FEASIBILITY STUDY FOR STABILISING OFFSHORE WIND FARM SERVICE VESSELS BY LOWERING THEIR CENTRE OF GRAVITY

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ABSTRACT

Small offshore wind farm service vessels (WFSVs), which are designed for delivering minor maintenance tasks, will be used more frequently in the future operation and maintenance of offshore wind farms. However, small WFSVs usually have insufficient seakeeping capability. Upon arriving at site, they will meet difficulty in realising the safe transfer of crew and parts between offshore wind turbines (OWTs) and WFSVs. Some methods are already developed for addressing this issue, but none of them is ideal in practical application. Therefore, a feasibility research is conducted in this paper in order to develop a new measure for stabilising small WFSVs based on the static stability theory of ships. From the experimental testing results, it is surprisingly found that it is difficult to stabilise the twin-hull WFSVs in waves by using the proposed method as the static stability theory fails to consider the overturning moment that is created by the ballast mass block when it is in flow, except that the ballast mass block has little volume or it is put down to a very deep position where waves cannot reach. However, this is not realistic.

NOMENCLATURE & ABBREVIATIONS

ϕ	Inclination angle of vessel body
m	Mass of the vessel
g	Acceleration of gravity
T	Wave period
x_i	Motion of the catamaran model
y_i	Wave amplitude corresponding to x_i
n	Number of samples in each data
$\bar{x}$	Average value of x_i
$\bar{y}$	Average value of y_i
ρ	Water density
ρ_b	Density of the ballast mass material
D	Diameter of ballast mass block
l	Height of ballast mass block
u	Flow speed
C_m	Inertia coefficient
C_d	Drag coefficient
F	Inline force
M_o	Overturning moment
M_u	Upright moment
OWF	Offshore wind farm
OWT	Offshore wind turbine
WFSV	Wind farm service vessel
VCG	Vertical centre of gravity
BC	Centre of buoyancy
MC	Metacentre
GZ	Lever arm
GM	Distance between VCG and Metacentre
PVC	Polyvinyl chloride
RAO	Response amplitude operator

1. INTRODUCTION

Thanks to the successful implementation of the Round 1 to Round 3 offshore wind development programs, the UK currently tops the international rankings for offshore wind market. It is predicted that the UK's total installed capacity of offshore wind will increase from the present 5.07 GW to 30 GW by 2030 and 50 GW by 2050 [1]. This will attract a significant investment in the UK. However, how to guarantee the economic return of so huge investment is a challenging issue particular from offshore, where there are many uncertainties may affect the safe power production of offshore wind farms [2]. One can take many measures to lower the risk, one of which is to enhance the maintenance of offshore wind farms (OWFs). In the process of designing OWF maintenance strategy, how to access offshore wind turbines (OWTs) is a question that needs to be answered firstly. In the present offshore wind practice, wind farm service vessels (WFSVs) are a popular tool used to access OWTs, although helicopters are also used occasionally. So far, there have been a few types of WFSVs operating in the offshore wind market. They were designed for various purposes. But the recent survey has shown that for onshore wind farms, '75% of faults causing 5% of the downtime are mostly associated with the electrical plant, the converter, electric pitch systems, control equipment and switchgear, whose defects are relatively easy to fix' and 'the failure rates offshore will be similar to onshore but that downtime will be hugely affected by the location of the offshore wind farm and its accessibility' [3]. For this reason, it can be predicted that small WFSVs will be used more frequency in the future maintenance of OWFS. However, due to the small sizes and limited deck spaces of small WFSVs, many existing seakeeping technologies that have been successfully applied to large vessels are not applicable to small WFSVs [4]. In order to address this issue, some efforts have been done previously. To date, a few techniques are adopted by small WFSVs to realise safe transfer on arrival. But the practice has shown that the application of these techniques is helpful to improve the situation. But they still show some various limitations in practical application. For example, the use of rubber friction method will consume more fuel, causing more carbon emission thereby; the roller clamper can set up fixed point easily, but the deck may be flooded in rough waves due to the fixed contact point; the gangway supported by an advanced wave compensation system enables safe transfer. However, it is quite costly and moreover needs a large deck space to host the facility [4]. This motivates the research of this paper.

