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Araştırma Makalesi

Pasif Yalpa Tankı ile Gemilerde Parametrik Yalpa Hareketinin Sönümlenmesi

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ÖZET

Bu çalışmada U-tüp formlu pasif yalpa önleyici tankların mekanik sönümleyici olarak kullanılmasının parametyrik yalpa hareketi üzerindeki etkileri araştırılmıştır. Özellikle, birlikte çözümü yapılan yalpa haraketi denklemi ile tank içindeki akışkanın hareket denkleminin başlangıç şartlarının yalpa önleyici pasif tankın performansını nasıl etkilediği üzerinde yoğunlaşılmıştır. Parametrik zorlamalı yalpa hareketi, dalıp-çıkma ve baş-kıç vurma hareketlerinin zamanla değişen geri getirici moment terimi ile temsil edildiği bir serbestlik dereceli lineer olmayan bir denklem ile modellenmiştir. Tank içindeki akışkan hareketi de benzer şekilde bir serbestlik dereceli lineer olmayan bir denklem ile modellenmiştir. Bu iki denklem ve birbirleri üzerindeki etkileri numerik yöntem kullanılarak çözülmüş ve sonuçlar zamana bağlı olarak gösterilmiştir. Bununla birlikte sonuçlar başlangıç şartları ve maksimum yalpa genlikleri ile karşılaştırmalı olarak verilmiştir.

Anahtar Kelimeler: Parametrik yalpa hareketi, Yalpa önleyici tanklar, Lineer olmayan etkiler.

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Research Article

Parametric Roll Motion Reduction of a Ship with a Passive Anti-Roll Tank

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ABSTRACT

In this study, the influence of a U-tube passive anti-roll tank on parametric roll motion has been investigated as a mechanical absorber of a dynamic system. Specifically, this paper concentrates on how the initial conditions of a coupled roll motion and fluid motion in the tank act on the performance of an anti-roll tank. Parametrically excited roll motion was modeled as a single degree of freedom system incorporating heave and pitch effects by means of a time varying restoring moment. Fluid motion in the tank was modeled as a single degree of freedom system. Coupled equations of motion were solved numerically and the results were presented in time domain. Furthermore, the results were comparatively depicted as maximum roll amplitudes vs. initial values for a ship with and without an anti-roll U-tube tank.

Keywords: Parametric roll motion, anti-roll tanks, nonlinearities.

Article history: Received 09/10/2023 – Accepted 08/03/2024

1. Introduction

The first publications on parametric roll motion were appeared in 1930s and early 1940s by Watanabe (1934) and Kempf (1938). Parametric roll motion has been studied by several researchers including Graff and Heckscher (1941), Kerwin (1955), Paulling and Rosenberg (1959), Gawthrop et al (1988), Sanchez and Nayfeh (1990), Nayfeh and Oh (1995) and Falzarano et al (1995). The first experimental study was done by Paulling et al (1972) in San-Francisco Bay. Although its theoretical existence has been known for a long time, parametric roll attracted a great deal of interest in recent years because of the incidents that resulted in casualties. In October 1998, a Post-Panamax C11 class containership encountered extreme weather and sustained extensive loss and damage to deck-stowed containers. Then, it was understood that post-Panamax containerships tend to experience parametric roll motion in extreme weather (France et al., 2003). These casualties led designers, researchers, and regulatory authorities to initiate further research and investigations. Among these researchers, Spyrou (2000), Neves and Rodrigues (2006), Bulian et al. (2004), Pesman and Taylan (2012) focused on nonlinear aspects and effect of changing tuning factors on parametric roll motion. Some researchers focused on probabilistic properties of parametric roll (Shin et al., 2004; ABS, 2004; Belenky, 2004; Hashimato et al., 2006). The state of the art in methodology development and regulations in assessment of ship intact stability can be found in (Francescutto, 2007). In recent years, researchers like Begovic et al (2019), Çakıcı (2019) and Çapuroğlu et al. (2023) focused on the parametric roll motion in the scope of second-generation intact stability rules of International Maritime Organization (IMO).

A ship sails in longitudinal waves excited by the hydrostatic and hydrodynamic forces. Variation of ship's underwater geometry with respect to wave crest position has an important role on roll motion. Roll restoring moment of the ship changes as a function of wave crest position relative to ship length. In other words, ships are excited by their varying underwater geometry with respect to wave crest position along the ship length in longitudinal waves. In regular waves, this excitation is periodic with a finite period and certain ratios of encounter and natural frequencies. The most dangerous situation usually occurs in which wavelength is approximately equal to the ship length at an encounter frequency twice (head waves) and equal (quarter waves) that of the roll natural frequency. In these cases, the variation of restoring moment causes the roll angle increasing dramatically requiring additional absorbers. In this study, U-tube passive anti roll tanks were considered as such mechanical absorber.

Generally, anti-roll tanks can be divided into passive, controlled–passive, and active tanks. In 1874 Froude installed water chambers in the upper part of a ship to prevent the ship from large roll angles. Then, Frahm began to use the U-tube tank in 1910 for the same purpose. Before World War II, Frahm's passive tanks had been installed in over 1,000,000 tons of German shipping fleet, including the passenger liners Bremen and Europa (Gawad et al., 2001). Vasta et al. (1961) made a review of the Navy's development and installation of passive tanks. They worked on equations, model techniques and tank design. Stigter (1966) derived the equations of motion of the fluid in the tank and obtained the coupling terms between the ship and the tank. Today, many researchers consider Stigter's equations of motion to be a classical basis for studies of U-tube tanks.

Bell and Walker (1966) investigated two types of controlled–passive tanks. First, control is affected by valves in the water channel, and second, control is affected by valves in the air channel. They also proposed an activated tank system with a propeller continuously driven in one direction to save power. Webster (1967) made a detailed study of the control of pump-activated U-tube tanks. Vugts (1969) designed and compared performance of four passive anti-roll tanks for the same ship.

