime indicating that the boundary layer along the columns may be laminar, while the wake may be turbulent.

For multi-column semi-submersibles not much is known about the Reynolds scale effects on VIM response. Roddier et al. [21] investigated the influence of Reynolds number on vortex induced motions for spars and concluded that testing at sub-critical Reynolds regime is slightly conservative at higher reduced velocities, but for reduced velocities below 7 the VIM phenomena on spars is relatively insensitive to Reynolds number.

Nowadays, CFD is a promising candidate to investigate scale effects. However, it should be noted that CFD results at full-scale Reynolds number available in the literature are not conclusive on the scale effects on VIM response as will be further discussed in this section.

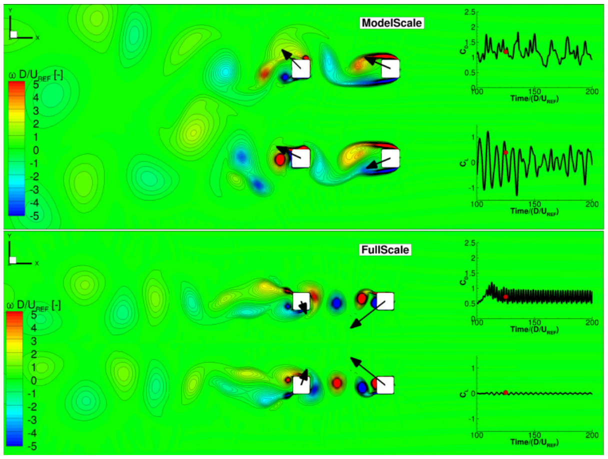
Within the VIM JIP CFD calculations have been carried out to determine where Reynolds scale effects might originate from if they are important for the VIM reduction in the field. As VIM is a resonance phenomenon, the following aspects are important for VIM motions:

- Excitation from the flow, which is driven by the lift forces on the columns;
- Hydrodynamic damping, which is mainly caused by dragging the floater through the water;
- Inertia of the floater and associated added mass.

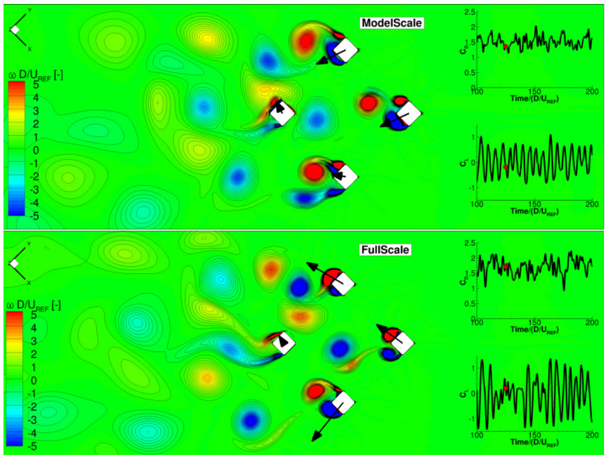
These aspects are considered separately below, but it should be noted that only three-dimensional calculations with a free-moving floater under VIM conditions can really show the Reynolds scale effects on the VIM response of the floater.

Lift forces on columns

In Figure 3 flow visualizations obtained with CFD for model- and full-scale Reynolds number are presented for 4 captive columns with rounded edges at 0 and 45 degrees heading with respect to the incoming flow.



(a) 0 degrees



(b) 45 degrees

Figure 3: Illustration of vorticity distribution from CFD calculations around four captive columns with rounded edges positioned at (a) 0 and (b) 45 degrees with respect to the incoming flow from the right. Presented are the results for model-scale (top picture) and full-scale (bottom picture) Reynolds number as well as the drag and lift coefficients for the four columns in the graphs to the right. The arrows on the columns indicate the force on each column. The flow solution presented is for the time-instant shown with the red dot in the graphs.

