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Analysis of the Roll Stabilizing Effect of a U-Tube Tank for a Ship in Regular Seaway

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ABSTRACT: *Ships in turbulent seas suffer a lot of unstable motions which results in discomfort of crew members and passengers, as well as creating unfriendly working environment on the main deck for the crew members. U-tube tank was designed and introduced to damping the roll motion in other to stabilize the ship in one-degree-of-motion. The U-tube tank has a different port and starboard sides connected by a channel between them. The U-tube tank acts as a damper to quickly mitigate roll motion of the rolling ship. The damping ratio is usually tuned through the size and shape of a valve in the connecting channel of the U-tube. When the tank is turned off the response amplitude operator (RAO) reaches a peak value of 12 at a frequency of 0.1 Hz and the RAO remains constant at the value of 0 as the wave encountered frequency increases when the tank is turned on. Effective control of ship roll motion can be achieved with a U-tube water tank as actuator. For the predictive control, system identification is applied to update the parameters of the linear ship roll model with a U-tube tank when the ship dynamics changes.*

KEYWORDS: RAO, roll motion, damping, u-tube tank, amplitude

INTRODUCTION

Ships sail in waters which may be either calm or turbulent at different times. This turbulent sea state can cause the ship to respond in six-degrees-of-freedom which may cause operational disturbances to marine activities and general comfort of the personnel on board. In order to design an effective ship motion control system, an accurate characterization of ship motions in different seaways is required. Considering that model tests entails cost and time, it is necessary for researchers to put in significant effort towards the development of numerical tools to characterize the motions and loads of a ship operating in seaways (1).

A ship has six-degrees-of-freedom (DOF); surge, sway, heave, roll, pitch, and yaw that allow it to move when forces act upon it. The forces that act upon a ship come from thrusters include propeller forces, control surfaces such as rudder forces, and environmental forces such as waves, wind, current, loading and unloading, and water motion in an internal compartment. The ship's restoring forces that counter the effects of roll, pitch, and heave enables it to oscillate in the sea. Loading and unloading are difficult operations, so operators should be trained under sea conditions. The real environment can be simulated by using a ship roll stimulator so that training can be conducted as needed. Active U-tube tanks, gyroscopes, and a moving mass can be used to stimulate the ship roll motion. Gyroscopes, however, have precision moving parts and rotate with high speed so are not suitable ship roll stimulators. Motion control of a ship operating in regular seaway has long been a topic of interest in ship design and operation. In recent years, this topic is becoming increasingly important due to the need for high-speed long-distance deployment of men and material and the emphasis on smaller, lighter assets (2). In these operation scenarios, crew factors are often the limiting criteria for cruise speed or operational effectiveness in a seaway, so the reduction of ship motions can have a significant impact on operability (3).

LITERATURE REVIEW

The angular degrees of freedom roll, pitch and yaw are vital characteristics for sea-keeping of any ship with the roll motion as the most critical of them (4). This is because ship roll is most lightly damped and the ship restoring moment is small in the cross-plane when compared with the other planes (5).

Excessive roll can occur under unfavorable or extreme sea conditions due to the light damping and small restoring moment of the ship (6). This can lead to several ship's operational problems such as reduced effectiveness of the crew, damaged or lost cargo, limited operability of the on-board equipment, or even fatal sea accidents which include capsizing of the ship and the loss of human lives (McTaggart, 2008). Keels, fin stabilizers, gyro stabilizers, Azimuthing propellers, and anti-roll tanks (ARTs) are effective roll reduction devices (7).

The U-tube tanks have proved most effective of the roll reduction devices and is given more attention. The U-tube is effective even at low forward speeds (8). This makes it relevant for vessels employed for offshore services such as the wind farm installation vessels, (9). Further advantage of the U-tube tank is that it does not cause highly concentrated loads like gyro stabilizers, and do not require complicated mechanisms such as Weis–Fogh flapping fin stabilizers, (10).

The operational costs related to U-tube tank are low. A major disadvantage of the U-tube tank technology is its space requirement for the installation which reduces the space available for transport of cargo (11). Also, the metacentric height of the ship is reduced by the tank free surface effect.

