Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering
OMAE2014
June 8-13, 2014, San Francisco, California, USA

OMAE2014-23702

AN EXPERIMENTAL INVESTIGATION OF CYLINDRICAL FLOATER VIM IN CURRENT AND WAVES

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ABSTRACT

VIM (Vortex Induced Motion) is one of the important issues in the safety evaluation for cylindrical floating offshore structures. The VIM is basically placed as a phenomenon to occur in strong current, but that also appears in current and waves in the sea where offshore structures are installed.

The authors have recognized the phenomenon that the motion amplitude of a cylindrical floater in current and irregular waves together is larger than the sum of the motion amplitude in current and in irregular waves respectively in a VIM experiment. This VIM amplification phenomenon in the current and waves is remarkable when wave height is relatively low that has high occurrence frequency in the sea. It is, therefore, expected that the amplification phenomenon has large influence on the accumulative fatigue damages of the offshore structure's mooring system.

In order to make clear this VIM amplification phenomenon, the authors have conducted detailed VIM experiment in waves using a circular cross sectional mono-column floater model. The results of the VIM experiment in current and waves are described in detail in this paper. The results of the experiment in irregular waves show different characteristics for VIM amplitude in current. The results in regular waves show the effect of wave height and wave period on VIM amplitude in waves. Using those results, the mechanisms of the VIM amplification in waves are investigated.

KEYWORDS

Vortex Induced Motion (VIM), VIM amplification, Current and waves, Model experiment, Cylindrical floater.

INTRODUCTION

The cylindrical floaters such as MPSO (Mono-column type Floating Production Storage and Offloading) or SPAR are widely used for developing offshore oil and gas fields and wind turbine facilities. It is known that VIM occurs to the cylindrical floater in strong current, and many researches have been conducted for VIM [1]~[6].

VIM is a phenomenon whereby a cylindrical floater sways strongly in transverse direction to the current, and the VIM amplitude becomes close to diameter of the floater or more in certain case of high current velocity. VIM is one of the important issues for mooring system of cylindrical floaters installed in strong current. However, there are generally waves together with current in the sea where these floaters are installed. The VIM under current and waves should be considered in the safety evaluation of cylindrical floater's mooring system.

Based on this idea, the authors had conducted a VIM experiment under current and irregular waves using a mono-column floater model with 16 square-shaped cross section and a moon pool in 2008[7]. As a result, it was revealed that the VIM amplitude in current and waves was larger than the sum of the each amplitude in current only and waves only in some experimental conditions. This phenomenon was remarkable when wave height was relatively low. We called this amplification phenomenon as 'VIM in waves'. As a past research example, Finnigan et al. carried out the experiments for the truss SPAR's VIM in current and waves in 2004[8]. They reported the VIM amplitude in waves larger than one in current only when the wave direction is not same as the current direction. However, the wave effect on VIM amplitude was very small.

In order to make clear the VIM amplification phenomenon, the authors have conducted detailed VIM experiment using a circular cross sectional mono-column floater model in regular and irregular waves. The experiment in irregular waves was carried out to reconfirm the phenomenon on the different cross sectional model[7] and to compare the VIM amplitude characteristics of 'VIM in waves' with one in current only. The cross section of the model in this time was circle form with and without a moon pool. The purposes of the experiment in regular waves are to make clear the effects of wave height and period on 'VIM in waves' and to investigate the mechanisms of the 'VIM in waves'.

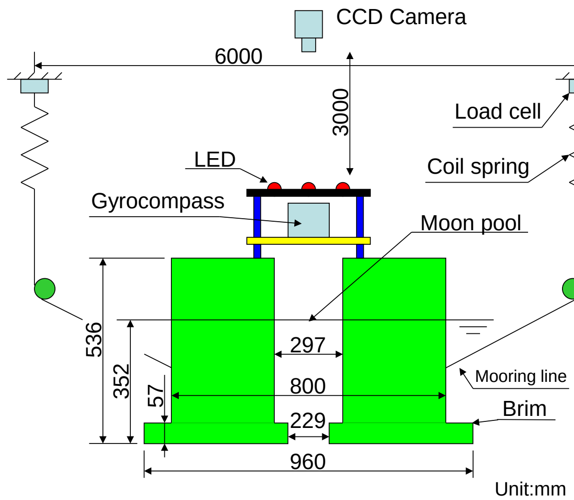

Figure 1. Model size and schematic view of the experimental model setup. (Side view)