For 0 degrees the Reynolds scale effects on the flow patterns seem to be large. At full-scale Reynolds number the generated vortices behind the columns are very compact compared with the size at model-scale Reynolds number. Furthermore, at model-scale Reynolds number the flow separates at the front leading corner while at full-scale Reynolds number the flow separates at the trailing corner. The lift coefficient at full-scale is zero as the forces on the port-side and starboard columns are mirrored with respect to the center-line of the four columns. At model-scale the lift coefficient shows large oscillations as this symmetry along the centerline is not present, probably due to larger interaction between the columns as the generated vortices are much larger. Note, that the VIM response of multi-column floaters at 0 degrees is usually small and thus the presented scale effects for this configuration are not of importance for the VIM response of the floater at full-scale Reynolds number.

For 45 degrees the differences in flow pattern seems to be small comparing the results for full-scale Reynolds number with the model-scale results. For this heading the flow separates at the corner of the rounded-square column, which is a well defined location. The vortices again seem to be more compact at full-scale Reynolds number. The lift coefficient at full-scale Reynolds number seems to have larger amplitudes than at model-scale but also to be less regular.

Based on these captive four column results for 45 degrees we are not able to explain where a Reynolds scale effect on VIM response would originate from considering the lift forces on the columns.

Hydrodynamic damping during decay

In Figure 4 sway-decay CFD results for a semi-submersible with four rounded-square columns are presented for model- and full-scale Reynolds number. As can be observed in Figure 4 the hydrodynamic damping of the floater is less (~50%) at full-scale Reynolds number than at model-scale Reynolds number, which would result in slightly larger VIM motions at full-scale Reynolds number.

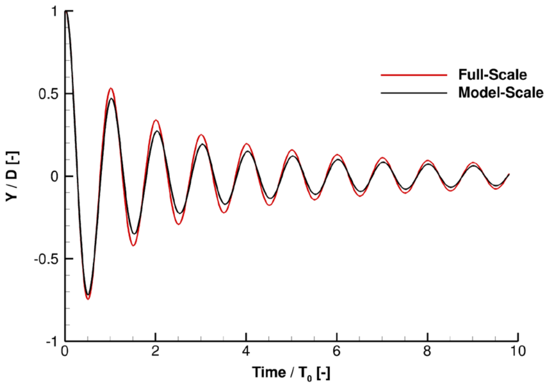


Figure 4: Calculated sway decay results at model- and full-scale Reynolds number for a semi-submersible with four rounded-square columns.

VIM: Inertia of the floater and associated added mass.

During VIM the vortex shedding frequency and the sway oscillation frequency of the floater adapt to each other which is called 'lock-in' [27]. This is assumed to occur due to adaptation of the 'added mass' of the floater as the vortex shedding interacts with the floater motions. Scale effects on VIM may occur when this adaptation of 'added mass' is different at full-scale Reynolds number than at model-scale Reynolds number. The decay results presented in Figure 4 do not show a change in added mass at full-scale Reynolds number during a decaying motion as the calculated scaled periods differ by at most 2% between model- and full-scale Reynolds number with the periods at full-scale Reynolds number being slightly smaller. This might be different during VIM in a current as the size of the generated vortices may be smaller at full-scale Reynolds number as illustrated in Figure 3.

Within the VIM JIP CFD results for a multi-column floater at full-scale and model-scale Reynolds number were compared to investigate the influence of Reynolds number on VIM response, see also [11]. As validation material for VIM response at full-scale Reynolds number does not exist, confidence in the CFD results at full-scale Reynolds number was obtained through numerical verification studies by means of variations in grid resolution, time step and turbulence model. After these investigations it was found that the VIM response at prototype Reynolds number is similar to the response at model-scale Reynolds number, but the response peak shifts to smaller reduced velocities at full-scale Reynolds number as shown in Figure 5.

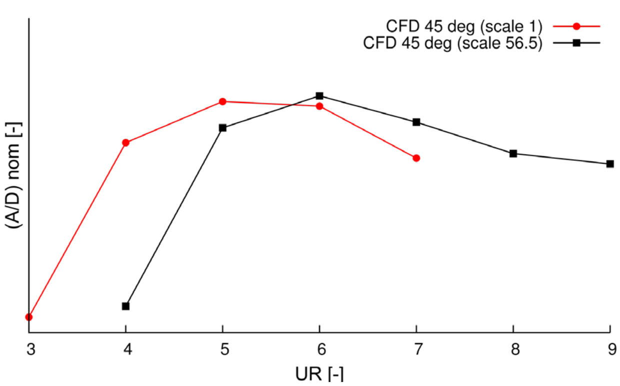


Figure 5: Calculated sway response of semi-submersible with four rounded-square columns for model-scale and full-scale Reynolds number. Results taken from [11].