A comparative study between U-tube and free-surface passive tanks in regular beam seas was carried out experimentally by Field and Martin (1976). Lewison (1975) proposed a mathematical model to optimize the design of free-surface passive tanks. Barr and Ankudinov (1977) provided a critical review of several predictive methods for roll motion and its reduction using anti-roll tanks. Webster et al. (1988) presented a detailed study of free-flooding anti-roll tanks which made for major upgrade of the USS Midway in 1986. Lee and Vassalos (1996) investigated the effect of flow obstructions inside the tank.

In all of the above investigations, researchers concentrated on either theoretical manipulation of the equations of motion or model testing and analyzing existing tanks. This study aims to present influence of initial values on parametric roll motion of ships equipped with passive U-tube tanks.

Initially, parametric roll phenomenon has been examined practically with the Mathieu's equation (Mathieu, 1868). However, this equation is able to predict the stability boundaries only for the upright condition. Setting up a mathematical model including nonlinear damping and restoring terms is necessary to predict large roll amplitudes. In this paper, parametrically excited roll motion is modelled as a single degree of freedom system which includes heave and pitch effects by means of time varying restoring moment. This model may be considered as a simplified version of some earlier attempts (Bulian, 2004). Unlike Bulian's study, restoring moment variation is modelled by using only wave crest and wave trough restoring moment curves. It has been observed that nonlinear effect of the passive anti-roll tanks on parametric roll motion has not been studied in the literature. The study aims to present the influence of passive anti-roll tank on parametric roll motion for various initial values of passive anti-roll tanks. Roll motion analyses were held for head waves and after quarter waves in the case study.

2. Equations of Parametric Roll Motion and Fluid Motion in Tank

In general, the equation of roll motion in regular longitudinal waves can be written as follows:

$$(I_{xx} + \delta I_{xx})\ddot{\varphi} + B(\dot{\varphi}, \varphi) + \Delta GZ(\varphi, t) = 0 \qquad (1)$$

Where $(I_{xx} + \delta I_{xx})$is the moment of inertia, φ is roll angle, $B(\dot{\varphi})$ is damping function and $\Delta GZ(\varphi, t)$ is restoring function. Eq. (1) may be re-written as.

$$\ddot{\varphi} + b(\dot{\varphi}) + \frac{{\omega_0}^2}{GM_0} GZ(\varphi, t) = 0 \qquad (2)$$

GM_0Here, ω_0 is the roll natural frequency, is the metacentric height for calm seas and b $b(\dot{\varphi}) = \frac{B(\dot{\varphi})}{I_{xx}+\delta I_{xx}}$.

In the above equation, $GZ(\varphi, t)$ is approximated using the following expression, neglecting surge and Froude-Krylov forces, as proposed by (Pesman and Taylan, 2012). Unlike Bulian's study (2004), the variation in restoring moment is simplified and modeled using only wave crest and wave trough restoring moment curves.

$$GZ(\varphi, t) = \sum_{n=1}^{N} (m_{2n-1} + k_{2n-1} \cos(\omega_e t)) \varphi^{2n-1} \qquad (3)$$

The coefficients "m" and "k" in Eq. (3) are obtained from righting lever curves in wave crest and wave trough conditions.

$$m_{2n-1} = \frac{c_{2n-1,trough} + c_{2n-1,crest}}{2} \qquad (4)$$

$$k_{2n-1} = \frac{c_{2n-1,trough} - c_{2n-1,crest}}{2} \qquad (5)$$

$$b(\dot{\varphi}) = 2\mu\dot{\varphi} + \beta\dot{\varphi}|\dot{\varphi}| + \delta\dot{\varphi}^3 \tag{6}$$

In Eq. (4) and (5), "c_{2n-1}, crest and c_{2n-1}, trough " represent the coefficients of polynomials fitted to restoring lever curves in wave trough and wave crest conditions, respectively and ω_e is the encounter frequency. In this work, seventh degree polynomials are employed to develop the restoring lever surfaces. The nonlinear damping term is used and is given in Eq. (6). The coefficients of the damping function were addressed by Ikeda, Himeno and Tanaka (1978).

Substitution of Eq. (6) and Eq. (3) in Eq. (2) leads to the following differential equation.

$$\ddot{\varphi} + 2\mu\dot{\varphi} + \beta\dot{\varphi}|\dot{\varphi}| + \delta\dot{\varphi}^3 + {\omega_0}^2 \frac{\left(\sum_{n=1}^{N}(m_{2n-1}+k_{2n-1}\cos(\omega_e t))\varphi^{2n-1}\right)}{GM_0} = 0 \tag{7}$$

The restoring moment term of Eq. (7) was developed to account for the encounter angle by incorporating a simple function in front of k_{2n-1} coefficient. Pesman and Taylan (2011) calculated restoring moment values for various encounter angles (χ) and the results showed that Cos(χ) function is applicable for describing the variation of restoring moment values with respect to encounter angle.

By adding the excitation term and a function of encounter angle, the model was generated as follows:

$$\ddot{\varphi} + 2\mu\dot{\varphi} + \beta\dot{\varphi}|\dot{\varphi}| + \delta\dot{\varphi}^3 + \frac{{\omega_0}^2}{GM_0}\sum_{n=1}^{N}(m_{2n-1} + Cos(\chi)k_{2n-1}\cos(\omega_e t))\varphi^{2n-1} = \left(\pi\frac{H}{\lambda}{\omega_0}^2\sin(\chi)\right)\cos(\omega_e t) \tag{8}$$

In Eq. (8), H represents the wave height, λ is the wavelength. A simple U-tube passive tank consists of two side reservoirs and a connecting duct of constant rectangular cross-section, as shown in Figure 1. The fluid velocity in the positive y direction is υ, and additional axes yd runs parallel to the duct, while yrp and yrs run parallel to the reservoir walls, as shown in Figure 1.

