Experimental and Numerical Study on Stability under Dead Ship Condition of a Tumblehome Hull

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ABSTRACT

The methods to be used for direct stability assessment of stability under dead ship condition are now under development by the International Maritime Organization (IMO) in the Second Generation Intact Stability Criteria. Model experiments and simulations are conducted to promote a reliable numerical method for predicting stability under dead ship condition. Firstly, an uncoupled roll mathematical model（1DOF） is used to calculating roll motion in irregular beam waves and wind. Secondly, one drift free experiment is conducted to measure roll motion in irregular beam waves without forward speed and then two restrained experiments with a counter weight and four springs are conducted at the same conditions respectively. Finally, the effects of drift and sway motions on stability under dead ship condition are validated by comparing the experimental results with three methods, and the numerical method is also validated through the comparisons between the model experiments and the simulations. Therefore, a more precise numerical method should be updated for direct stability assessment of stability under dead ship condition.

KEYWORDS

Stability under dead ship condition; irregular waves; IMO second generation intact stability criteria

INTRODUCTION

The methods to be used for direct stability assessment of stability under dead ship condition are now under development by the International Maritime Organization (IMO) in the Second Generation Intact Stability Criteria (IMO SLF 55, 2013). The worst case of harmonic roll under dead ship condition can be regarded as a situation of a ship in irregular beam wind and waves without forward velocity (Umeda et al., 2007).Japan propose to use Monte Carlo simulation using an uncoupled roll model with irregular beam wind and waves (1-DOF) in time domain for direct stability assessment of stability under dead ship condition (Japan,2010,2011), and Italy consider a 1-DOF approach could be too simplistic for direct stability assessment and could be not accepted by the majority of the working group(Italy,2011).

Umeda et al.(2011) executed physical model of capsizing in irregular beam wave with non-fluctuating wind and validated the numerical method with an uncoupled roll equation bases on piece-wise linear approach. Kubo et al.(2012) validated developed a coupled sway-heave-roll-pitch(4-DOF) numerical model for stability under dead ship condition and pointed out that 4-DOF numerical model could better than 1-DOF numerical model by compared with model experiments of capsizing in irregular beam waves with fluctuating wind. Ogawa et al. (2006) pointed out that the drift speed has effect on the capsizing probability under dead ship condition and the capsizing probability of their passenger ship with drift motions is higher than that without drift motions by executed model experiments of a passenger ship in irregular beam wave with non-fluctuating wind under moored and drift conditions.

In order to promote a reliable numerical method for drafting criteria on stability under dead ship condition, the authors conduct model experiments with three methods including drift free test and restrained test with a counter weight and four springs respectively. The effects of drift and sway motions on stability under dead ship condition are validated by comparing the experimental results with three methods, and the uncoupled roll mathematical model (1-DOF) is also validated through the comparisons between the model experiments and the simulations. Therefore, a more precise numerical method should be updated for direct stability assessment of stability under dead ship condition.

The authors (2012) pointed out that the tumblehome hull could be vulnerable to stability under dead ship condition with a low freeboard, and in this study the ONR tumblehome ship is selected as a subject ship which is provided by the corresponding group as a standard model for making second generation intact stability criteria.

MATHEMATICS

In order to calculate the probability of stability failure under dead ship condition, the following nonlinear and uncoupled equation with stochastic wave excitation and wind moment taken into account is used.

$$\ddot{\phi}+2\mu\dot{\phi}+\beta\left|\dot{\phi}\right|\dot{\phi}+\frac{W}{(I_{xx}+J_{xx})}GZ(\phi)=\frac{M_{wind}(t)+M_{wave}(t)}{(I_{xx}+J_{xx})} \quad (1)$$

where ϕ : roll angle, μ: linear roll damping coefficient, β : quadratic roll damping coefficient, W: ship weight, Ixx: moment of inertia in roll, Jxx: added moment of inertia in roll, GZ: righting arm, $M_{wind}(t)$: wind induced moment consisting of the steady and fluctuating wind moment. $M_{wave}(t)$ is wave exciting moment of Froude-Krylov component, and this because the roll diffraction moment and roll radiation moment due to sway can cancel out when the wave length is sufficient longer than the ship breadth(Japan,2010).The dot denotes the differentiation with time.