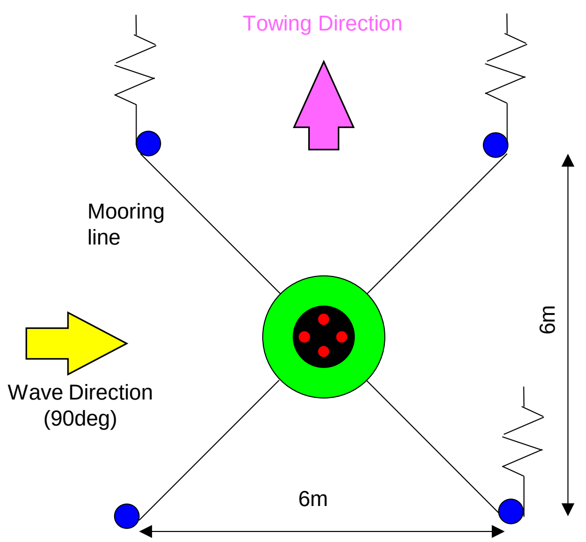

Figure 2. Schematic view of the mooring line and external force direction. (Top view)

EXPERIMENT

Model and setting

Figure 1 and 2 show the model size and the schematic view of the experimental setup, and Table 1 shows the model specifications in full scale values. The scale 1:87.5 circular column model with a brim was prepared from a 70m column diameter mono-column floater, with and without moon pool. The natural periods of the model with the mooring lines and the damping coefficients are obtained from free decay tests.

Table 1. Model specifications in full scale.

Item	With moon pool	Without moon pool	Unit
Model scale	1/87.5	1/87.5	-
Diameter	70.0	70.0	m
Displacement	1.12×10^{8}	1.27×10^{8}	kg
Center of gravity KG	18.9	18.9	m
Mooring stiffness	88.0	88.0	kN/m
Natural period	299.8	296.3	sec
Damping coefficient	7.15	7.00	% critical

Figure 3. Actual sea model basin.

The VIM measurement tests were carried out by towing the model moored to the towing carriage in still water and in waves. The model was moored by four mooring lines to the towing carriage. Each line consisted of a linear coil spring and a wire. The mooring line tensions were measured by load cells equipped at the top of each line. The horizontal motion caused by VIM was measured by optical measurement system with LED equipped on the top of the model. The measured displacement of LED was translated into the displacement of center of gravity using the gyrocompass data. The in-line drag was calculated from the line tensions and the model position.

VIM amplitude characteristic is described as a function of reduced velocity V_r in general. V_r is defined as follows:

$$V_r = VT_n / D \tag{1}$$

where V Current velocity that is towing velocity in the experiment, T_n Natural period of transverse motion and D Column diameter of the floater (800mm).

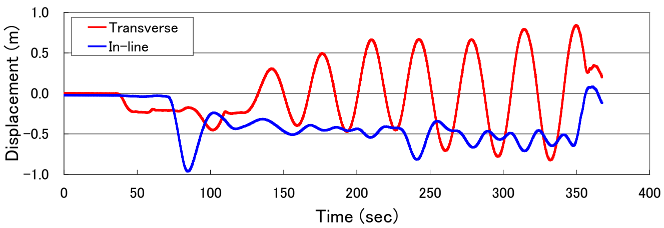

Figure 4. Example of too small initial displacement case. (Vr=7.9 in still water)

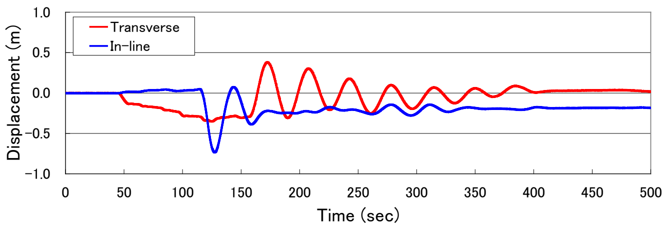

Figure 5. Example of too large initial displacement case. (Vr=5.9 in still water)

