Study on Numerical PMM Tests in Incident Waves

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1 INTRODUCTION

Recently, extensive researches are being carried out to understand the ship manoeuvring performance in waves. Since the coupled seakeeping-manoeuvring effect is getting more important, the conventional manoeuvring simulation methods should be enhanced or a new theory must be developed. One of the typical methods is the two-time-scale model, and its works enhanced by considering the steady-flow induced coupling effect [1] and the bilinear model for wave drift force computation [2] have emphasized the necessity to investigate the wave effect on ship manoeuvring coefficients.

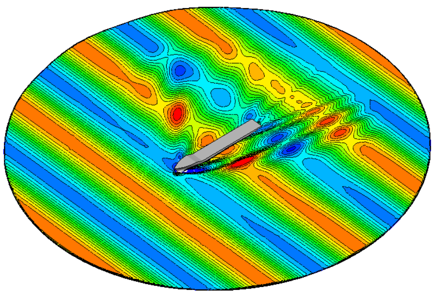
The traditional Planar Motion Mechanism (PMM) test originally designed to generate a group of body manoeuvring coefficients (also named manoeuvring derivatives or hydrodynamic coefficients) is based on the experiment in calm sea, therefore the PMM test in incident waves must be considered to this end. Analysing a static motion in waves is relatively straightforward, whereas the dynamic PMM tests that are proposed under the quasi-steady assumption still have some unknowns when the incident waves are presented.

This study mainly discusses a comparison between the static drift test and the dynamic sway test. These two tests have very different motion patterns: one has static motion and another one has dynamic harmonic motion. However, they can generate the same manoeuvring coefficients with respect to sway velocity. Comparing with the static drift test could provide an indirect understanding of the dynamic PMM test.

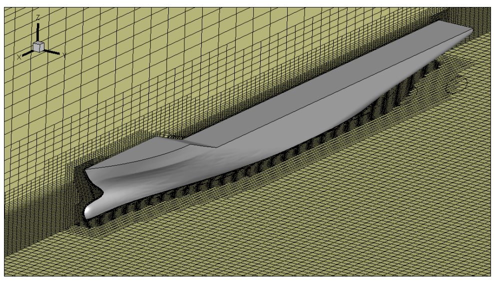
2 TEST OVERVIEW

2.1 Numerical Model

To carry out the PMM test under various wave conditions, a numerical circular tank is chosen to overcome the physical limitations of traditional towing or manoeuvring tanks. The numerical tank is built by using the PMM module of the *snuMHLFoam* package that the Marine Hydrodynamic Lab of Seoul National University develops based on the OpenFOAM+ v1912 platform. A moving circular domain is considered for the numerical computation and a typical wave pattern is shown in Fig. 1. The current circular computational domain has a diameter of 5λ where λ is the wavelength. Correspondingly, a circular wave forcing region of forcing length λ is implemented at the circular boundary using the exponential forcing function. A quaternion-based body motion algorithm is used to handle the ship motion that is combined with prescribed PMM movement and wave-induced motions.



(a) Wave pattern inside the circular computational domain



(b) Mesh structure near hull

Fig. 1 The numerical model

The time-step Δt is selected to be $T_e/\Delta t = 500$ where T_e is the wave encounter period. The mesh resolution around the free-surface is specified as $H/\Delta z = 16$, $\lambda/\Delta x = 120$, where Δx and Δz indicate the horizontal and vertical size of the mesh covering the propagating waves, and H is the wave height. Boundary layer mesh is applied to ensure a $y+$ field that is generally less than 30 near the bow region. The validation works of the present numerical solver are not shown here, but it has generally achieved satisfactory results on both the KCS PMM test in calm-sea and the KCS seakeeping tests.