The wind induced excitation moment can be calculated by following equation:

$$W_{wind}(t)=0.5\times\rho_{air}C_mU_w^2A_LH_C+\rho_{air}C_mA_LH_CU_WU(t) \quad (2)$$

where: ρ_{air} :air density, C_m: the aerodynamic drag coefficient, U_w : mean wind velocity, and $U(t)$ is fluctuating wind velocity calculated by the Davenport spectrum(Japan,2010,Umeda, 1992). Furthermore, A_L: lateral windage area and H_C: the height of the center of the wind force from the center of the hydrodynamic reaction force.

The fluctuating wind velocity is calculated by following equation and Davenport spectrum is used.

$$U(t)=\sum_{i=1}^{N_w}b_i\sin(\omega_it+\varepsilon_i)$$
$$b_i=\sqrt{2S_{wind}(\omega_i)\delta\omega} \quad (3)$$
$$S_{wind}(\omega_i)=K\frac{U_w}{\omega_i}\frac{X_D^2}{(1+X_D^2)^{4/3}}$$

where

$$K=0.03,X_D=600\frac{\omega_i}{\pi U_w} \quad (4)$$

The wave exciting moment of Froude-Krylov component can be calculated by following equation:

$$W_{wave}(t)=W\cdot GM\cdot\gamma\cdot\Theta(t) \quad (5)$$

where γ is the effective wave slope coefficient calculated by recommended formula in 2008IS code, and $\Theta(t)$ is a wave slope calculated by ITTC wave spectrum $S_{wave}(\omega)$ as follows.

$$\Theta(t)=\sum_{i=1}^{N_w}\frac{\omega_i^2}{g}a_i\sin(\omega_it+\varepsilon_i)$$
$$a_i=\sqrt{2S_{wave}(\omega_i)\delta\omega} \quad (6)$$

$$S_{wave}(\omega_i) = \frac{A}{\omega_i^5}\exp\left(\frac{-B}{\omega_i^4}\right)$$
$$A = 172.5\frac{H_{1/3}^2}{T_{01}^4} \quad (7)$$
$$B = \frac{691}{T_{01}^4}$$

$H_{1/3}$ is the significant wave height and T_{01} is the mean wave period.

MODEL AND TESTS DESCRIPTION

The tested model is the ONR Tumblehome which is provided by the coordinator of corresponding group of second generation intact stability criteria and its superstructure is replaced by a quadrate organic glass (Figs. 1, 2). The adopted scale is λ = 40.526 and the model length between perpendiculars (L_{PP}) is 3.8 m. The other geometrical and mechanical data of the model are reported in table 1.

The experiment was tested in the the seakeeping basin (length: 69m, breadth: 46m, height: 4m) of China Ship Scientific Research Center, which is equipped a flap wave maker at the two adjacent sides of the basin. A servo-needle wave height sensor was used to measurement the incoming waves. It was positioned in the port side, 1 meter far from the model, in respondence of the left-fore perpendicular.

Three mooring-fixed model methods have been adopted during the test. Firstly, the model was drifting freely in beam seas with two protected ropes which could also avoid the ship escaping from the worst scenario due to yaw moment (Umeda et al., 2007) as show in Fig.3 (a). Secondly, the ship model was orthogonal to the wave direction during the test through a wire system in which four wires connected to the ship model at bow and the stern respectively where the height was set be equal to water surface as show in Fig.3 (b). In the second method the drift and yaw could be softly restrained by the counter weight and heave, pitch, roll and sway could be free. Thirdly, the ship model was also kept to be orthogonal to the wave direction by a wire system, however, in which four wires with four short springs connected to the ship model at bow and the stern respectively where the height was set be equal to water surface as shown in Fig.3(c). In the third method, the other ends of the four wires are fixed steadily, so the drift could be restrained and sway, heave, pitch and yaw could be softly restrained.