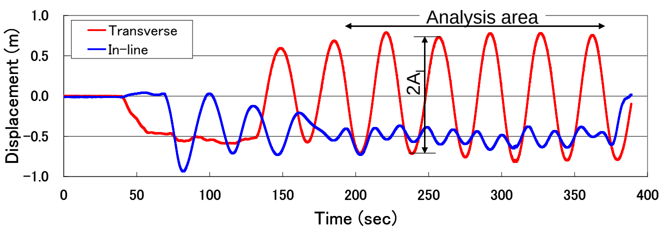

Figure 6. Example that initial displacement has been adjusted. (Vr=7.5 in still water)

Experimental facility

The experiments were conducted in the ‘Actual sea model basin’ at NMRI in Tokyo as shown in Figure 3. The size of basin is L80 × B40 × D4.5m, and 382 absorbing wave generators have been installed all around.

Test procedure

The maximum towing length for the experiment is 60m. It is little short for obtaining sufficient data of stable VIM. In order to reduce the transient time for stable VIM, initial displacements were set on the model toward the transverse direction just before towing. The towing in same condition was done several times for adjusting the initial displacements until the stable VIM data were obtained.

Figure 4, 5, and 6 show examples of the adjustment. Figure 4 is an example in case of the initial displacement is too small, because this time series shows the tendency that amplitude of the VIM is expanding to the end of time series, and it seems the stable amplitude is larger than one in measured. Figure 5 is an example in case of too large initial displacement, because the tendency for the amplitude is decreasing. Figure 6 shows that the initial displacement has been adjusted for obtaining the stable sufficient analysis area. At this time, the analysis area is the second half of the time series in where both the transverse and in-line motions are stable. The number of cycles of transverse motion for analysis is more than 4.5 in each towing. We defined the local amplitude A_l as half of the difference between local maximum and local minimum. At the test in irregular waves, the towing was carried out twice or three times in different random phase irregular waves each other for each test condition. The mean amplitude A is defined as follows:

$$A = \left(\sum_{i=1}^{N} A_{li}\right) / N \qquad (2)$$

where N is the total number of amplitude in analysis area of all towing experiment in same condition.

Table 2. Experimental condition in irregular waves.

V_r	4.5~7.9
H_s	1.0m
T_p	8.4sec
ψ_w	90deg

Table 3. Experimental condition in regular waves.

Moon pool	V_r	H_w [m]	T_w [sec]	ψ_w [deg]
without	5.0	0.9	6.0~14.0	90
		0.9~1.25	9.0	
with	5.0	0.9	6.0~16.0	
		0.9~1.25	9.0	
	5.9	0.9	7.0~14.0	
		0.9~1.25	9.0	
	8.3	0.9	7.0~16.0	
		0.9~1.25	9.0	

Test condition

The test conditions are shown in Table 2 and 3 for in irregular and regular waves, respectively. The tests in irregular waves were carried out using only the model without the moon pool. The wave conditions in the Tables are expressed in full scale values. Since the phenomenon ‘VIM in waves’ was remarkable in lower wave height in the previous VIM experiment[7], the significant wave height H_s and wave height of regular waves H_w are set up as low as possible in this VIM experiment. The irregular waves have JONSWAP spectrum with the enhancement factor γ=2.5, peak period T_p. The T_w in the Table 3 means regular wave period. The relative angle of current and wave ψ_w is set as 90deg. The Reynold’s numbers of this experiment based on the column diameter and towing velocity are $1.1\text{~}1.8\times10^5$.