In addition to the VIM JIP results presented in [11] and Figure 5, three-dimensional CFD VIM calculations at full-scale Reynolds number have been carried out in a number of studies as well, see for instance [1], [3], [9], [28]. Most studies went through grid and time step refinement studies to investigate the numerical sensitivity of the full-scale results as full-scale validation data does not exist. From those papers different trends can be deduced for prototype VIM response. Some studies indicate a similar response between model- and full-scale Reynolds number [1], [9], [11], other studies indicate a decrease in response at full-scale Reynolds number [3], [28].

The observed differences in trend at full-scale Reynolds number might be floater dependent. For instance differences in draft, mass ratio, column and pontoon geometry might have an influence on the full-scale VIM response. However, it is more likely that numerical settings such as iterative convergence levels for the flow and coupling with structure motions, code-dependent parameters, solver settings, local grid resolution and turbulence models, may result in different trends at full-scale. Comparing the different grids and turbulence models used in the papers it is not clear where the difference in results originate from. In some cases even the same code, the same turbulence models and similar level of grid refinement were used. We suspect that iterative convergence levels during a time step are an important factor to consider especially at full-scale Reynolds number as discussed in [11].

As the response at full-scale Reynolds number is very important for the fatigue analysis in the design stage of the floater and as model tests cannot provide results at full-scale Reynolds number, the industry should make an effort to better understand the observed differences in trends in the full-scale CFD results. Furthermore, commonly accepted "best practices" for full-scale VIM CFD calculations should be drafted in a joint effort.

Conclusion Reynolds scale effects

Based on the results presented in this section we have not found an indication or a reason for a possible Reynolds scale effect on VIM motions from the point of view of excitation (lift forces on the columns), hydrodynamic damping and VIM response.

INFLUENCE OF UNSTEADY AND SHEARED CURRENT CONDITIONS

In the VIM model tests the model is towed through an otherwise calm basin and thus the current is uniform and stationary. In the field the incoming current velocity and current heading may be constantly varying in time. Furthermore, the vertical profile of the current in the field may be varying over the water depth. However, not much is known on the actual current variations in the field as the field measurement of current is usually available at one vertical location, averaged over 20min, and with an ADCP looking down from keel level without information on the variation in current over the column height of the floater.

To investigate the influence of unsteady current conditions on the VIM response, instationary tow tests were carried out within the VIM JIP, see also [14]. During the tow run a sinusoidal variation of the tow velocity was applied with an oscillation amplitude of 10-20% of the current velocity and a oscillation period of 30-80% of the natural sway period of the floater. Note that in these tests only the current velocity is varied and not the current heading.

In these unsteady tow runs no significant influence on the VIM response was observed compared with the traditional runs with constant tow velocity. So, based on those observations we conclude that a varying current velocity is not responsible for the VIM reduction in the field.

For truss spars it was observed that in a sheared current modeling a hurricane current profile, the VIM response significantly increased compared with the response in a loop current profile [2]. This is mainly due to an increased level of damping arising from the truss of the spar in a loop-current profile.

For a semi-submersible it is expected that sheared currents have less influence on the VIM response as the draft of the semi-submersibles, and thus the variation in current profile, is less for semi-submersibles than for spars. Note however, that the damping on the risers might increase in a loop-current due to higher current velocities at deeper water depth, which may result in a higher damping level from the risers and thus a reduction in VIM response as observed for the truss spars.

We recommend to investigate this further through CFD calculations as it is difficult to carry out VIM model tests with sheared currents for semi-submersibles. An attempt can be made in an in-place semi-submersible test in a generated current, but care has to be taken that the possible observed sway motions of the floater are due to VIM response and not due to variations in the incoming current.

Based on the discussed results we suspect that possible unsteady or non-uniform currents are not the main reason for the VIM reduction in the field, but we recommend to further investigate the time-varying current conditions in the field and investigate their influence on the VIM response of the semi-submersible in model tests and with CFD calculations.