2.2 Test Condition

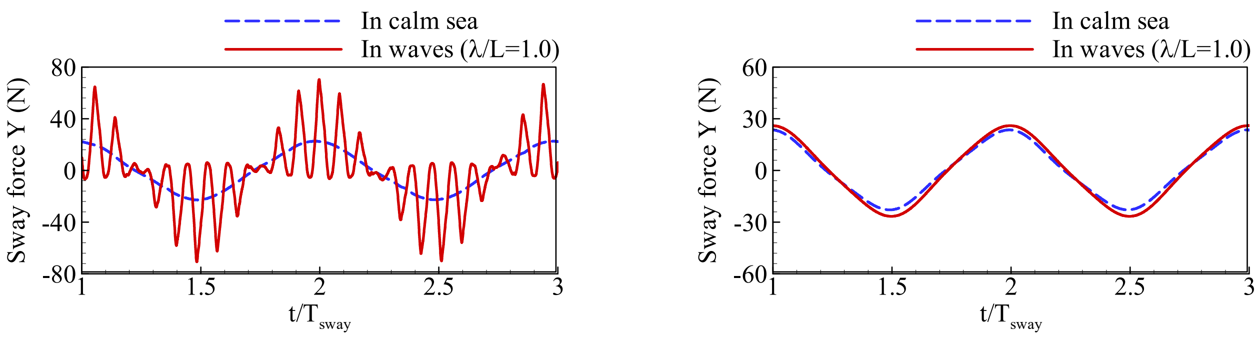
The test model is a 3.07-meter KCS bare hull with the Froude number of 0.16, following the model condition used by the direct manoeuvring test in wave [3]. A static drift test with drift condition β_0 = 18° (v' = v/U = 0.309) and a pure sway test with the sway condition, v_0' = v_0/U = 0.309 and ω_0' = 1.90, are considered in this work. For the static drift test, the drift angle β_0 is defined as atan(-v/u), where u and v represent the surge velocity and sway velocity of ship static motion. For the pure sway test that ship has a harmonic sway velocity $v = v_0 \cdot \cos(\omega_0 \cdot t)$, v_0 represents the maximum sway velocity, and ω_0 is sway frequency. U is the ship total velocity determined by Froude number. The ship has a fixed roll condition, and its heave and pitch motion are released during the PMM motion. The current work chooses one wave condition that the wavelength λ/L is 1.0 and the wave slope H/λ is 1/60, and several wave directions are considered.

2.3 Wave Added Force/Moment

Table 1. The added force/moment components of interest

	Static drift test	Pure sway test
Added sway force	$Y_{AW}^{(0)} = Y_{\text{wave}}^{(0)} - Y_{\text{calm}}^{(0)}$	$Y_{AW}^{(1,\cos)} = Y_{\text{wave}}^{(1,\cos)} - Y_{\text{calm}}^{(1,\cos)}$
Added yaw moment	$N_{AW}^{(0)} = N_{\text{wave}}^{(0)} - N_{\text{calm}}^{(0)}$	$N_{AW}^{(1,\cos)} = N_{\text{wave}}^{(1,\cos)} - N_{\text{calm}}^{(1,\cos)}$

Table 1 lists the added force/moment components that are mainly considered in this work, some are the mean components and some are the harmonic components depending on the test type and target manoeuvring coefficients. For the components listed in Table 1, the term "AW" indicates the values increased in waves, the terms "wave" and "calm" indicate the results obtained under wave condition and calm-sea condition respectively. The superscript $^{(0)}$ and $^{(1,\cos)}$ represent the mean component and the 1st-order cosine component of force and moment obtained by discrete Fourier transform. The pure sway test generates the periodical and nonlinear force/moment signals so the Fourier transform is performed based on the prescribed sway frequency which is much lower than the wave encounter frequency. Fig. 2 compares the original signals and the reconstructed signals of the sway force obtained from the pure sway test.



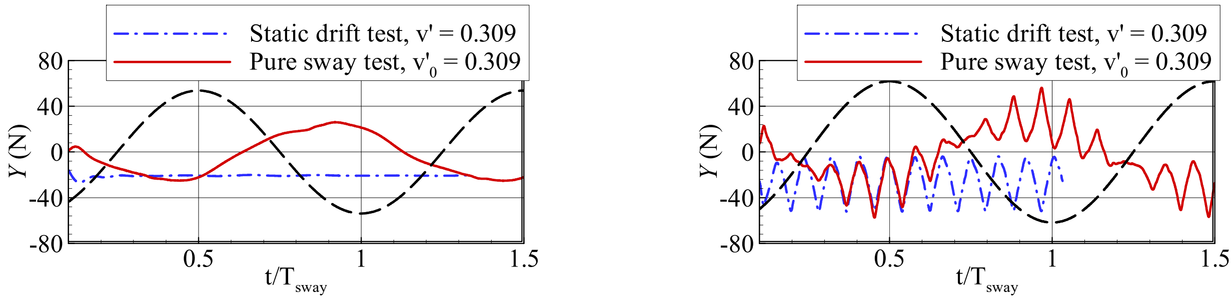
(1) The original signals from numerical computation (2) The reconstructed signals by Fourier transform

Fig. 2 The sway force signals of the pure sway test. (ω_0' = 1.90, v_0' = 0.309)

3 RESULT AND DISCUSSION

Ship dynamic PMM test is proposed under a quasi-steady assumption that some considerations such as memory effect [4][5] would become more concerned when incident waves are involved. Meanwhile, the accuracy of the force/moment components that are directly obtained by the Fourier transform is also questionable. Therefore, a comparison is carried out using the pure sway test and static drift test since both two tests can provide the manoeuvring coefficients Y_v, Y_{vvv}, N_v, N_{vvv} that represent the derivatives of sway force and yaw moment with respect to sway velocity; a comparison on the development of flow fields, such as wave pattern, could help to understand those concerns for the dynamic test in waves.