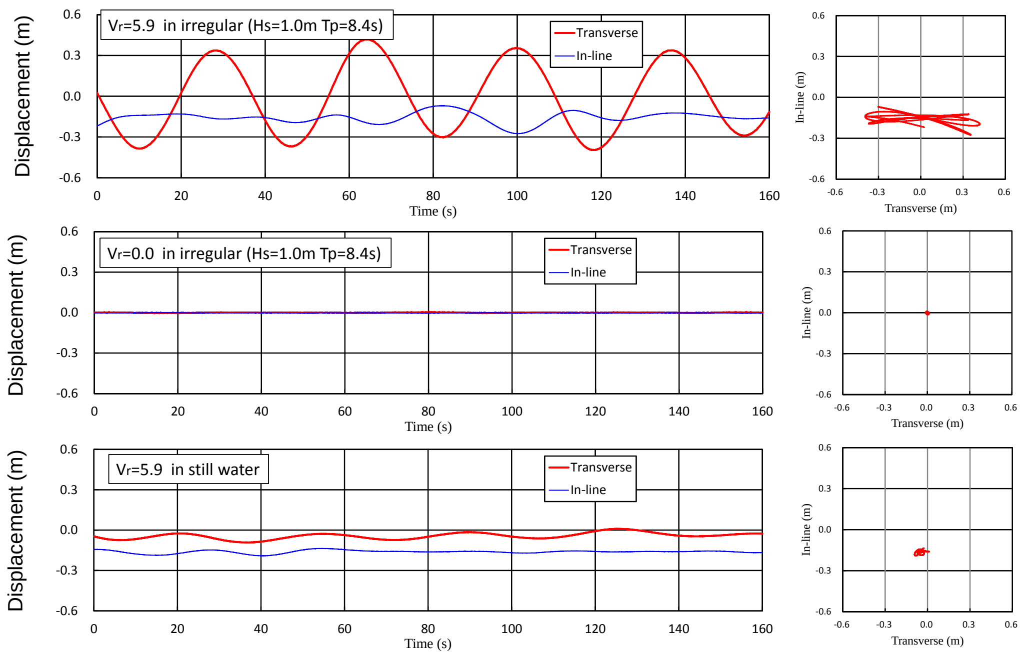

Figure 7. Examples of measured time series and trajectories in the experiment in still water and waves.

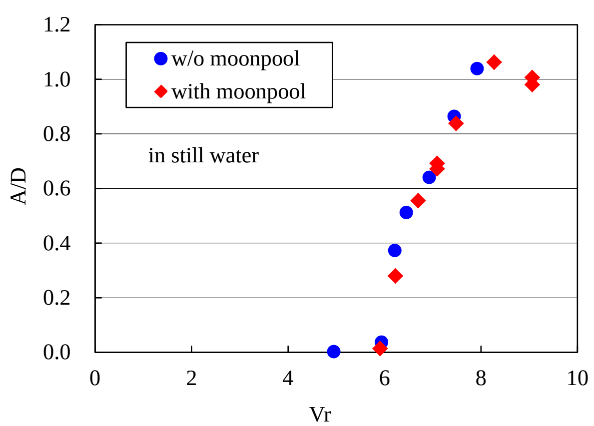

Figure 8. VIM amplitude in still water.

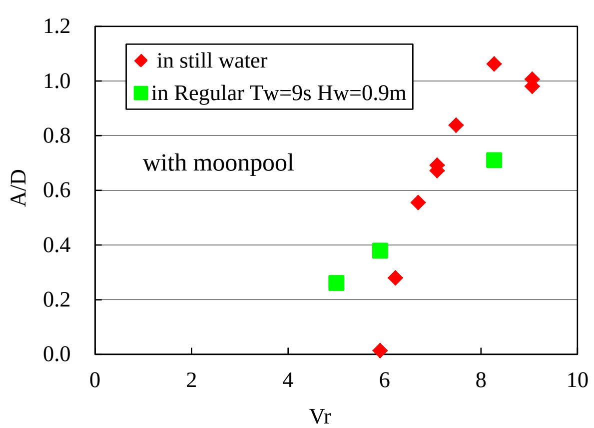

Figure 9. VIM amplitude on the model with the moon pool in regular waves.

EXPERIMENTAL RESULTS

Comparison of measured time series

Figure 7 shows examples of measured time series. The top of the figures is measured time series in still water, the middle is in irregular waves only, and the bottom is in current and irregular waves. The test conditions are V_r=5.9, H_s=1.0m T_p=8.4sec and ψ_w=90deg. In this condition, the VIM amplitude becomes large in waves obviously.