Table 1: Principal particulars of the ONR tumblehome

Items	Ship	Model
Length:L	154.0m	3.800m
Draft:T	5.494m	0.136m
Breadth:B	18.8m	0.463m
Depth:D	14.5m	0.358m
Displ.:W	8507ton	127.8kg
C_B	0.535	0.535
GM	1.781m	0.044m
T_φ	12.38s	1.945s
K_{XX}	0.38B	0.38B
K_{YY}	0.25L	0.25L

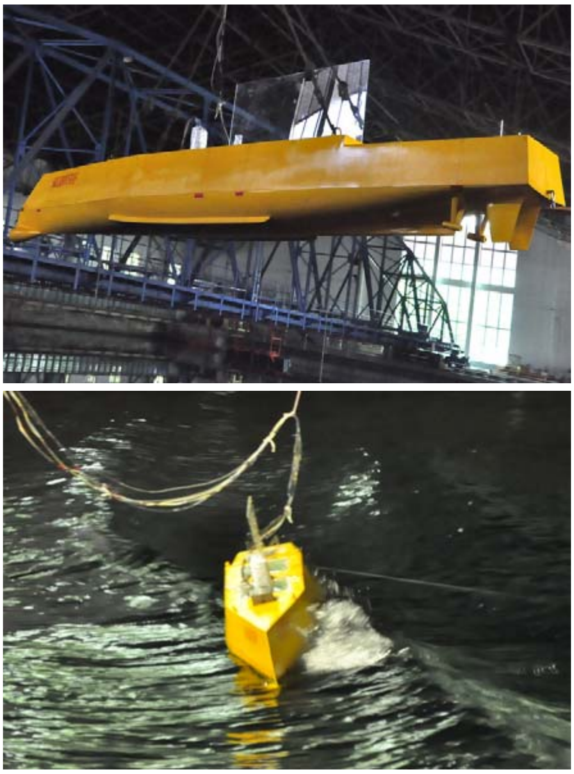


Fig. 1: Photo of the ONR Tumblehome model.

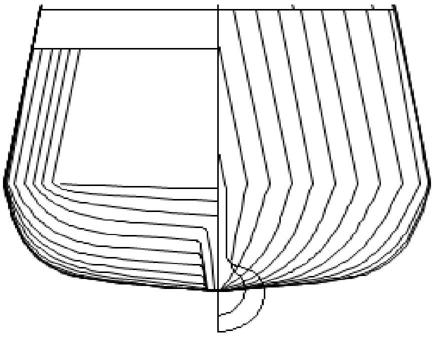
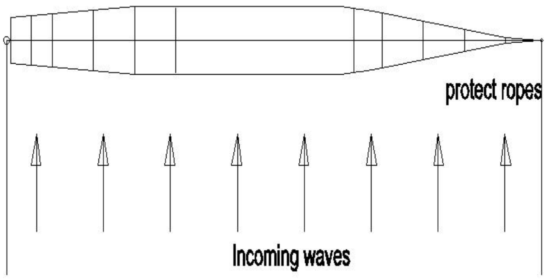
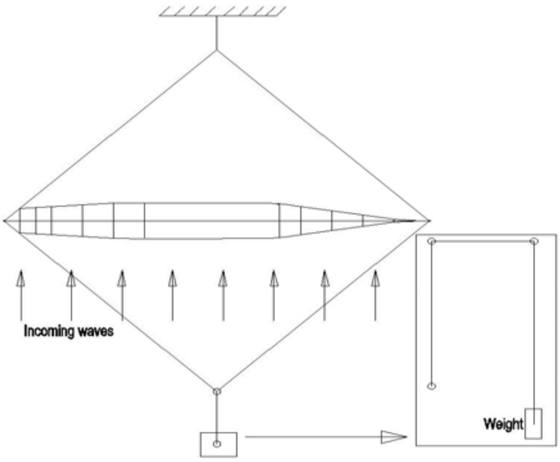


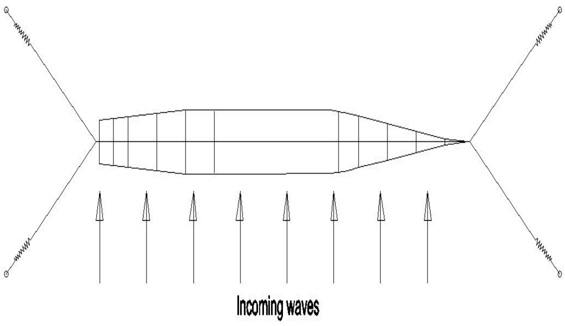
Fig. 2: ONR Tumblehome lines.