Fig. 3(a) compares the sway force signal obtained under calm-sea condition. The blue dashed-dotted line is the steady result of the static drift test. The red line represents the periodical result of the pure sway test, and the black dashed line is the sway velocity of the pure sway test. The sway force signal of the pure sway test have nonlinear components, but its out-of-phase component is almost equal to the steady value of the static drift test, as observed in Fig. 3(a). It means that two tests could generate very similar results as well as the corresponding manoeuvring coefficients, which could also show the reliability of the present numerical model. Similar agreements are also observed in Fig. 3(b) which compares the results obtained under waves. Although the signal of sway test shows a high-frequency oscillation of varying amplitude which is caused by the varying ship sway velocity in waves, the results of the two tests have almost matched signals at the phase that target sway velocity is reached.

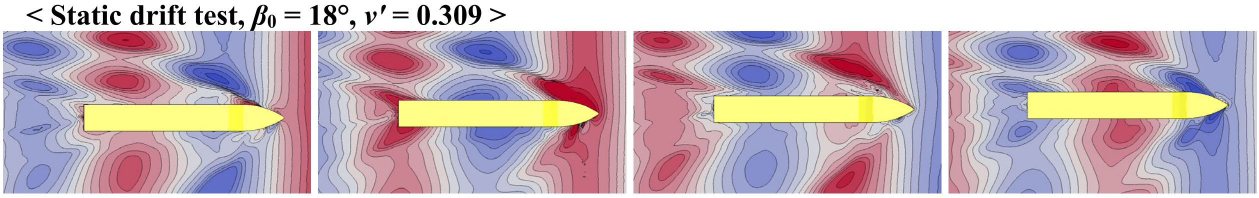


(a) in calm-sea condition (b) in wave condition, λ/L=1.0

Fig. 3 Comparison on the sway force *Y* between the two tests
(black dashed line: the sway velocity history of pure sway test)

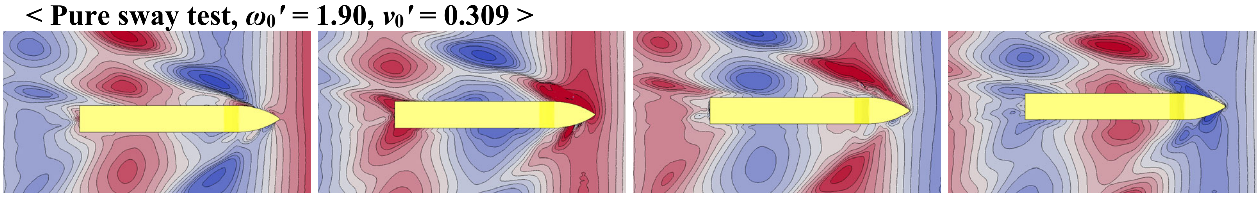
The agreement of the two tests can also be observed from the history of wave patterns. For Fig. 5, t is the time instant, T_e is the wave encounter period and T_0 is the prescribed sway period. Static drift test has a constant sway velocity v'. For the wave patterns of the pure sway test shown by Fig. 5, subfigure (b) is the time instant ($2.5T_0$) that the swaying ship has reached the target sway velocity v_0', and very similar wave patterns are observed comparing with that of static drift test. Subfigure 5(f) indicates a phase that the ship also reached the target sway speed but it is under a negative swaying condition, and the sequential wave development is almost identical to that of the positive swaying stage.