2. HYPOTHESIS OF A NEW VESSEL STABILISING TECHNIQUE

In this section, a potential technique for stabilising twin-hull WFSV is proposed based on the static stability theory of ships [5]. According to the static stability theory, when the ship is sitting in still water its vertical centre of gravity (VCG) and its centre of buoyancy (BC) will rest in the same vertical line, as illustrated in Fig.1. Where, 'M' indicates the Metacentre (MC) of the ship, 'G' is the VCG, and 'B' indicates the BC of the ship.

Since the direction of the gravity of the ship and the direction of the buoyancy is opposite to each other, the ship will achieve equilibrium. But when the ship rotates in either roll or pitch direction, the vessel body will leave the original equilibrium position and show an inclination angle ϕ, which is the included angle between line $\overline{\mathrm{MG}}$ and line $\overline{\mathrm{MB}}$. Consequently, the buoyancy and the gravity of the ship will generate a restoring torque to upright the ship [5]. It is known as upright moment M_u, as shown in Fig.1.

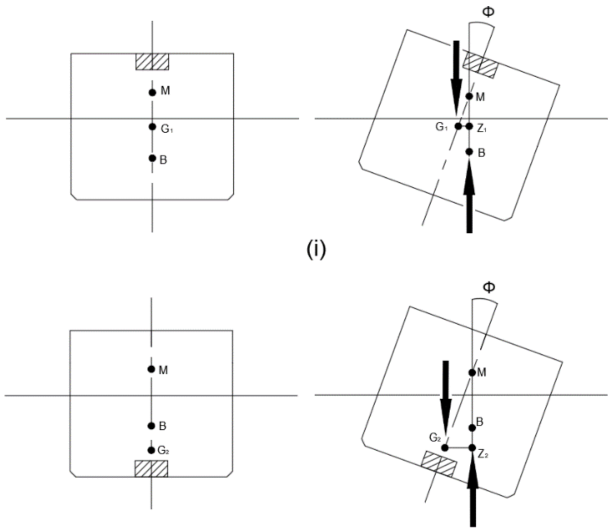


Fig.1 Static stability theory of ships. (i) when VCG is above BC, (ii) when VCG is below BC.

In Fig.1, there are two scenarios are considered, both of which may happen in the real-life operation of the WFSVs. Through comparing Figs.1(i) and (ii), it is found that when the VCG of the ship is below its BC (i.e. the scenario shown in Fig.1(ii)), a longer force arm $\overline{\mathrm{GZ}}$ can be achieved, which will be beneficial to create a larger upright moment of the vessel. Moreover, the lower the position of the VCG away from the BC, the larger the upright moment of the ship will tend to be. The relationship of the lines $\overline{\mathrm{GZ}}$ and $\overline{\mathrm{MG}}$ and inclination angle ϕ is

$$\overline{\mathrm{GZ}} = \overline{\mathrm{MG}} \sin\phi \quad (1)$$

Then the upright moment will be

$$M_u = m \times g \times \overline{\mathrm{GZ}} \quad (2)$$

From (1) and (2), it can be inferred that the longer the distance $\overline{\mathrm{MG}}$, the larger upright moment M_u will be created. Inspired by such a phenomenon, it is proposed to stabilise twin-hull WFSVs via lowering their VCG.

3. LABORATORY DESIGN FOR REALISING THE PROPOSED IDEA

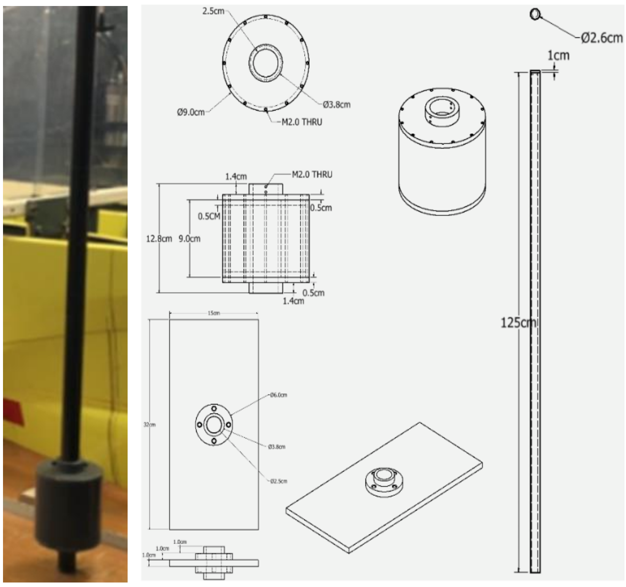
In order to realise the idea proposed in Section 2 and investigate its feasibility in stabilising twin-hull WFSVs, a catamaran model in the hydrodynamics laboratory of Newcastle University was employed in the study. It is shown in Fig.2. The dimensions and parameters of the catamaran model are listed in Table 1.

