The Inertia Contributions Due to Floodwater Mass

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Abstract The Stability in Waves committee of the 27th ITTC investigated how to deal with the inertia due to floodwater mass from three points of view: (1) floodwater domain, (2) floodwater inertia itself, (3) floodwater entering ship. The committee suggested three criteria indicating the concept of how to deal with floodwater and providing clues on what to consider as floodwater when examining damage ships: (1) whether the water is moving with the ship or not, and amount of that water, (2) whether there is a significant pressure jump across the compartment boundary or not, (3) whether the dynamics of water can be solved separately or not. For floodwater inertia, the committee divided this into the partially flooded case and fully flooded case, and investigated the properties and showed how to deal with floodwater inertia for each case. For the case of the floodwater entering ship, the treatment of inertia

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change due to floodwater was made clear using the momentum change principle. The related procedure was updated reflecting this work.

Keywords Floodwater · Inertia of floodwater · Domain of floodwater

1 Introduction

In the literatures on flooding simulations, Spouge [1] opened the simulation method to investigate the sinking accident of a damaged ship. In the earlier period, the free surface of a damaged compartment was treated as horizontal by many studies. The movement of flood water became more realistic, as the concept of 'lump mass' was introduced (see [2, 3]). Valanto [4, 5] treated the flood water as point mass when the water height is higher than the breadth of damaged compartment, and if the water height is lower the flood water would be calculated by the shallow water equation. And CFD was also used in flooding calculations in many studies like van't Veer [6], Cho [7]. Recently SPH method was also tried. Nowadays, a study on the damaged ship uses one or two methods above mentioned, according to the dynamic characteristics of a damaged ship and the computational power provided.

One of the tasks of the committee on Stability in Waves of the 27th ITTC is to investigate how to deal with the inertia due to the flood water mass [8, 9], and update the relevant procedure [10]. The committee investigated this task from three points of view: (1) floodwater domain, (2) floodwater inertia itself, (3) floodwater entering ship.

The boundary of floodwater domain is hard to determine for a large damage opening. The committee suggested three criteria indicating the concept of how to deal with floodwater and providing clues on what to consider as floodwater when examining damage ships: (1) whether the water is moving with the ship or not, and amount of that water, (2) whether there is a significant pressure jump across the compartment boundary or not, (3) whether the dynamics of water can be solved separately or not.

For the partially flooded compartment, the motion of floodwater is usually analysed by three analysing techniques, namely quasi-static, quasi-dynamic, full dynamic analysis. In quasi-static and quasi-dynamic analysis, because it considers only the centre of gravity of the flood water, the mass of flood water should be included in the ship's mass. However in full dynamic analysis, the pressure includes all the static and dynamic pressure, the force derived from the pressure integration on the surface of the compartment includes all the effects of floodwater inertia and flow properties. This is subject to the condition that the body force includes the actual acceleration, that is, the gravitational acceleration and the acceleration of the flood water. In this case, the mass of flood water should not be included in the ship's mass.

In the case of fully flooded compartment, the floodwater is often treated as solid and is included in the ship's mass in many studies for the motion dynamics of ships. In order to clarify this problem, the committee reviewed the work of [11]. In his study, the inertial properties of fully filled liquid in a tank were studied based on the potential theory. The analytic solution was obtained for the rectangular tank, and the numerical solutions using Green's 2nd identity were obtained for other shapes. The inertia of liquid behaves like solid in recti-linear acceleration. But under rotational acceleration, the moment of inertia of liquid becomes small compared to that of solid. The shapes of tank investigated in his study were ellipse, rectangle, hexagon, and octagon with various aspect ratios. The numerical solutions were compared with analytic solution, and an ad hoc semi-analytical approximate formula is proposed herein and this formula gives very good predictions for the moment of inertia of the liquid in a tank of several different geometrical shapes. The results of his study will be useful in analysing of the motion of LNG/LPG tanker, liquid cargo ship, and damaged ship.

For the case of the floodwater entering ship, the treatment of inertia change due to floodwater was made clear using the momentum change principle. The related procedure was updated reflecting this work.

2 Floodwater Domain

There is the problem of which region should be treated as floodwater if the damage opening is large enough. So we first need a more reasonable and clear definition of floodwater in the analysis of a damaged ship. If we focus on the inertia properties, the floodwater can be determined by looking at whether the water is moving together with the ship or not. If we focus on the hydrodynamics, floodwater may be determined by investigating whether the pressure of it is strongly related with outside water level or not, and whether the hydrodynamic problem of floodwater can be analysed separately or not, provided that the boundary condition is given for the matching of inner and outer flow domains.