VIM amplitude in regular waves

Figure 8 shows the VIM amplitude characteristics of the model in still water. The vertical axis denotes mean amplitude divided by outer diameter of the model (*D*=800mm). The characteristic of the model with and without the moon pool are almost same. This result shows the effect of moon pool is negligible.

Figure 9 shows the comparison between the VIM amplitudes of the model with the moon pool in still water and in regular waves. The trend of the VIM amplitude in still water is increasing from about V_r=6. The VIM amplitudes in regular waves are larger than those in still water at V_r=5 and V_r=5.9, and the amplitude in regular waves at V_r = 8.3 is smaller than that in still water. When we look from a different viewpoint, it means that the increasing rate of amplitude characteristic in regular waves against reduced velocity is smaller than that in still water.

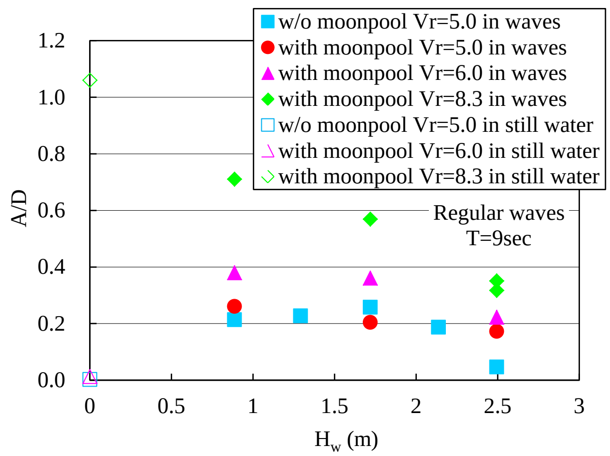

Figure 10. VIM amplitude in regular waves. (Effect of wave height)

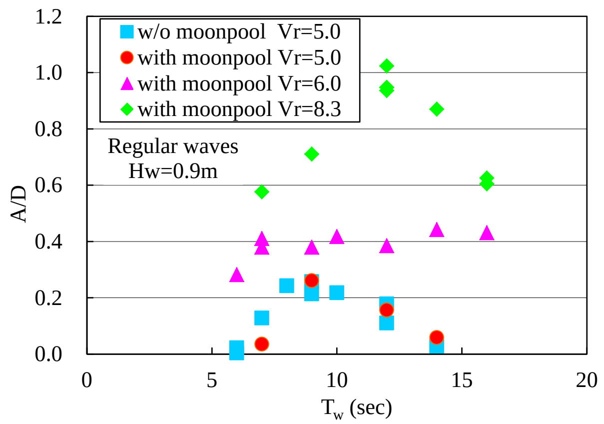

Figure 11. VIM amplitude in regular waves. (Effect of wave period)

In here, it needs to redefine of 'VIM in waves' based on Figure 9. The 'VIM in waves' should be defined as the change of VIM amplitude characteristic in waves, which includes not only increase of the VIM amplitude but also suppress of the amplitude development of the VIM. In an engineering viewpoint, it had better to take into account the increased phenomenon of the 'VIM in waves' when assessing accumulative fatigue damage of mooring system because there is a possibility to appear the significant VIM amplitude in wide range of the reduced velocity under the large occurrence frequency wave height condition more than in calm sea condition.

Normally, 10~30 stable VIM cycles are required in the experiments. About 5 stable VIM cycles obtained in one test seem to be small number for quantitative discussion. However the difference between the A/D=0.002 in still water and A/D=0.21 in waves at Vr=5 is clearly understood in the experiments. 'VIM in waves' shows different trend for sway motion of a floater in calm water.

Figure 10 shows the effect of wave height on VIM amplitude in regular waves. The open markers are the VIM amplitude in still water. The VIM amplitude trends to decrease with the increasing wave height. According to these results, the amplitudes at the limit of H_w=0m seems to be different from the amplitude in still water. This means that the 'VIM in waves' is not resulting from wave induced forces such as wave exciting force, wave drifting force, and wave drift damping. It is thought that the vortex shedding patterns, i.e. the shedding point on floater's wall, are changed by the influence of orbital motion of water particle. This is also expected from the remarkable wave period effect on the amplitude characteristics of 'VIM in waves' as stated below.