Fig.2 The catamaran model used for the research.

Table 1. Dimensions of the catamaran model

Length	1.49 m
Overall beam	0.58 m
Beam of hull	0.174 m
Height	0.25 m
Draft	0.12 m
Weight	11.30 kg

As shown in Fig.2, the two hulls of the model are held using an aluminium frame, which also allows the installation of a customised PVC base plate for holding the VCG adjustment device whilst not causing the permanent change of the ship structures. In the study, the VCG adjustment device is mainly composed of a 5 kg ballast mass block and a slider pole, as shown in Fig.3.



(i) (ii)

Fig.3 VCG adjustment device. (i) the VCG adjustment device, (ii) the parts of the VCG adjustment device.

As shown in Fig.3, the slider pole is made of carbon fibre to ensure it is strong enough to hold the ballast mass block while not being deflected when moving in flow. The ballast mass block can move up and down along the slider pole, so as the VCG of the catamaran model can be changed as required. Herein, the mass of the ballast mass block is exactly same as the ballast mass of the model, so that the application of the VCG adjustment device will not alter the original waterline of the model. This will, to a large extent, guarantee the comparability of the testing results that are obtained before and after using the VCG adjustment device. In the research, the VCG adjustment device will be installed between the two hulls of the catamaran model and held using a fixture tool, which is installed on the aluminium frame and is consisted of plates, nuts and screw, see Fig.3.

4. SET-UP OF EXPERIMENTS

The experiments in this feasibility study were conducted in the towing tank of the hydrodynamics laboratory at Newcastle University. The towing tank is 37 m long and 3.7 m wide. The usual water depth in the tank is 1.25 m. The tank is equipped with wavemakers, which are capable of producing waves. In the study, both bow waves and beam waves were considered, as illustrated in Fig.4.

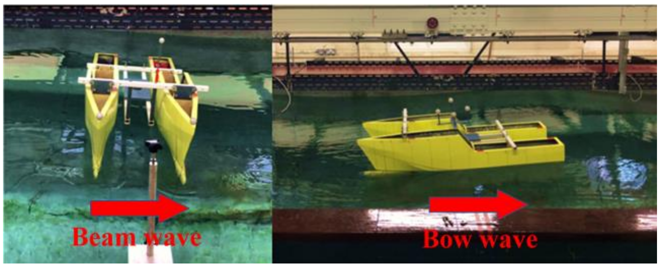


Fig.4 Bow and beam waves considered in the study

The wave height can be from 0.02 m to 0.12 m and wave period can be set in the range of 0.5 s to 2.0 s. But due to the limited time, the wave height in all tests below was fixed at a constant value 0.12 m. The wave period was set to be 1.0 s, 1.25 s, 1.5 s and 1.75 s, respectively. The submersion depth of the ballast mass block was 0.2 m, 0.4 m, 0.6 m, and 1.0 m. The testing scenarios considered in this feasibility study are listed in Table 2.

Table 2. Testing scenarios considered

Wave type	**Submersion depth (m)**	**Wave period (s)**			
	0.0	1.0	1.25	1.5	1.75

Bow waves	0.2	1.0	1.25	1.5	1.75
	0.4	1.0	1.25	1.5	1.75
	0.6	1.0	1.25	1.5	1.75
	0.8	1.0	1.25	1.5	1.75
	1.0	1.0	1.25	1.5	1.75
Beam waves	0.0	1.0	1.25	1.5	1.75
	0.2	1.0	1.25	1.5	1.75
	0.4	1.0	1.25	1.5	1.75
	0.6	1.0	1.25	1.5	1.75
	0.8	1.0	1.25	1.5	1.75
	1.0	1.0	1.25	1.5	1.75