(a) Drifting freely



(b) Wire system with weight



(c) Wire system with springs

Fig. 3: Layout of experimental set-ups.

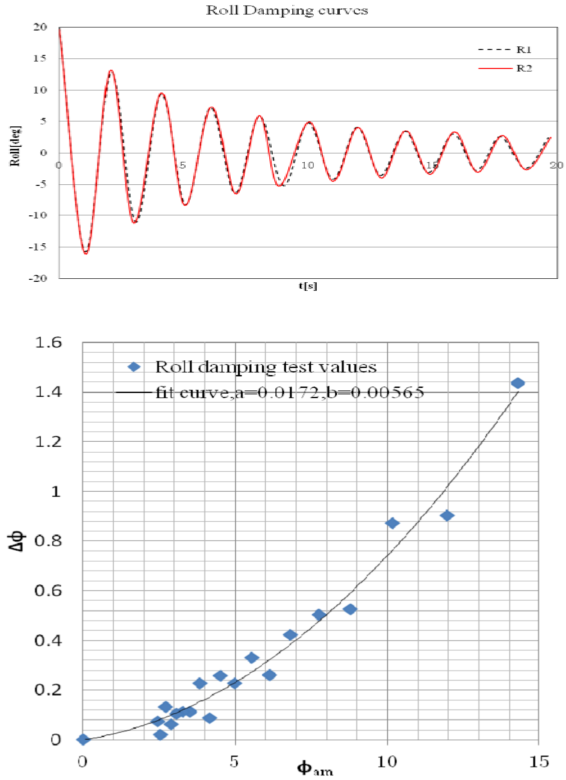


Fig. 4: Roll damping curves and Extinction curve (a, b are linear and square extinction coefficient).

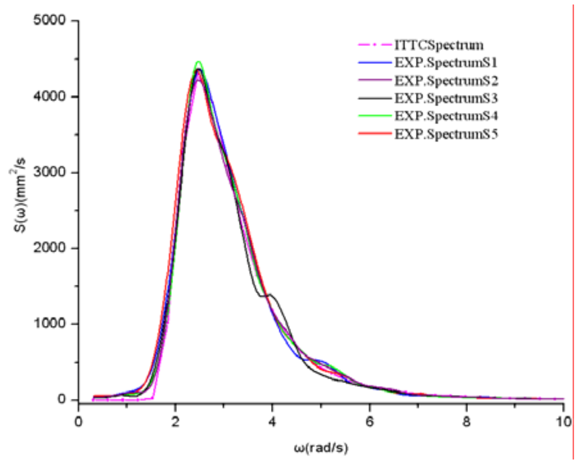


Fig. 5: Wave spectrum.

The roll decay tests were carried out in calm water. The model was towed with an initial heeling angle and then released. This series of tests gives the roll damping and its linear and nonlinear components were adopted in simulations approaches, as shown in Fig.4.

Irregular wave's spectrums with five seed numbers by wave maker are good agreed with ITTC Spectrum as shown in Fig.5. Roll, pitch and yaw amplitudes are measured by the MEMS (Micro Electro-Mechanical System) based gyroscope placed on the ship model.

RESULTS AND DISCUSSIONS

The rolling amplitudes by simulations with 1-DOF approach in regular beam wave are larger than those in experiments except small wave height as shown in Fig.6, and this because wave forces have a liner relation with wave height in 1-DOF simulation that result in rolling amplitudes have a liner relation with wave height while rolling amplitudes should have a nonlinear relation with wave height. The rolling amplitudes by drift free test and restrained test with counter weight have a good agreement with each other and also agree with that by restrained test with four springs at small wave heights while larger than that by restrained test with four springs at the highest wave height. This because in the second method only drift and yaw could be softly restrained by the counter weight while in the third method the drift could be restrained and sway, heave, pitch and yaw could be softly restrained and the effect of different test methods on rolling amplitudes could be decreased at small wave height.