Figure 11 shows the effect of wave period on the VIM amplitude in regular waves. The 1/2 wavelength of the wave period 9~14sec, in where the VIM amplitude peak appear in the experimental condition, is 65~150m that is roughly corresponded or twice to the floater diameter. It is observed that 'VIM in waves' has a relation between wave period and diameter of a floater.

VIM amplitude of the model with and without the moon pool at V_r=5.0 mostly coincides each other in the figure for the effect of wave height and period. It seems that there is no influence of the moon pool on 'VIM in waves'. Referencing with the results of the experiment in 2008 [7], the 'VIM in waves' independently occurs on small difference of cross sectional shape of cylindrical floaters, such as circle or 16 square-shaped, with or without the moon pool.

The relative angle between waves and current was only 90 degree in this experiment. However it is thought that the 'VIM in waves' in other relative angles show the similar tendency as in relative angle 90 degree, if the 'VIM in waves' occurs by changing vortex shedding point from the influence of orbital motion of water particle.

The results of only one experimental setting for the model draft are presented in this paper. It is thought that the 'VIM in waves' is affected by the draft, that is displacement condition of a floater. More detail experiments with several conditions are needed to make clear the phenomenon of 'VIM in waves'.

Motion period and drag coefficient

Figure 12 shows the relation of the motion period in transverse direction and the VIM amplitude, and Figure 13 shows the relation of the in-line drag coefficient and the VIM amplitude. The motion period T is the mean period in analysis area shown in Figure 6 for example, and it is non-dementionarized by the natural period T_n.

From these figures, the characteristics of the motion period and the in-line drag coefficient are mostly in agreement on all conditions. The motion period represents the relation between the added mass and the exciting force for VIM on the model. The added mass concerns the acceleration proportional component of hydrodynamic force, while the exciting force for VIM is the velocity proportional component of hydrodynamic force. The results in Figure 12 and 13 mean that it has a possibility to change the vortex shedding point on the floater's wall by waves but the whole mechanism of VIM is not changed.

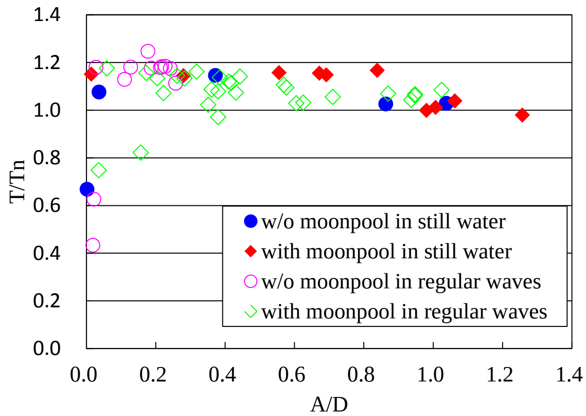

Figure 12. Comparison of motion period between the results in still water and those in waves.

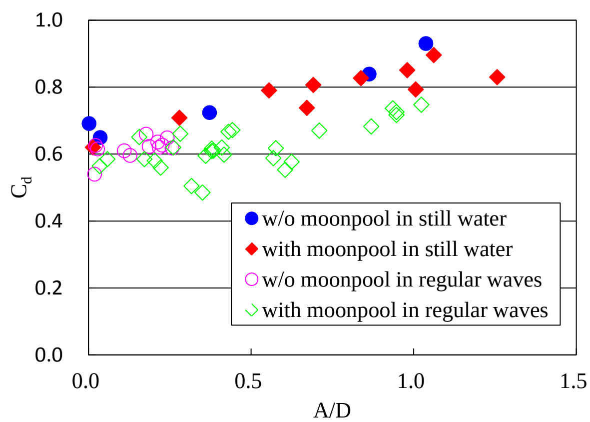

Figure 13. Comparison of in-line drag coefficient between the results in still water and those in waves.