In the tests, 'Qualisys', a motion capturing system was employed to measure the six degrees of freedom motions of the catamaran model. It utilizes special cameras, as shown in Fig. 5, to track reflective points attached to the model within a virtually calibrated volume to obtain data in six degrees of freedom. Notably, these tracking points were strategically placed to avoid overlapping or falling out of range when the vessel underwent a test. Additionally, the registered sample size and time interval were adjusted according to ensure sufficient data is gathered for an accurate analysis. For this study, data was recorded by using a sampling frequency of 100 Hz. In order to minimize the negative influence of reflected waves, only 20 s data were collected in each testing scenario.

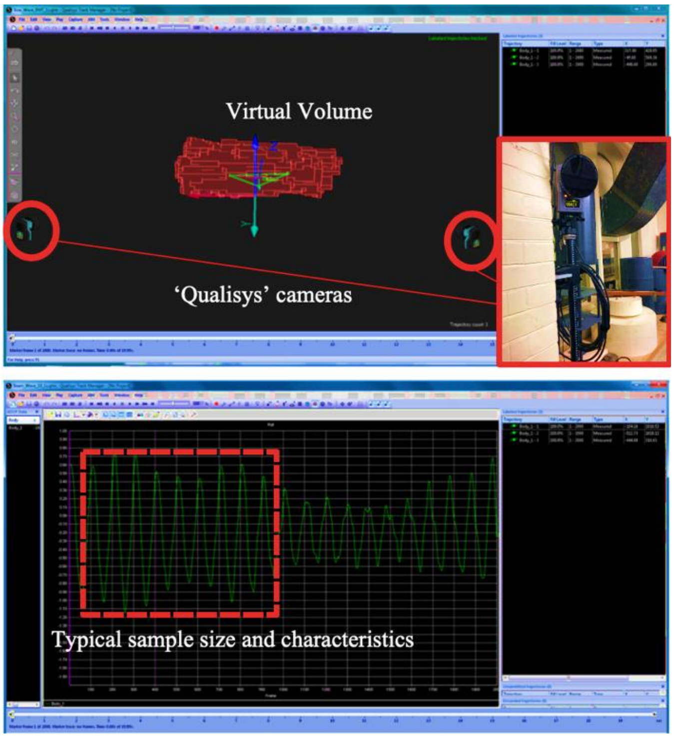


Fig.5 Qualisys data acquisition system

5. TESTING RESULTS ANALYSIS

The six degrees of freedom motions of the catamaran model were measured in all testing scenarios listed in Table 2. Since the motions of the vessel in roll and pitch directions have significant influence on the safety and comfort of crew members, here only the motions collected in these two directions will be analysed. They are shown in Fig.6. Where, the motion data collected in only 4 testing scenarios rather than in all testing scenarios are shown in order to ease the observation of the measured data.

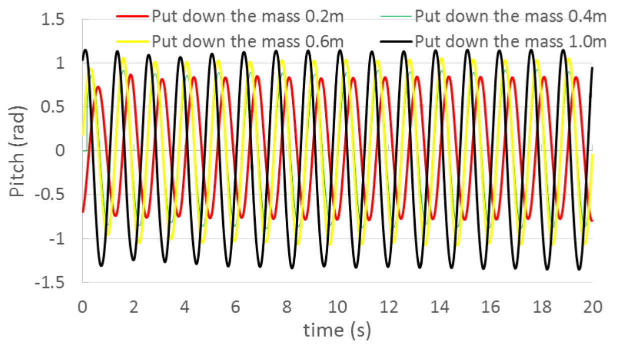
From Fig.6, it is surprisingly found that the application of the VCG adjustment device did not reduce the motions of the catamaran model in almost all testing scenarios. This is different from our prediction in Section 2 based on the static stability theory of ships. Moreover, the deeper the ballast mass block is placed under water, the less effective it will become in stabilising the model.