< Static drift test, β_0 = 18°, v' = 0.309 >

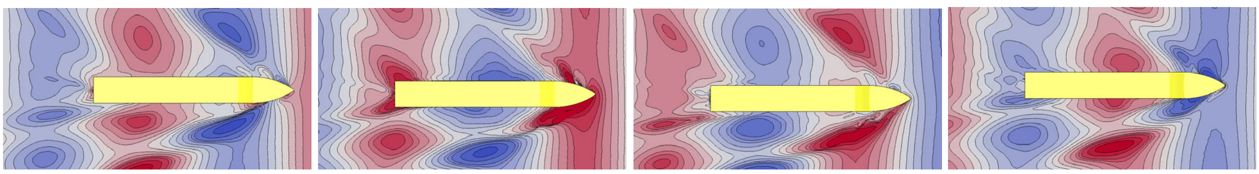


(a) $t = 12T_e - 0.25T_e$ (b) $\boldsymbol{t = 12T_e}$ (c) $t = 12T_e + 0.25T_e$ (d) $t = 12T_e + 0.5T_e$

< Pure sway test, ω_0' = 1.90, v_0' = 0.309 >



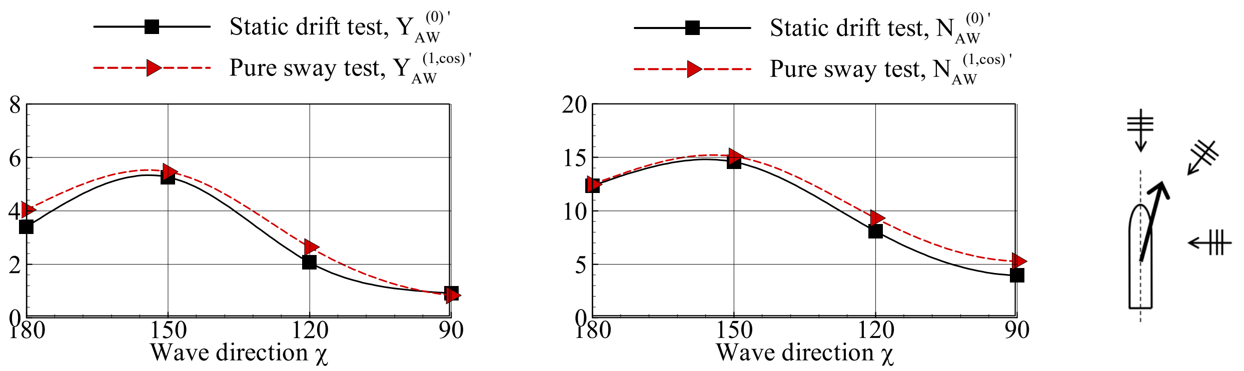
(a) $t = 2.5T_0 - 0.25T_e$ (b) $\boldsymbol{t = 2.5T_0\ (v' \approx v_0')}$ (c) $t = 2.5T_0 + 0.25T_e$ (d) $t = 2.5T_0 + 0.5T_e$



(e) $t = 2.5T_0 + 6T_e - 0.25T_e$ (f) $\boldsymbol{t = 2.5T_0 + 6T_e \approx 3.0T_0}$ (g) $t = 2.5T_0 + 6T_e + 0.25T_e$ (h) $t = 2.5T_0 + 6T_e + 0.5T_e$

Fig. 4 Comparison on the sequential wave patterns between the static drift test and the pure sway test

Fig. 5 compares the results of two tests under various wave directions. The relative direction between the static drift motion and incident wave is shown in Fig. 5, χ = 180° indicates the head sea condition and χ = 90° indicates the beam sea condition. The added sway force has been normalized by ($\rho g A^2 B^2/L$) and the added yaw moment has been normalized by ($\rho g A^2 B^2$). The pure sway test has provided agreeable results compared with that of static drift test at various wave heading directions, indicating a satisfactory quasi-steadiness for the current dynamic sway test. Meanwhile, Fig. 5 shows a tendency that bow quartering waves generally provide strong added force and moment, which means the increased derivative Y_v and N_v of sway force and yaw moment with respect to sway velocity.



(1) Added sway force (2) Added yaw moment

Fig. 5 Comparison between the static drift test (v' = 0.309) and the pure sway test (ω_0' = 1.90, v_0' = 0.309)

4 CONCLUSIONS

This study has applied the numerical tank to carry out the pure sway test and the static drift test under incident waves. Through the comparison between these two tests, the following conclusions can be made:

- By comparing with the static drift test, the dynamic sway test has generated very similar force component and sequential wave development at its motion stage of interest, which indicates an acceptable quasi-steadiness for the current dynamic PMM test in waves. Therefore, this numerical model is possible to be extended to more complicated PMM motions, such as the pure yaw test and the combined drift-yaw test, to observe other manoeuvring coefficients with respect to wave conditions.
- The application of numerical tank to PMM tests has shown more advantages than the conventional indoor tanks, for example, the unlimited space for captive motion in waves and the more detailed observation of flow fields.

ACKNOWLEDGEMENT

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