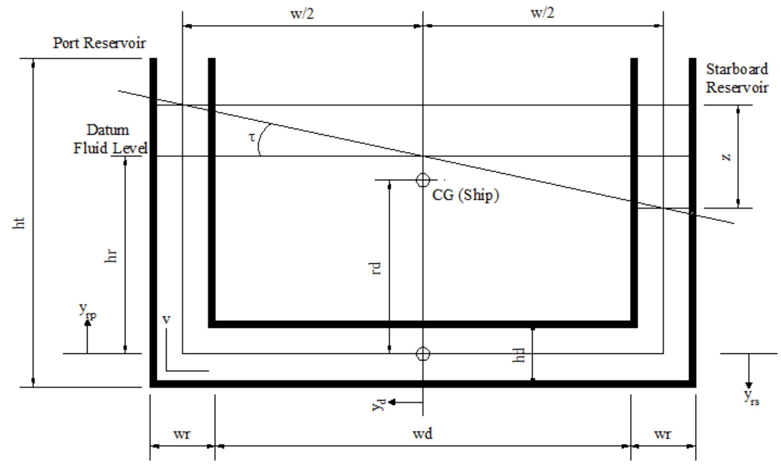

Figure 1. U-tube tank and its geometric parameters (Gawad et al., 2001).

The motion of unit mass of liquid in tank is presented by the following one-dimensional simplified Euler's equation.

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial y} = Y - \frac{1}{\rho_t}\frac{\partial P}{\partial y} \tag{9}$$

In Eq. (9), Y is the external forces per unit mass and ρt is the mass density of the tank liquid. Eq. (9) reduces to Eq. (11) by assuming the cross sections of the duct and reservoirs are uniform.

$$\frac{\partial v}{\partial y} = 0 \tag{10}$$

$$\frac{\partial v}{\partial t} = Y - \frac{1}{\rho_t}\frac{\partial P}{\partial y} \tag{11}$$

Velocity and tank angle are found by integration along the tank y-axis from external forces and static pressure as detailed by Lloyd (1989). The equation of tank angles takes the form Eq. (12) by suppressing surge, sway, heave pitch and yaw motions.

$$a_{\tau\tau}\ddot{\tau} + b_{\tau\tau}\dot{\tau} + c_{\tau\tau}\tau + (a_{\tau 4}\ddot{\varphi} + c_{\tau 4}\varphi) = 0 \tag{12}$$

Here,

$$a_{\tau 4} = Q_t(r_d + h_r), \tag{13}$$

$$c_{\tau 4} = c_{\tau\tau} = Q_t g, \tag{14}$$

$$a_{\tau\tau} = Q_t w_r \left(\frac{w}{2h_d}\frac{h_r}{w_r}\right), \tag{15}$$

$$b_{\tau\tau} = Q_t q_v w_r \left(\frac{w}{2{h_d}^2} + \frac{h_r}{{w_r}^2}\right), \tag{16}$$

$$Q_t = \frac{1}{2}\rho_t w_r w^2 x_t \tag{17}$$

x_t is the length of the tank, and q_υ is the coefficient of the linear damping in the tank. The trem $(a_{\tau 4}\ddot{\varphi} + c_{\tau 4}\varphi)$ in Eq. (12) is the term that couples the motion of the liquid to the motion of the ship.

The following equation is derived for parametric roll motion of a ship with passive tank.

$$\ddot{\varphi} + 2\mu\dot{\varphi} + \beta\dot{\varphi}|\dot{\varphi}| + \delta\dot{\varphi}^3 + \frac{{\omega_0}^2}{GM_0}\sum_{n=1}^{N}(m_{2n-1} + Cos(\chi)k_{2n-1}\, cos(\,\omega_e t))\varphi^{2n-1} + \left(\frac{a_{4\tau}}{I_{xx}+\delta I_{xx}}\ddot{\tau} + \frac{c_{4\tau}}{I_{xx}+\delta I_{xx}}\tau\right) = \left(\pi\frac{H}{\lambda}{\omega_0}^2\, sin(\chi)\right) cos(\omega_e t) \tag{18}$$

Here, $a_{4\tau}$ is equivalent to $a_{\tau 4}$ and $c_{4\tau}$ is equivalent to $c_{\tau 4}$. The term $\left(\frac{a_{4\tau}}{I_{xx}+\delta I_{xx}}\ddot{\tau} + \frac{c_{4\tau}}{I_{xx}+\delta I_{xx}}\tau\right)$ represents the roll stabilizing moment of the liquid inside the tank.

Coupled nonlinear ordinary differential equations and their subfunctions just like damping coefficients were calculated with prepared code on Matlab MATLAB Compiler. The solution method of nonlinear ordinary differential equations is Dormand-Prince Method.

2. Equations of Parametric Roll Motion and Fluid Motion in Tank

In this study, a Series 60 ship form was used as the sample. The sample ship was equipped with a U-tube passive anti-roll tank at mid-ship section, as shown in Figure 2. The main dimensions of ship and the simple anti-roll tank are given in Table 1 and Table 2, respectively. C_B is block coefficient, C_M is the midship section coefficient and k_{xx} is the roll gyration radius in Table 1. The symbols in Table 2 are explained in detail in Figure 1. Analyses are held with using 7th degree odd polynomials. The coefficients “m” and “k” in Eq. (3) are given in Table 3.

4. Effect of Initial Values on Coupled Motion

Parametric roll motion is a phenomenon that is highly sensitive to initial conditions. In this study, we considered the initial values of roll motion and the initial values of fluid motion in the U-tube tank to calculate the safe motion basins. A safe basin is defined as the area where maximum roll amplitudes are less than 60°. The analysis was conducted for two ship speeds and directions: 5 m/s in head waves and 11 m/s in quartering waves (χ=130°). Initial values of fluid motion in the tank were chosen to be 100%, 75%, 50%, 25% and 0% of the initial values of roll motion, as indicated in Figure 4-8 and Figure

14-18. Safe basin graphs for the ship without a U-tube tank are also included for comparison in Figure 3 and Figure 13. Erosion percentages of the safe basins caused by the presence of a U-tube tank are shown in Figure 23, with respect to initial values of fluid motion in tank as percentages of initial values of the roll motion. Roll motion, both with and without passive U-tube tanks, was simulated in the time domain for various conditions in Figure 9-12 and Figure 19-22.