CONCLUSIONS AND RECOMMENDATIONS

The VIM JIP was started to evaluate possible candidates for differences between model tests, CFD and field observations.

Based on the results of the JIP we conclude that external damping is probably the main candidate for the observed difference between model test results and field observations. When applying external damping a significant reduction of VIM amplitude is observed. When 20% of external damping is applied the VIM response is reduced by more than a factor two.

Further investigation is recommended to assess the damping from riser and mooring configurations which occurs at prototype semisubmersibles, so that the correct VIM response can be considered in the design phase. The question here is how to estimate the correct damping levels for different riser layouts as this damping level will vary depending on number of risers, water depth, current profile, current orientation and shielding effects between riser members and between hull and risers.

The mass ratio was found to have a small effect on the VIM response, but the small reduction observed for a high mass ratio situation does not explain a large reduction in VIM response as observed in the field.

Although an influence of the waves on the VIM response is observed in this JIP, we state that waves are not the main reason for the observed differences between field observations and model test results. During loop-current events in the field the waves are small. We found that small waves do not have a large effect on the VIM response and thus they cannot explain the significant decrease in response as observed in the field.

Based on the discussed results we suspect that possible unsteady or non-uniform currents are not the main reason for the VIM reduction in the field, but we recommend to further investigate the time-varying current conditions in the field and investigate their influence on the VIM response of the semi-submersible in model tests and with CFD calculations.

From the extensive CFD campaign carried out within the VIM JIP we can conclude that CFD results at model-scale Reynolds number match the experimental results quite accurately. From the CFD results more insight can be obtained in the VIM phenomenon, especially detailed flow visualizations can be made to better understand the interaction of the flow with the columns.

From the CFD results at full-scale Reynolds number it is found that the VIM response at prototype scale is similar to the response at model-scale Reynolds number, but that a shift to lower reduced velocities occurs. It should be noted that some studies in the literature indicate a different trend. Therefore, it is recommended to the industry to jointly investigate why the CFD predictions at full-scale Reynolds number are predicting different trends.

ACKNOWLEDGMENTS

This study was carried out within the VIM JIP, which is run by the partnership between MARIN and USP, and for whose participants the authors are grateful. The participants of the VIM JIP are: MARIN, USP, Granherne, KBR, GVA, SBM Offshore, Petrobras, Aker Solutions and ConocoPhilips.

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APPENDIX A: LITERATURE REVIEW ON THE INFLUENCE OF WAVES ON VIM

In this appendix a short literature review is presented on the effect of waves on the VIM response of multi-column semi-submersibles.

Hong et al. [8] experimentally investigated the motions of multi-column semi-submersible in current and waves including a 100 year loop current sea-state with Hs equal to 4.5m and Hurricane conditions with larger waves with Hs above 11m. They observed that the VIM response in the large waves disappeared and that in the lower waves some VIM motions remained. They tested for one current velocity only so no results for the complete lock-in range were presented.

Goncalves et al. [6] experimentally investigated the effects of regular and irregular surface waves in the same direction of the current on the VIM response. In regular waves the VIM response was absent, but regular waves do not exist in the field. The wave heights for the irregular waves were above 4.4m. For these wave heights it was shown that for in-line irregular waves the VIM response decreased by 30%. In [6] the authors state that the dependence of VIM response in irregular waves can be deduced from the equivalent KC_{irr} number and ratio α defined by

$$KC_{irr} = \frac{\sqrt{2}\sigma_U}{f_p D}, \; \alpha = \frac{\sigma_U}{\sigma_U + U_{mean}} \qquad (3)$$

where σ_U is the root-mean-square value of the fluid velocity of oscillatory wave-flow, f_p the peak frequency of the flow, 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 to deduce whether the results fall within the 'viscous' region or 'inertia' region. When the results fall within the 'inertia' region the forces due to vortex shedding are small compared to the wave forces and consequently the VIM response will disappear. It should be noted that in the results of [6] it is shown that in regular waves the results fall within the 'inertia' range and in irregular waves the results fall within the 'viscous' range.

Martin and Rijken [13] focused on the effect of operational sea-states on VIM with Hs below 5m and found a minimal effect of these waves on the VIM response. In their tests they towed the model in three different sea-states into and with the waves to simulate current collinear with and opposite to the direction of wave propagation. Reduced velocities around lock-in, i.e. $6 \leq UR \leq 8$, were investigated for a bare hull and a hull with appendages.