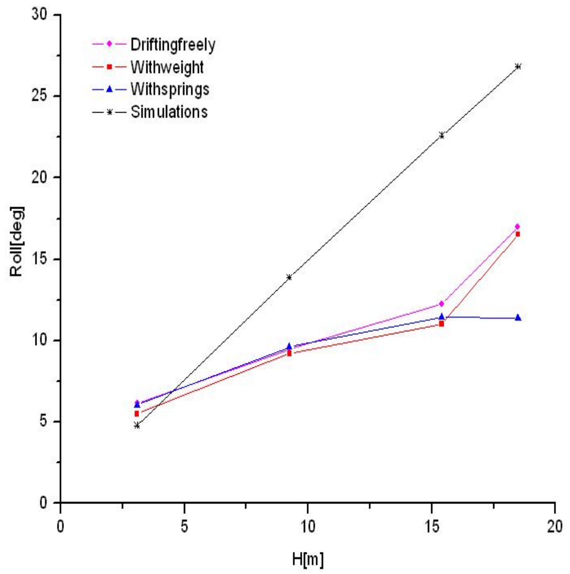


Fig. 6: Roll amplitudes in experiments and simulations with T =12.38s,*Fn*=0.0, χ=90^0, GM=1.781m and different wave heights.

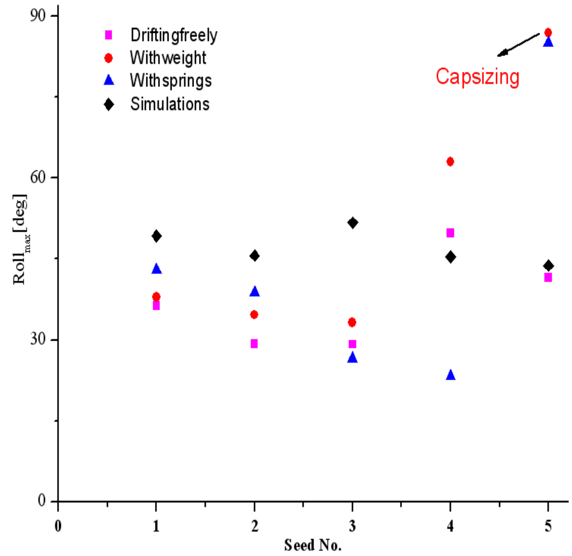


Fig. 7: Maximum roll angles in experiments and simulations with $H_{1/3}$=14.0m,T_{01}=12.38s,*Fn*=0.0, χ=90^0, GM=1.781m and different seed numbers.

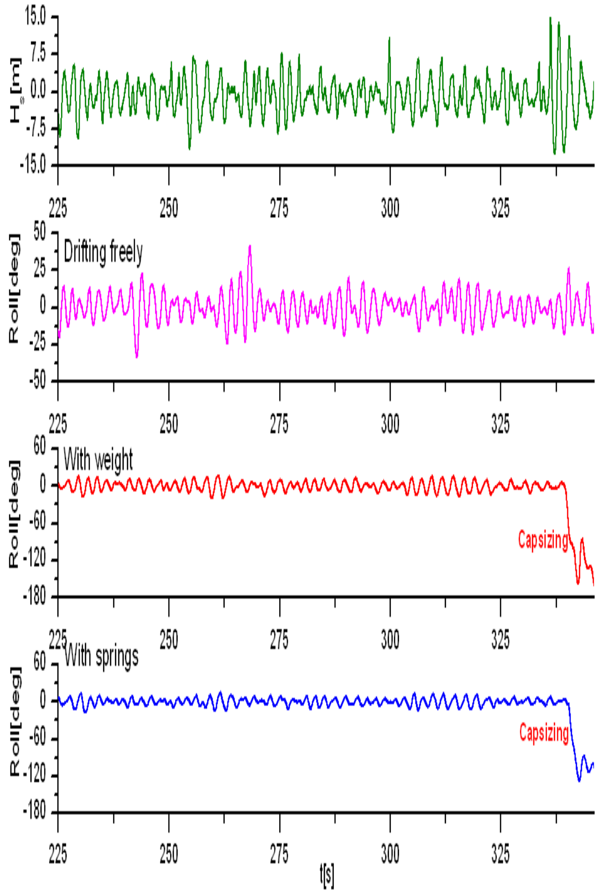


Fig.8: Wave profile and roll in time series with $H_{1/3}$=14.0,T_{01}=12.38,*Fn*=0.0, χ=90^0, GM=1.781m and seeds number 5.