In order to describe the phenomena in a clearer way, the Response Amplitude Operators (RAOs) of the catamaran model in different testing scenarios are calculated based on the measurement data shown in Fig.6. IN each testing scenario, the RAO is calculated by using the following equation:

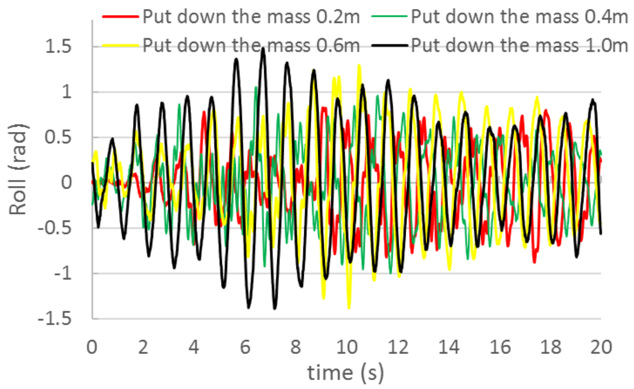
$$\text{RAO} = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{\sum_{i=1}^{n}(y_i-\bar{y})^2}} \tag{3}$$

where x_i $(i = 1, 2, \ldots, n)$ are the motion data measured from the model, y_i $(i = 1, 2, \ldots, n)$ are the corresponding wave amplitude data measured simultaneously, and n refers to the number of samples collected in the data. $\bar{x}$ and $\bar{y}$ are the average values of x_i and y_i, respectively.

(i)



(ii)



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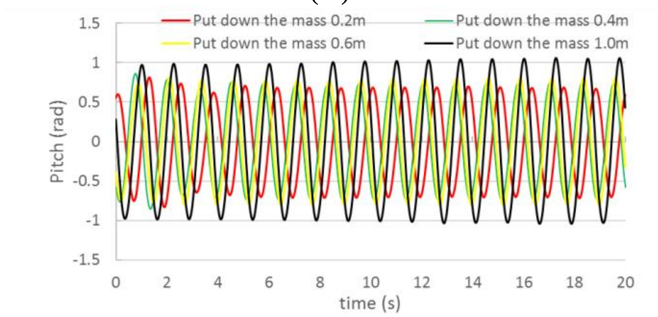
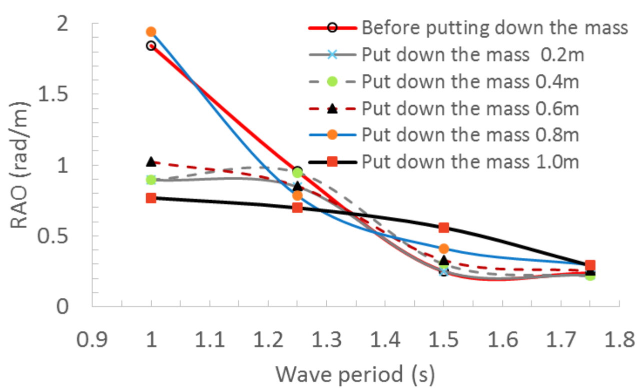


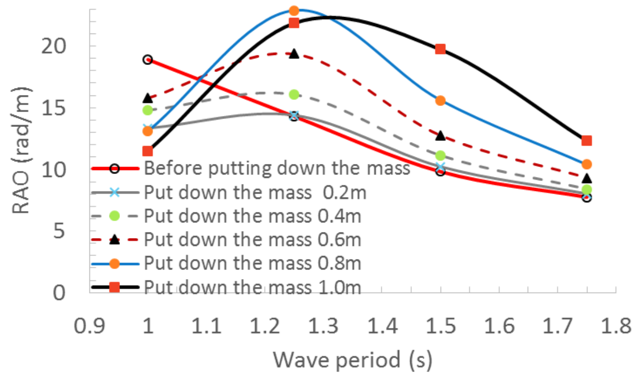
(iv)

Fig.6 Motions of the model in roll and pitch directions. (i) Roll direction motions in beam waves, (ii) Pitch direction motions in beam waves, (iii) Roll direction motions in bow waves, (iv) Pitch direction motions in bow waves.