VIM amplitude in irregular waves

The authors also conducted VIM tests in irregular waves by using a model without moon pool. The results of VIM amplitude in irregular waves is shown in Figure 14 compared with one in still water. From this figure, the result in irregular waves shows difference with one in still water for Vr<6. This result is same tendency as comparisons between in regular wave and in still water as shown in Figure 9.

Damping force in waves

Figure 15 shows the time series of free decay tests of sway motion in still water and in regular waves. The wave height is 1.75m, the wave period is 9sec in full scale.

The result shows that the damping in regular waves are smaller than one in still water at the final part of the tests with amplitudes approaching zero. However the damping in regular waves at about A/D=0.26, which is equal to the VIM A/D in 1.75m height regular waves in Figure 10, is slightly larger than one in still water. The damping quality in waves has no relation to the'VIM in waves'.

Moreover, from the view point of test accuracy, it may be thought that the small dither of the model from waves affects the small friction of the pulleys. From the result shown in Figure 15, the effect of pulleys damping, as adverse effect, on the results in experiment seems to be very small.

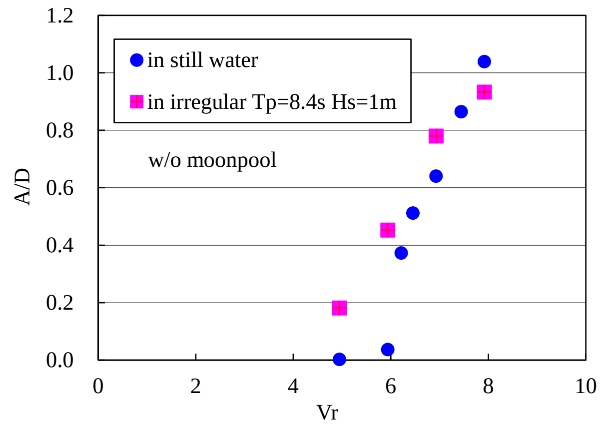

Figure 14. VIM amplitude on the model without the moon pool in irregular waves.

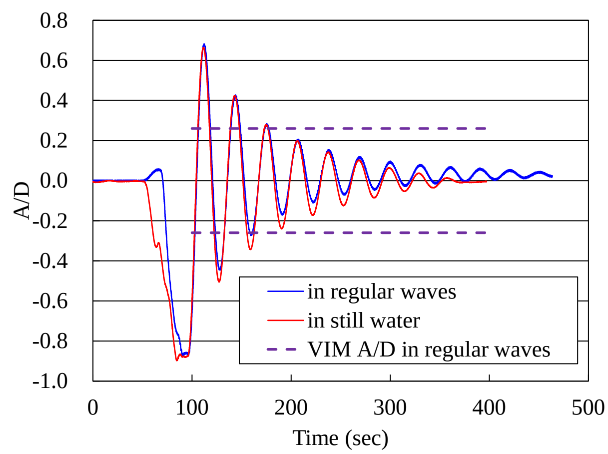

Figure 15. Time series of free decay tests of sway motion in regular waves and in still water.

CONCLUSIONS

The authors had recognized the amplification phenomenon on VIM amplitude for low Vr of a cylindrical floater in waves some years ago. In order to make clear this phenomenon, VIM experiment in regular and irregular waves were conducted. The conclusions obtained from these experiments are summarized as follows:

1) The 'VIM in waves', called in this paper, is phenomenon that VIM amplitude of a cylindrical floater is different in current and waves comparing with one in current only in

same reduced velocity. In low Vr conditions (Vr<6 in this experiment), the VIM amplitude in current and waves is larger than one in current only.

2) It is reasonable and expected to take into account the 'VIM in waves' when assessing accumulative fatigue damage of mooring system because there are a possibility to occur the significant VIM amplitude in large range of reduced velocity in the low wave height conditions more than in calm sea condition.
3) The amplitude of the 'VIM in waves' becomes small with the increasing of wave height, and there are remarkable influence of wave period on the amplitude characteristics of the 'VIM in waves'.
4) The relations between motion period and VIM amplitude, and between in-line drag coefficient and VIM amplitude seem to be mostly independent on wave condition.
5) The 'VIM in waves' occurs in the certain waves irrespective of the floater's hull with or without a moon pool.

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