Therefore the followings may be criteria that will be used to determine the floodwater.

- Whether the water is moving with the ship or not, and amount of that water.
- Whether there is a significant pressure jump across the compartment boundary or not.
- Whether the dynamics of water can be solved separately or not.

The above three criteria indicate the concept of how to deal with floodwater and provide clues on what to consider as floodwater when examining damage ships.

3 Inertia of Floodwater

3.1 Partially Flooded Compartments

The hydrodynamics and its force on the compartment partially filled with flood water can be calculated by theory or numerical scheme, such as resonant mode analysis, potential theory, CFD with free surface etc. In these methods, the force originated from flood water is treated as external forces, and the motion of a ship is affected by it. However in this case, there is a problem to consider i.e. whether the mass of flood water should be included in the ship's mass or not.

The forces due to floodwater can be divided into three parts by considering their origins. The first is the one due to gravitational acceleration, the second one is due to the acceleration by a ship's motion, and the last one is due to the dynamic pressure of the flow of floodwater. The interactions of floodwater and ship motion were summarised in 26th ITTC report by Stability in Waves committee. The interaction concept was given as Table 1, and the concept of these three models was drawn as in Fig. 1.

The quasi-static model (like [1]) represents one in which the free surface remains horizontal and the floodwater mass is included in ship's mass. In the quasi-dynamic

Table 1 Three models of interactions (from 26th ITTC report)

	Floodwater treatment	Interaction concept
Quasi-static	Static	Added weight
Quasi-dynamic	Dynamic	Added weight
Dynamic	Dynamic	Added force

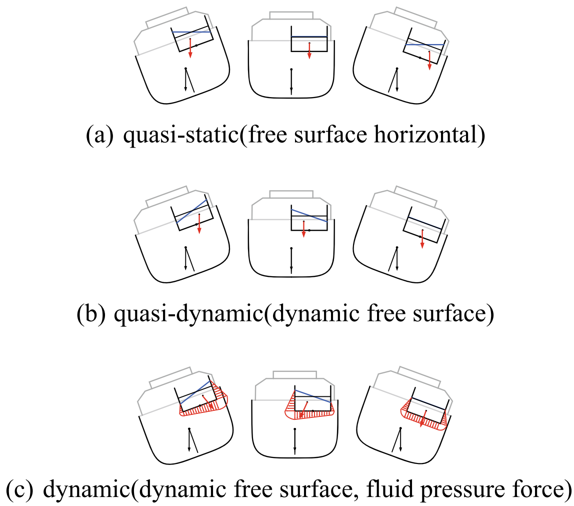

Fig. 1 Concept of floodwater and ship motion interaction (from 26th ITTC report)

model (like [2–5], the free surface and the center of gravity of floodwater could be calculated as mass-damper-spring dynamic system or the equivalent dynamic system, and the floodwater mass is treated as in the quasi-static model. The dynamic model (like [6, 7]) usually use CFD method, so the pressure forces acting on the compartment can be directly calculated and would be acting as the external forces in the equation of motion of a damaged ship.

In quasi-static or quasi-dynamic analysis, because it considers only the centre of gravity of the flood water and only the gravitational force, the mass of flood water should be included in the ship's mass in order to represent the inertia force, that is, the force due to the acceleration by the ship' motion. However in fully dynamic analysis, the pressure includes all the static and dynamic pressure, the force derived from the pressure integration on the surface of the compartment includes all the effects of floodwater inertia and flow properties. This is subject to the condition that the body force includes the actual acceleration, that is, the gravitational acceleration and the acceleration of the flood water due to the ship's motion. In this case, the mass of flood water should not be included in the ship's mass. The following conceptual equations of motion show in which side of the equation the floodwater inertia should be included.

Quasi-static, quasi-dynamic analysis,

$$(m + m_F)\ddot{x} + b\dot{x} + cx = F_{ext} + F_G \tag{1}$$

Fully dynamic analysis,

$$m\ddot{x} + b\dot{x} + cx = F_{ext} + F_{FL} \tag{2}$$

As explained above, in quasi-static or quasi-dynamic analysis, the force due to the floodwater is gravitational force, this is included in the right side as external force. In this case, the mass of floodwater, m_F should be included into the ship's mass, as in Eq. (1). And in fully dynamic analysis, if the floodwater force, F_{FL} includes all the forces due to gravitational acceleration, the acceleration by a ship's motion, and dynamic pressure of the flow, the mass of floodwater should not be included into the ship's mass.