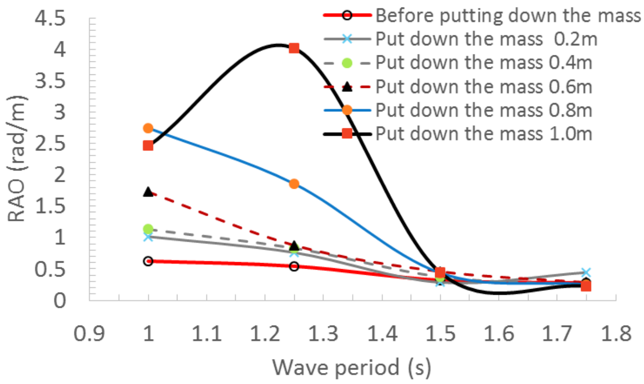
The calculated RAOs obtained in different testing scenarios are shown in Fig.7.



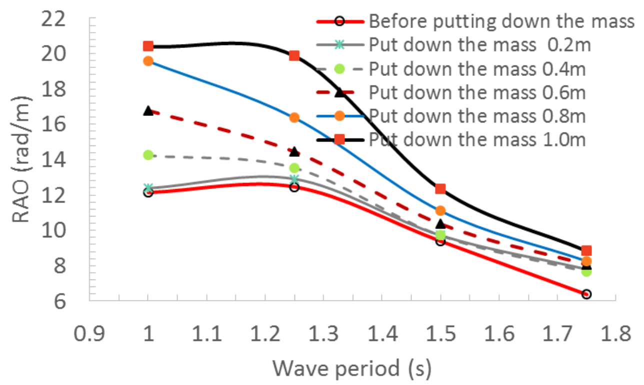
(i)



(ii)



(iii)



(iv)

Fig.7 RAOs of the model in roll and pitch directions. (i) Roll direction RAOs in beam waves, (ii) Pitch direction RAOs in beam waves, (iii) Roll direction RAOs in bow waves, (iv) Pitch direction RAOs in bow waves.

From Fig.7, it is found that in most testing scenarios, the application of the VCG adjustment device did not reduce the roll and pitch motions of the catamaran model whatever the catamaran model was in beam waves or bow waves. This is because the static stability theory of ships only considers the upright moment created by the gravity and buoyancy of the vessel. However, the theory fails to consider the influence of waves and tidal current. According to Morrison equation [6], when the influence of the slider pole is ignored the inline force *F* acting on the ballast mass block can be estimated by

$$F = \frac{1}{4}\rho\pi l D^2 C_m \frac{\partial u}{\partial t} + \frac{1}{2}\rho D l C_d u|u| \quad (4)$$

where D and l are the diameter and height of the ballast mass block, C_m and C_d are the inertial and drag coefficients of the ballast mass; ρ refers to water density; u stands for the relative speed between the ballast mass and water flow. In the following calculations, it can be estimated by $u \approx \frac{gT}{2\pi}$. Where, T refers to the period of the sea waves. Then, when the fluid flow passes through the ballast mass block an overturning moment M_o will be created, as shown in Fig.8.

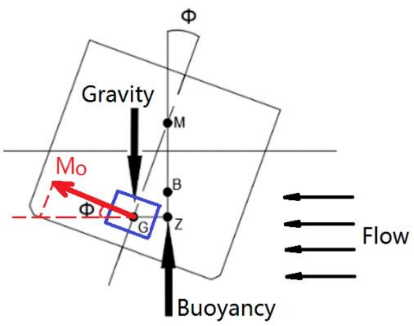


Fig.8 Overturning moment caused by flow.

The overturning moment M_o can be estimated using the following equation:

$$M_o = F \times \overline{\mathrm{MG}} \times \cos\phi \quad (5)$$

From (1) and (2), it is known that the upright moment created by the gravity and buoyancy is

$$M_u = m \times g \times \overline{\mathrm{MG}} \times \sin\phi \quad (6)$$

Then whether the vessel can be successfully stabilised will depend on the values of M_o and M_u. When the former is smaller than the latter, the vessel will be stabilised; otherwise the vessel will become more unstable, i.e.

$$\begin{cases} M_o/M_u < 1 & \mathit{Stabilise\ the\ vessel} \\ M_o/M_u \geq 1 & \mathit{Not\ stabilise\ the\ vessel} \end{cases} \quad (7)$$

In order to explain the phenomena observed from Figs.6 and 7, a theoretical study is conducted below, which considers the worse situation in each testing scenario, i.e.

$$\begin{cases} u(t) = u_{max} \\ \frac{\partial u}{\partial t} = 0 \end{cases} \quad (8)$$