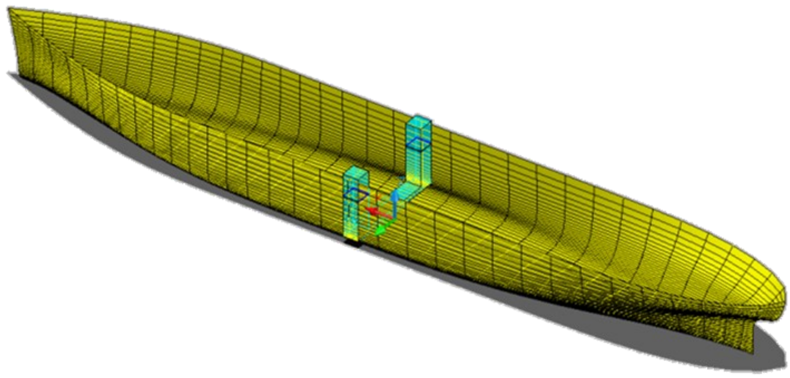

Figure 2. The sample ship and the location of passive U-tube tank.

Table 1. The main dimensions of the sample ship.

Main dimensions	
LBP	124.264 m
B	17.5 m
T	6.97 m
C_B	0.7
C_M	0.98
k_{xx}	0.399

Table 2. The dimensions of the passive anti-roll tank.

Dimensions	
wb	14.92 m
wr	2.5 m
hd	0.75 m
hr	6.34 m
rd	5.965 m

Table 3. m and k coefficients of case study.

Coefficients	
m1	1.12194
m3	-1.36621
m5	0.49685
m7	-0.12053
k1	0.30270
k3	0.38896
k5	-0.8297
k7	0.32677

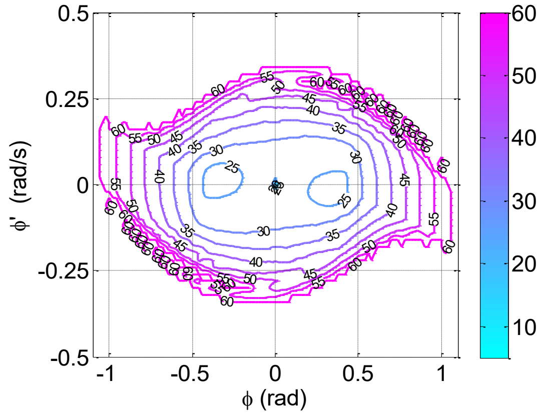

Figure 3. Roll amplitudes related to initial values (without u-tube tank, U=5 m/s, χ=0°)

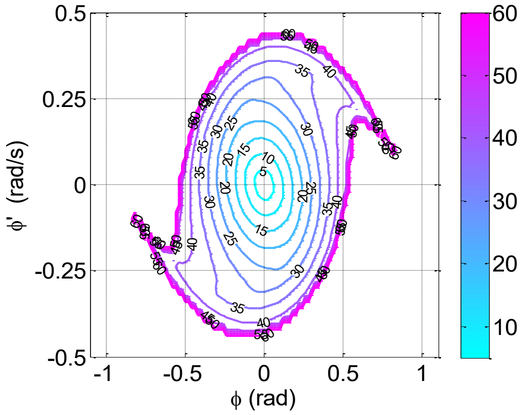

Figure 4. Roll amplitudes related to initia values (with u-tube tank, U=5 m/s, χ=0°) (τ=100% ϕ τ'=100% ϕ')

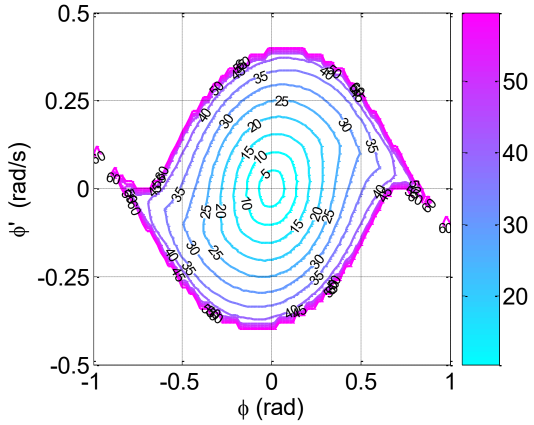

Figure 5. Roll amplitudes related to initial values (with u-tube tank, U=5 m/s, χ=0°) (τ=75% ϕ τ'=75% ϕ')

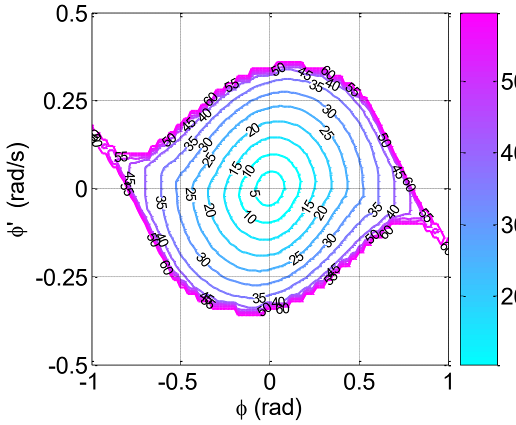

Figure 6. Roll amplitudes related to initial values (with u-tube tank, U=5 m/s, χ=0°) (τ=50% ϕ τ'=50% ϕ')

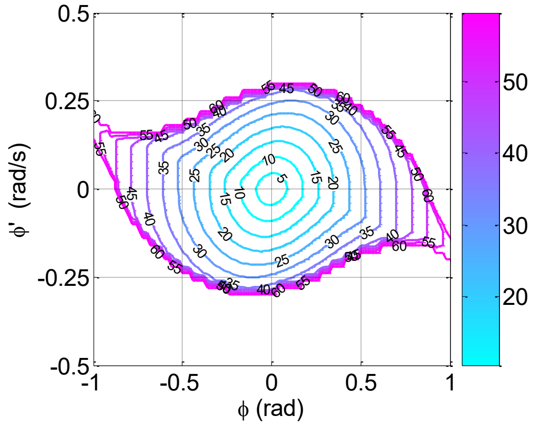

Figure 7. Roll amplitudes related to initial values (with u-tube tank, U=5 m/s, χ=0°) (τ=25% ϕ τ'=25% ϕ')