Pontaza et al. [16] investigated the VIM motions of a semi-submersible with round columns in a background sea state with Hs of 2m using CFD and model tests. They conclude that both in the CFD results as in the model tests the VIM response in background waves diminishes. It should be noted however, that the tow tests described in [16] only covered 5 VIM cycles as the basin used was too short for long tow runs and around 8 cycles were calculated in the CFD results as the calculations including the waves were very computationally expensive. It is not clear at this moment why the VIM response diminishes for a semi-submersible with round columns whereas in [13] the background sea state had a minimal effect on the VIM response of a semi-submersible with rounded-square columns. As the runs in [16] were short it could be that this observed difference is caused due to a delay of VIM motions in wave conditions as pointed out in [17] and thus that longer runs are required for the semi-submersible with round columns to make a solid conclusion.

APPENDIX B: LITERATURE REVIEW ON THE INFLUENCE OF DAMPING AND MASS RATIO ON VIM

In this appendix a short literature review is presented on the influence of damping and mass ratio on the VIM response of multi-column semi-submersibles.

Influence of damping

Martin and Rijken [13] used an external damping system including two wheels and an electrical clutch to introduce an equivalent linear damping ratio up to 17%. They observed a significant decrease in VIM response of almost 50% due to increased external damping. However, they remarked that their damping system introduced an increase in surge stiffness of 30% resulting in different natural frequencies in basin-surge and basin-sway directions, which may have caused a shift to a lower response branch as discussed for spars in [21].

Rijken and Leverette [17] used a damping device that provided a near constant force opposite in magnitude to the direction of motion. This damping device provided approximately 10% of equivalent linear damping at sway amplitudes of half a column diameter. From their tests it was concluded that with this external damper the onset of VIM was delayed in time, but that the motion amplitude was not distinctively reduced.

Irani et al. [3] evaluated the damping characteristics of an operating semi-submersible located in the Gulf of Mexico through a fully coupled global performance numerical model. The damping contributions from the mooring and risers were calculated by conducting numerical forced oscillation tests. The damping characteristics were obtained in the form of energy dissipated per oscillation cycle, which were then used in model tests. In the model tests a novel damping mechanism using magnetic discs was developed to provide controlled damping of cross flow motions of the floater. In the model tests it was found that increasing the damping resulted in a decreasing VIM response. However, it should be noted that the results in [3] were not reported in terms of damping ratios, but in terms of number of magnets used in the model test set-up.

Wu et al. [28] investigated the effect of damping through CFD calculations. First, the amount of damping from the mooring and risers was estimated using an OrcaFlex numerical model by performing prescribed motion simulations covering the expected range of VIM amplitudes. The equivalent linear damping ratio was found to vary from 6 to 10%. Then, two different damping ratios were included in model- and full-scale CFD calculations. As the damping increased the VIM response decreased. Applying 9.2% linear damping the model-scale VIM response decreased by 59% at model-scale and 48% at full-scale.

Antony et al. [1] investigated the effect of linear damping on the VIM response at model-scale using CFD calculations. Applying 10% linear damping with reduced velocity equal to 8 they found a reduction of 32% in the VIM response of a paired-column semi-submersible.

Sterenborg et al. [23] developed an active damping system which introduces an actively controlled external force mimicking a damping force based on the floater sway motion and sway velocity. With this system the introduced damping level can easily be controlled and verified without changing the stiffness of the system. In [23] it was observed that the VIM response quickly reduces with increasing damping levels until the VIM response reduces to 50% when 20% of equivalent linear damping was introduced.

Influence of mass ratio

Rijken [20] investigated the effect of higher mass ratio using CFD for two-dimensional four-column configurations, but the response at a mass ratio of 0.8 was found to be similar to the response at a mass ratio of 1.5.

Waals et al. [26] investigated the effect of smaller mass ratios on the VIM response of a multi-column semi-submersible using an air-bearing plate which restricts the motions of the floater in vertical direction. Reducing the mass by 32%, but with the same displacement, the maximum VIM response increased by 10-15% and over a wider range of reduced velocities.