Therefore, the overturning moment is

$$M_o = \frac{1}{2}\rho D l C_d u|u| \times \overline{\mathrm{MG}} \times \cos\phi \quad (9)$$

The ratio of M_o/M_u will be

$$M_o/M_u = \frac{\rho D l C_d u|u|}{2mg} \times \cot\phi \quad (10)$$

Since

$$m = \frac{1}{4}\rho_b \pi D^2 l \quad (11)$$

have

$$M_o/M_u = \frac{2\rho}{\pi\rho_b g} \times \frac{C_d}{D} \times u^2 \times \cot\phi \quad (12)$$

where ρ_b refers to the density of ballast mass material. From the size and weight of the ballast mass block described in Section 3, it can be easily known that $\rho_b = 8737\ kg/m^3$.
From (12), it can be inferred that whether the vessel can be stabiliser by the ballast mass block is irrelated to the submersion depth of the ballast mass block. But it relies on the material and geometric design of the ballast mass block, the flow speed, as well as the inclination angle of the vessel body. From Fig.3, it is known that the diameter of the ballast mass block $D = 0.09\ m$. Assume drag coefficient $C_d = 1.5$ for a cylinder structure, then (12) can be further simplified as

$$M_o/M_u = 0.1239u^2 \times \cot\phi \quad (13)$$

Based on (13), the contributions of the ballast mass block under different wave conditions are predicted. The prediction results are shown in Fig.9.

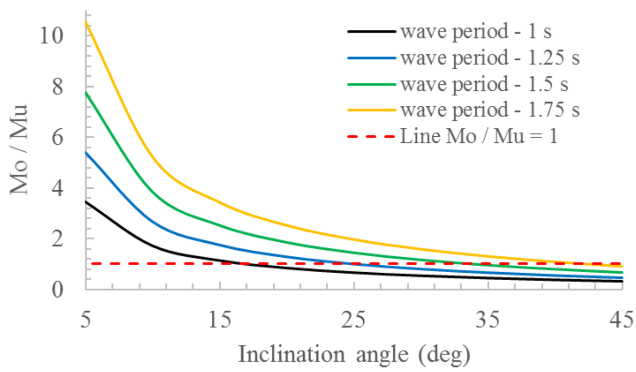


Fig.9 Contributions of the ballast mass under different wave conditions

From Fig.9, it is seen that despite the wave conditions, the application of the VCG adjustment device will make the vessel more unstable when the vessel has small rolling and pitching movements; The VCG adjustment device will start to stabilise the vessel only after the vessel shows a large inclination angle, which is different under different wave conditions. The shorter the wave period, the earlier the VCG adjustment device will start to stabilise the vessel. The proposed VCG adjustment device will not stabilise the vessel when the wave period is long. These theoretical calculation results fully explain why the proposed VCG adjustment device does not work as expected in stabilising the two-hull WFSVs.

6. CONCLUSIONS

In order to explore an approach to stabilise the twin-hull WFSVs and realise the safe transfer of maintenance crew and parts between the OWTs and the WFSVs when the vessels arrive at OWTs, an VCG adjustment device is proposed based on the static stability theory of ships. Then, the feasibility study of such a device is conducted in the paper in order to understand its effectiveness in stabilising WFSVs. From the experimental and theoretical research described above, the following conclusions can be drawn:

(1) The VCG adjustment device that is proposed based on the static stability theory of ships does not work very well in stabilising twin-hull WFSVs. This is because the static stability theory only considers the upright moment created by gravity and buoyancy, however it does not consider the overturning moment introduced by the VCG adjustment device when it experiences flow;

(2) It is interestingly found that the motion stability of the twin-hull WFSV is irrelated to the submersion depth of the ballast mass block. However, it is affected by the material and geometric design of the ballast mass block, the flow speed, and the inclination angle of the vessel body; Usually, the proposed VCG adjustment device will play a negative role in stabilising the vessel when it experiences waves of short wave periods;

(3) Despite the wave conditions, the VCG adjustment device will start to stabilise the vessel only after the vessel body exhibits a large inclination angle, which will be different under different wave conditions. In theory, the longer the wave period, the larger such an inclination angle will tend to be.

ACKNOWLEDGEMENTS

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