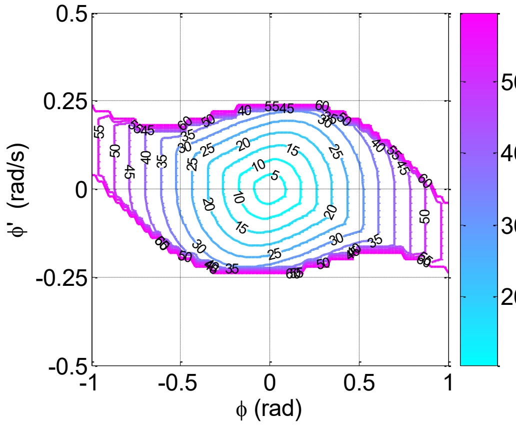

Figure 8. Roll amplitudes related to initial values (with u-tube tank, U=5 m/s, χ=0°) (τ=0 τ'=0)

In head waves, the results given in Figure 3 show that the ship without a passive anti-roll tank oscillates with amplitudes exceeding 25° throughout the region, except for very small initial values close to zero roll angle. In contrast, the ship equipped with a passive anti-roll tank exhibits roll amplitudes of less than 25°, especially at small initial values, as shown in Figure 4-8. The increase in roll amplitudes with respect to the initial values of roll motion is mitigated when a passive anti-roll tank is used. This suggests that the passive anti-roll tank performs better at small initial values of roll motion (Figure 9

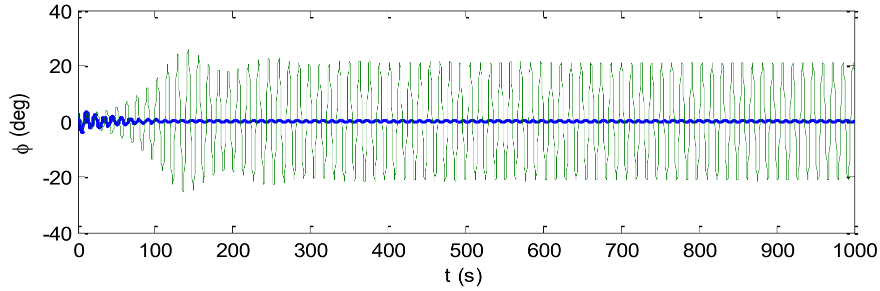

Figure 9. Roll amplitude with respect to time with initial values ϕ=0.05 rad and ϕ'=0 rad/s (U=5 m/s, χ=0°, τ=100% ϕ τ'=100% ϕ', ___ without u-tube tank, ___ with u-tube tank)

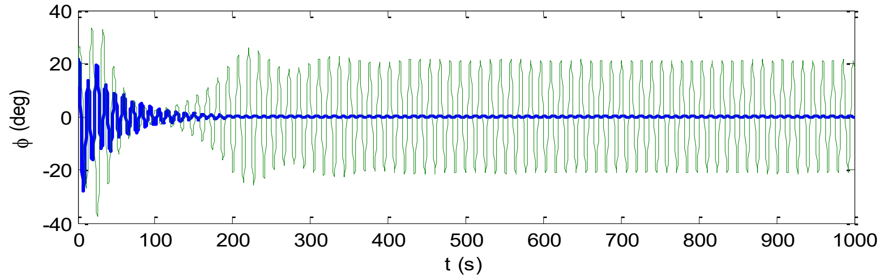

Figure 10. Roll amplitude with respect to time with initial values ϕ=0.2 rad and ϕ'=0.2 rad/s (U=5 m/s, χ=0°, τ=100% ϕ τ'=100% ϕ', ___ without u-tube tank, ___ with u-tube tank)

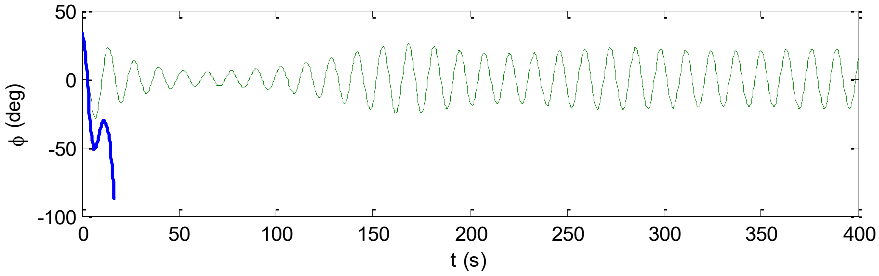

Figure 11. Roll amplitude with respect to time with initial values ϕ=0.6 rad and ϕ'=0 rad/s (U=5 m/s, χ=0°, τ=100% ϕ τ'=100% ϕ', ___ without u-tube tank, ___ with u-tube tank)