3.2 Fully Flooded Compartments

The flood water in a fully filled compartment is often treated as a part of the ship and treated as a solid. In rectilinear acceleration, the flood water acts like a solid. In rotational acceleration, the moment of inertia is smaller than that of a solid, because there is a part of water that does not rotate with the ship. Lee [11] shows the ratio of the moment of inertia of flood water and that of solids for various shapes of compartments.

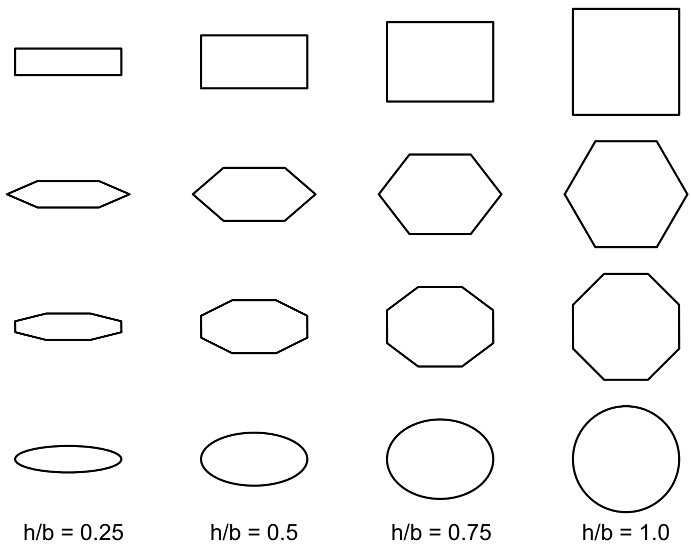

Fig. 2 Various shapes of tanks useful for application from Lee [11]

$$C_R = I_{Liquid}/I_{Solid} \tag{3}$$

where I_{Liquid} and I_{Solid} are the moment of inertias of the flood water when treated as liquid and solid respectively.

The following, Fig. 2 shows the shapes of compartment treated in his study.

The inertias of the fluid in tanks of different aspect ratios and shapes, Fig. 3, become small as the aspect ratio goes to unity.

The solid lines in Fig. 3 are analytical or numerical results while the dashed lines are an estimation formula that provides accurate results. His estimation formula is as follows,

$$I_{Liquid} = I_{Solid} - I_e = I_{Solid} - \rho k_e \frac{A^2}{\pi}\left(\frac{hb}{h^2 + b^2}\right) \tag{4}$$

where the shape correlation factor k_e is

$$k_e = \left(\frac{A_{ellipse}}{A}\right)^{2/n} = \left(\frac{\pi hb}{4A}\right)^{2/n} \tag{5}$$

If we put the area A from Table 2, the factor k_e turns out the coefficient dependant only on the type of the shape as follows,

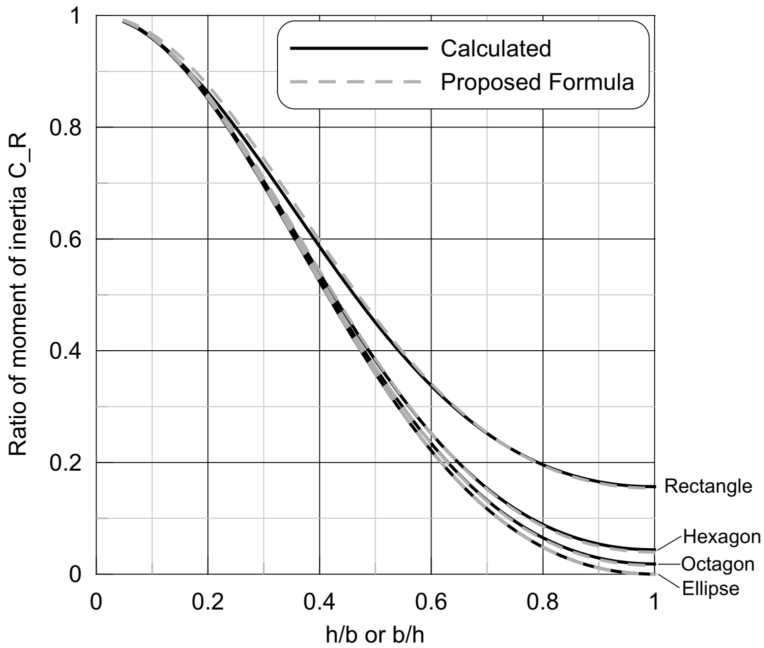

Fig. 3 Moment of Inertia prediction of fully filled liquid for various shaped tanks; calculated and estimated from Lee [11]

$$k_e = \begin{cases} (\pi/4)^{1/2} & \text{for rectangle} \\ \left(\pi/2\sqrt{3}\right)^{1/3} & \text{for hexagon} \\ \left(\frac{\pi}{8(\sqrt{2}-1)}\right)^{1/4} & \text{for octagon} \\ 1 & \text{for ellipse} \end{cases} \tag{6}$$

The experimental validation of the above has not been performed yet, and expected.