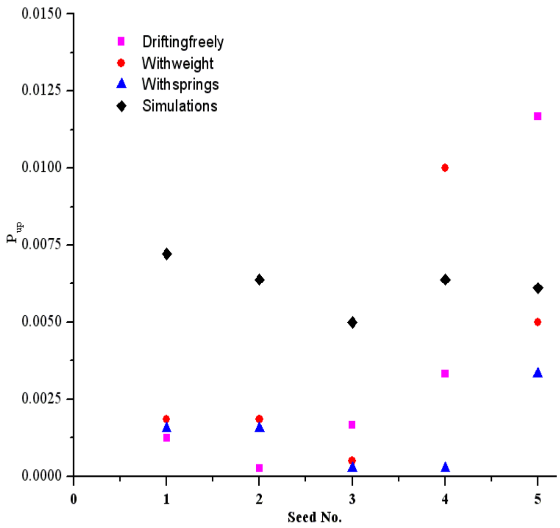


Fig.9: Probability of upcross in experiments and simulations with $H_{1/3}$=14.0,T_{01}=12.38,*Fn*=0.0, χ=90^0, GM=1.781m and different seed numbers.

Capsizing happened at seed number 5 in both restrained tests with counter weight and with four springs due to encounter a large wave height as shown in Fig.7 and 8. However, capsizing did not happen at seed number 5 in drift free tests though the maximum roll angle reached 41.5 degrees. The reason is that free drift and sway could reduce risk of capsizing or buffer instantaneous large wave force on ship hull.

Maximum roll angle was 63 degrees in the restrained tests with counter weight while 50 degrees in free drift test at seed number 4 when encounter two serial large wave heights as shown in Fig.7 and the difference of maximum roll angles could due to the same reason as above. Maximum roll angle was only 23.4 degrees in the restrained test with four springs at seed number 4.This because the ship motion is affected by the wire system with four wires and four springs. The different of maximum roll angles were not very large at seed number 1, 2, 3 between the three model tests without encountering severe wave heights as shown in Fig.7.

Numerical simulations with different seed numbers had steady maximum roll angles as show in Fig.7 and capsizing did not happen in simulations due to the largest encounter wave heights in experiments are not reproduced in numerical simulations.

Probability of Up-cross (Belenky et al., 2008) in experiments and simulations are also analyzed as shown in Fig.9. P_{up} is Up-cross numbers per second, and each experimental time is 10 minute while each simulating time is 1 hour. Although capsizing did not happen at seed number 5 in the free drift test, the probability of Up-cross at seed numbers 3 and 5 is larger than that in other two tests. So capsizing probability with drift motions could higher than that without drift motions which is same with the conclusion pointed out by Ogawa et al. (2006), but the capsizing happened in both restrained tests while capsizing did not happen in drift free tests.

Although capsizing did not happen in simulations, 1-DOF simulating results overestimate the maximum roll angle and probability of Up-cross as shown in Figs.7 and 10 except at seed numbers 4 and 5.As discussed above, a more precise numerical model should be updated with drift and sway motion taken into account.

CONCLUSIONS

As a result of experimental and numerical studies on stability under dead ship condition, the following remarks and recommendations are noted:

1) Capsizing probability with drift motions could higher than that without drift motions but capsizing only happened in both restrained tests of this experimental investigation.

2) A more precise numerical model should be updated for direct stability assessment under dead ship condition due to drift and sway could affect roll motion in beam seas.

3) Restrained tests with counter weight could be more conservative than free drift test for capsizing events.

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