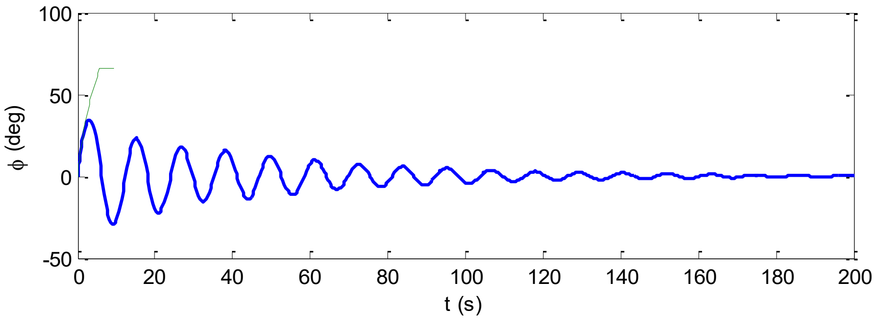

Figure 12. Roll amplitude with respect to time with initial values ϕ=0 rad and ϕ'=0.35 rad/s (U=5 m/s, χ=0°, τ=100% ϕ τ'=100% ϕ', ___ without u-tube tank, ___ with u-tube tank)

and Figure 10). However, when comparing Figure 3 and Figure 4, it is observed that the safe basin narrows at roll angle direction, expands in the roll angular velocity direction, and erodes when a passive anti-roll tank is used (τ=100% ϕ, τ'=100% ϕ'). The passive anti-roll tank caused the ship to capsize at initial value of ϕ=0.6 rad and ϕ'=0 rad/s, as shown in Figure 11, while preventing the ship from capsizing at initial values of ϕ=0 rad and ϕ'=0.35 rad/s, as shown in Figure 12. Erosion percentages of the safe basin, relative to initial values of fluid motion (as percentages of initial values of roll motion), are given in Figure 23. In quartering waves, similar results were obtained, and it is evident that the safe basin is changed and eroded with respect to the initial values of fluid motion (Figure 13-18).

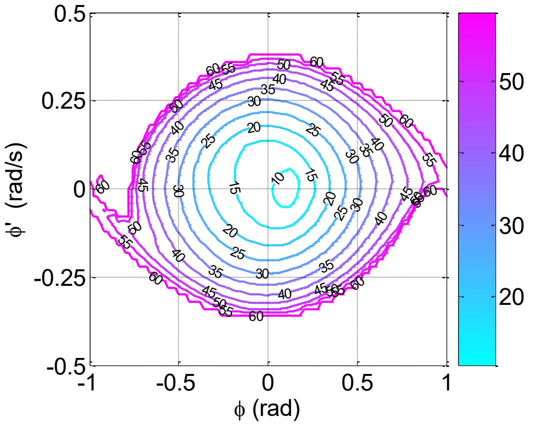

Figure 13. Roll amplitudes related to initial values (without u-tube tank, U=11 m/s, χ=130°)

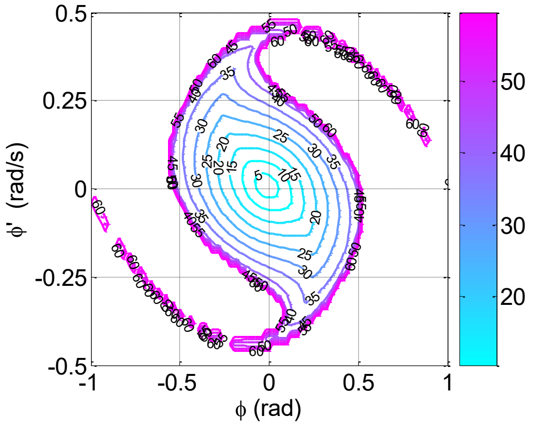

Figure 14. Roll amplitudes related to initial values (with u-tube tank, U=11 m/s, χ=130°) (τ=100% ϕ τ'=100% ϕ')

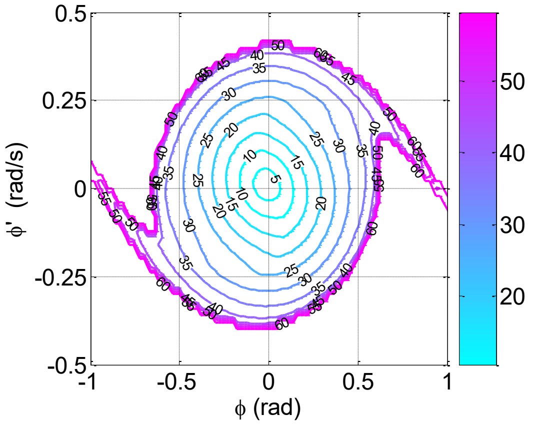

Figure 15. Roll amplitudes related to initial values (with u-tube tank, U=11 m/s, χ=130°) (τ=75% ϕ τ'=75% ϕ')

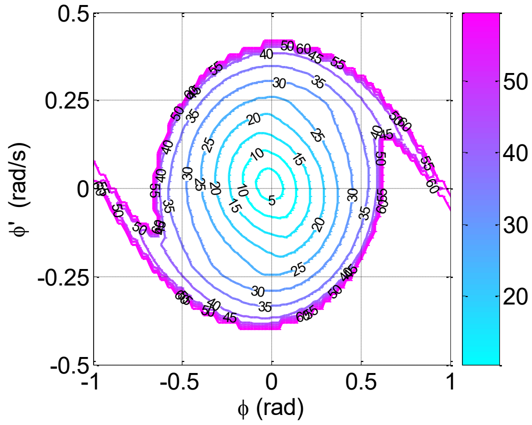

Figure 16. Roll amplitudes related to initial values (with u-tube tank, U=11 m/s, χ=130°) (τ=50% ϕ τ'=50% ϕ')

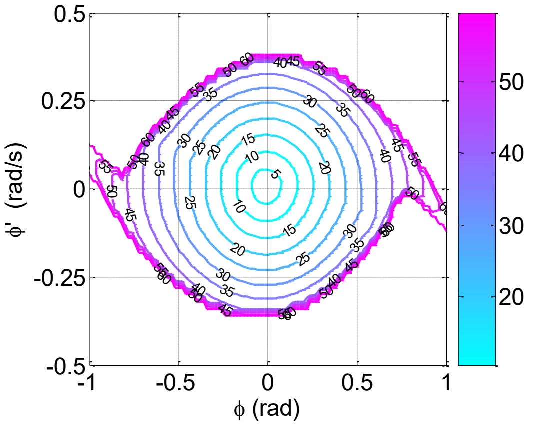

Figure 17. Roll amplitudes related to initial values (with u-tube tank, U=11 m/s, χ=130°) (τ=25% ϕ τ'=25% ϕ')