Table 2 Area and moment of inertia of solid for various shapes from Lee [11]

Shape	Number of edge (n)	Area	Moment of inertia for roll
Rectangle	$n = 4$	$A = hb$	$\frac{I_{Solid}}{\rho} = \frac{1}{12}A\left(h^2 + b^2\right)$
Hexagon	$n = 6$	$A = \frac{\sqrt{3}}{2}hb'$	$\frac{I_{Solid}}{\rho} = \frac{5}{72}A\left(h^2 + b^2\right)$
Octagon	$n = 8$	$A = 2\left(\sqrt{2} - 1\right)hb$	$\frac{I_{Solid}}{\rho} = \frac{3-\sqrt{2}}{24}A\left(h^2 + b^2\right)$
Ellipse	$n = \infty$	$A = \frac{\pi}{4}hb$	$\frac{I_{Solid}}{\rho} = \frac{1}{16}A\left(h^2 + b^2\right)$

4 Inertia of Floodwater Entering Ship

Newton's Second Law states that the force (moment) on a body is equal to its time rate-of-change of momentum (angular momentum). For a body of constant mass (moment of inertia) this translates to $F = ma$ ($M = Id\omega/dt$). However, for a body such as a rocket which is burning fuel and ejecting gas or a damaged ship in a seaway taking on and possibly discharging water, the $F = ma$ analogy is not correct, but in fact the time-rate-of-change of mass must be taken into account. As the force must remain independent of the coordinate system, a simple application of the rule for differentiation of the product of two functions is not correct. The contribution from the time-rate-of-change of mass term belongs on the left-hand side of the equation with the force. In the context of rocket propulsion, the time-rate-of-change of mass contribution is the equivalent of the thrust of the rocket motor. Similar analogies apply to the time-rate-of-change of moment of inertia.

If we represent the momentum of the vessel as p and the angular momentum as L, where $p = mv$ and $L = I\omega$, with m the mass of the ship, v the velocity, I the moment of inertial tensor and ω the angular velocity, then Newton's second law can be written as:

$$\begin{aligned} F &= m\frac{dv}{dt}, \\ M &= I\frac{d\omega}{dt}. \end{aligned} \tag{7}$$

When the mass and hence the moment of inertia are constant, then these equations reduce to the traditional $F = ma$ form. However, in the damaged condition, the vessel's mass and moment of inertia vary with time and the equations of motion must be written in the above form. Rewriting Eq. (7) to account for the intake or discharge of floodwater as for a closed system yields:

$$\begin{aligned} F - v'\frac{dm}{dt} &= m\frac{dv}{dt}, \\ M - \omega'\frac{dI}{dt} &= I\frac{d\omega}{dt}, \end{aligned} \tag{8}$$

where v' and ω' are the relative velocity and angular velocity of the flooding (discharging) water relative to the vessel, respectively. All of the quantities v', dm/dt, and ω' can be determined from analysis of the flow at the damaged opening (if there is flow between flooded compartments, then the flow between the compartments must be incorporated in a similar manner). The evaluation of dI/dt is somewhat more complex as it involves the actual shape of the compartment.

The above material dealing with the inertia change due to floodwater was included in the procedure ITTC 7.5-02-07-04.4 [10].

5 Conclusions

The committee investigated how to deal with the inertia due to floodwater mass from three points of view: (1) floodwater domain, (2) floodwater inertia itself, (3) floodwater entering ship.

For the floodwater domain, the committee proposed the criteria that will be used to determine the floodwater. For floodwater inertia, the committee divided this into the partially flooded case and fully flooded case, and investigated the properties and showed how to deal with floodwater inertia for each case. For the case of the floodwater entering ship, the treatment of inertia change due to floodwater was made clear using the momentum change principle. The related procedure was updated reflecting this work.

Acknowledgements The aim of this paper is to introduce the work of ITTC Stability in Waves committee on the damage model test. The large part of this material is come from the report of ITTC and rearranged.

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