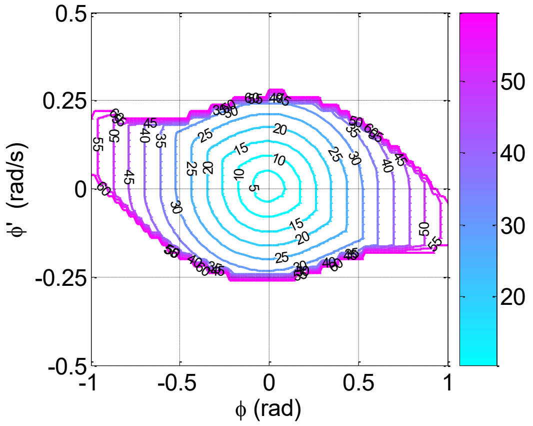

Figure 18. Roll amplitudes related to initial values (with u-tube tank, U=11 m/s, χ=130°) (τ=0 τ'=0)

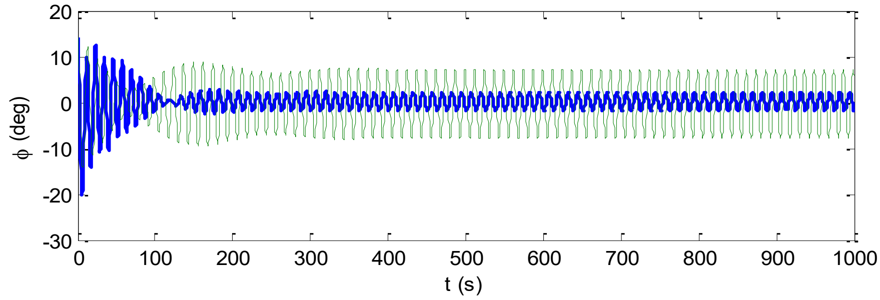

Figure 19. Roll amplitude with respect to time with initial values ϕ=0.25 rad and ϕ'=0 rad/s (U=11 m/s, χ=130°, τ=100% ϕ τ'=100% ϕ', ___ without u-tube tank, ___ with u-tube tank)

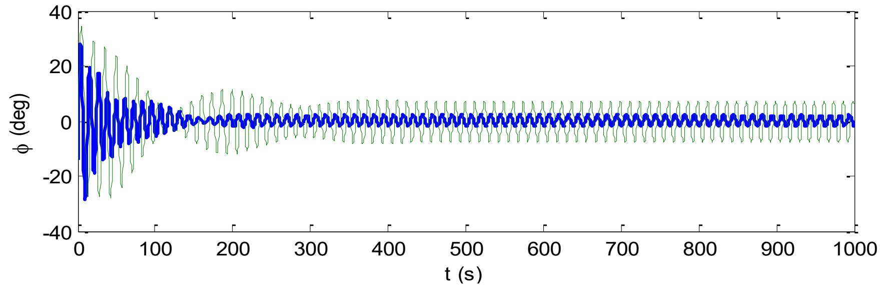

Figure 20. Roll amplitude with respect to time with initial values ϕ=-0.25 rad and ϕ'=0.25 rad/s (U=11 m/s, χ=130°, τ=100% ϕ τ'=100% ϕ', ___ without u-tube tank, ___ with u-tube tank)

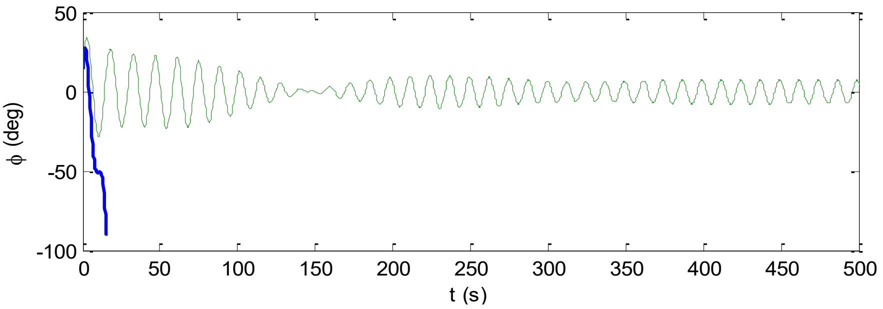

Figure 21. Roll amplitude with respect to time with initial values ϕ=0.25 rad and ϕ'=0.25 rad/s (U=11 m/s, χ=130°, τ=100% ϕ τ'=100% ϕ', ___ without u-tube tank, ___ with u-tube tank)

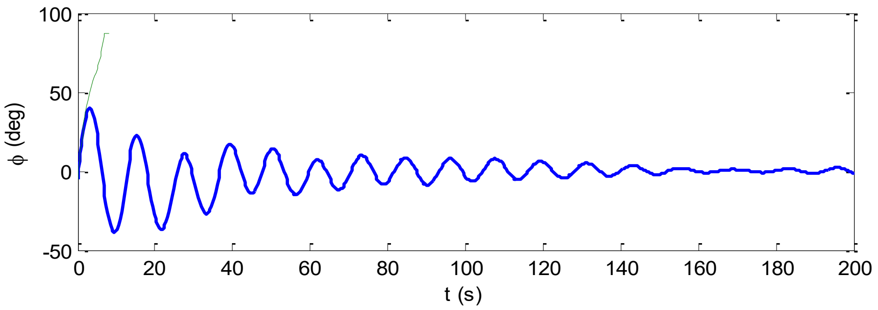

Figure 22. Roll amplitude with respect to time with initial values ϕ=-0.1 rad and ϕ'=0.4 rad/s (U=11 m/s, χ=130°, τ=100% ϕ τ'=100% ϕ', ___ without u-tube tank, ___ with u-tube tank)

The ship capsized at initial values of ϕ=0.25 rad and ϕ'=0.25 rad/s (Figure 21) but was prevented from capsizing at initial values of ϕ=-0.1 rad and ϕ'=0.4 rad/s by using a passive anti-roll tank (Figure 22). Furthermore, it was observed that the passive anti-roll tank corrected the asymmetry of the safe basin. Erosion percentages of the safe basin related to initial values of fluid motion are given in Figure 23.

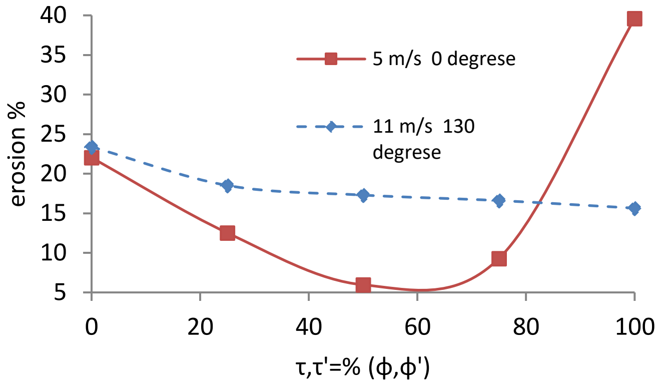

Figure 23. Erosion percentages of U-tube tank related to τ=% ϕ τ′=% ϕ′

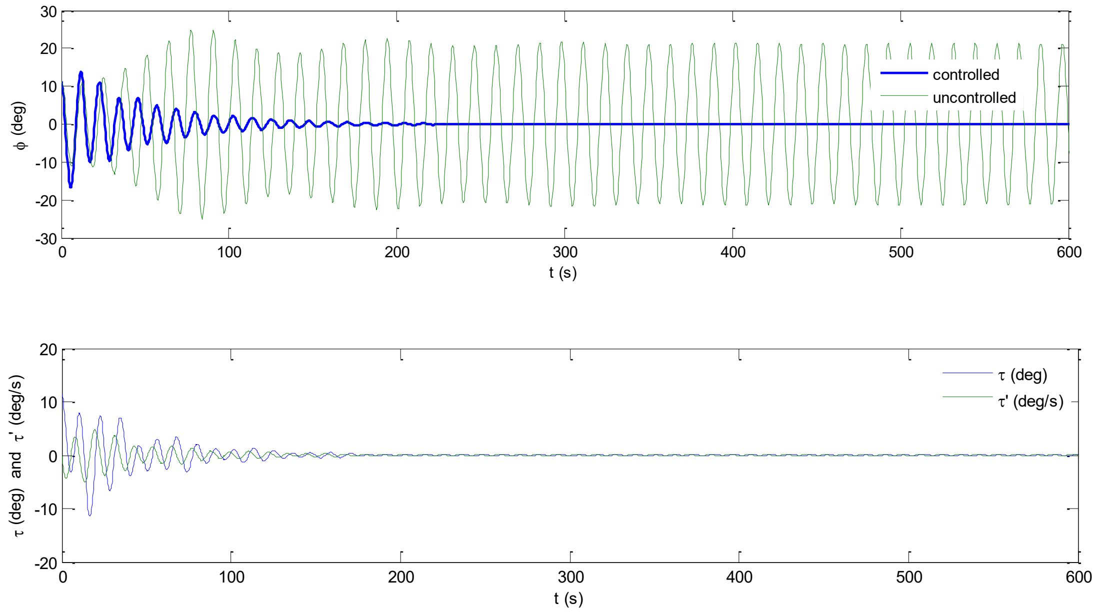

Figure 24. Sample of instantaneous difference between roll angle and liquid angle for the initial values ϕ=0.2 rad and ϕ′=0 rad/s (U=5 m/s, χ=0°, τ=100% ϕ τ′=100% ϕ′)

5. Conclusions

While using passive anti-roll tanks can effectively reduce roll amplitudes, it is important to consider the motion of fluid within tank, which can be influenced by tank may be dangerous based on the tank characteristics and initial conditions. This paper focuses on exploring the reasons behind the differences in safe basin graphs for ships with and without U-tube anti-roll tanks, particularly concerning the impact of initial conditions. The study finds that passive anti-roll tanks perform satisfactorily with small initial values of roll angle and angular roll velocity. However, at certain large initial values, the ship can capsize due to changes in the safe basin shape caused by the coupling effect of fluid motion in the anti-roll passive tank.

For example, the sample ship, without an anti-roll tank, starts to roll at 0.6 radians with a roll angular velocity of zero rad/s, oscillating at a 25° amplitude. However, when equipped with an anti-roll tank and set to have initial values of liquid in tanks equal to 100% of the initial values of roll motion ((τ,τ′) = (φ, φ′)) , the ship capsizes, as shown in Figure 11. This raises the question: Are the initial values of liquid in tanks always equal to or almost equal to the initial values of roll motion ((τ,τ′) = (φ, φ′))?. To answer this question, we compare the angles of roll motion and liquid motion in the tank in Figure 24. Initial values of coupled motion were chosen near zero. The results indicate that angles and angular velocities of roll and liquid motions may not always be equal due to factors such as sudden cargo shifts or gusting wind forces. As a result, we varied the initial values of fluid motion in the tank 100% to 0% of the initial values of roll motion to examine the influence of these initial values. It was also observed that the shape of the safe basin graphs changes as the ratio of initial values of liquid motion to roll motion varies. The safe basin graphs narrow in the angular velocity direction and expand in the angle direction of initial values as the percentages change from (τ,τ') = 100% (φ, φ') to (τ,τ') = (0, 0). This suggests that the uncertainty of coupled motion increases depending on the initial values of liquid motion.

Finally, the use of passive anti-roll tanks narrows the safe basins, affecting the working conditions of the ship, ever if passive anti-roll tanks provide good performance at small initial values. It is recommended that safe basins for ships equipped with passive anti-roll tanks be determined during the preliminary design stage. A core safe basin, which is a subset of (τ,τ') = 100% (φ, φ'), (τ,τ') = 75% (φ, φ'), (τ,τ') = 50% (φ, φ'), (τ,τ') = 25% (φ, φ'), (τ,τ') = (0, 0) conditions, must be established. If passive anti-roll tanks restrict the working conditions of a ship, other roll stabilizing methods such as active anti-roll tanks or active anti-roll fins should be considered instead.

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