METHODOLOGY

The method adopted is theoretical analysis to predict dynamic responses. Six-degree-of-freedom mathematical equation of roll motion and its forces are used to represent the possible translations and rotation of the ship. The behaviour of the U-tube tank in roll motion will be defined. The vessel and tank parameters used for this analysis are shown on Table 1 and Table 2 respectively.

Ship Roll Motion Due to Sinusoidal Stimulation

The combined simulator and ship roll model derived from the six-degree-of-freedom dynamic equations for the motion of a ship adopted from (12) gives the simulator and ship roll motion equation as

$$\begin{bmatrix} m_{hh} & m_{h\phi} \\ m_{\phi h} & m_{\phi\phi} \end{bmatrix}\begin{bmatrix} \ddot{\tau} \\ \ddot{\phi} \end{bmatrix}+\begin{bmatrix} b_{hh} & 0 \\ 0 & b_{\phi\phi} \end{bmatrix}\begin{bmatrix} \dot{\tau} \\ \dot{\phi} \end{bmatrix}+\begin{bmatrix} k_{hh} & k_{h\phi} \\ k_{\phi h} & k_{\phi\phi} \end{bmatrix}\begin{bmatrix} \tau \\ \phi \end{bmatrix}=\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \frac{1}{2}LA_t\Delta P \\ K_{wave} \end{bmatrix} \quad (1)$$

When both wave moments input K_{wav} and differential pressure ΔP of the axial pump are sinusoidal functions, we have

$$K_{wave} = K_0 e^{jw_r t+\phi_2}$$
$$\frac{1}{2}LA_t\Delta P = P_0 e^{jw_r t+\phi_1} \quad (2)$$

Considering a single input of wave moment exciting on the ship with zero phase shifts, the U-tube tank acts as a passive damper and the magnitude of tank angle and ship roll angle become.

$$\tau_0^2 = \frac{K_0^2}{k_{\phi\phi}^2\left(D_R^2 + D_I^2\right)}\left(f^2 G_2 - q^2 G_1\right)^2$$
$$\phi_0^2 = \frac{K_0^2}{k_{\phi\phi}^2\left(D_R^2 + D_I^2\right)}\left\{\left(f^2 - q^2\right)^2 + \left(2q\frac{b_{hh}}{C_c}\right)^2\right\} \quad (3)$$

The phase shifts of tank angle and ship roll angle become

$$\phi_{h/w} = a\tan 2(-\sin\phi_2, -\cos\phi_2) - a\tan 2(D_I, D_R)$$
$$\phi_{\phi/w} = a\tan 2\left(2qb_{hh}\mu/C_c, f^2 - q^2\right) - a\tan 2(D_I, D_R) \quad (4)$$

Where,

K_i is the restoring moment coefficient, K_{wave}, is the external moment acting on the ship roll ϕ_o is the ship roll amplitude due to external moment and pump pressure, b is the friction coefficient of resistance, ϕ_h is the phase shift of pump pressure, and m is the mass of fluid in U-tube tank.

Roll Motion on the Pontoon

Analysing the roll motion on the vessel due to the U-tube tanks, the effects of roll motion on the vessel was determined as the depth of the sea increases and also on regular seaway of the vessel. In this paper, a transverse meta-centric height of the vessel was used.

$$I_4 = 0.16\rho V B^2 \quad (5)$$

Where

I_4 is the Roll inertia moment, V is the Ship volume, and B is the Ship breadth (= 41m)

$$A_{44} = 0.15 I_4 \quad (6)$$

Where

A_{44} is the Hydrodynamic roll added mass coefficient.

$$C_{44} = \rho g V GM_T \quad (7)$$

Where

C_{44} is the stiffness constant.

GM_T is the Transverse meta-centric height.

$$B_{44} = 2\sqrt{C_{44}(I_{44} + A_{44})} \quad (8)$$

Where

B_{44} is the hydrodynamic roll damping coefficient.

Calculation of wave exciting force (F_{44}) in roll

The wave exciting force in roll motion is calculated using

$$F_{44} = A_{44}\ddot{\zeta}^* + B_{44}\dot{\zeta}^* + C_{44}\zeta^* \quad (9)$$

Calculations of wave roll force excitation due to wave ($F_{\varphi 4}$)

The wave roll force excitation due to wave is

$$F_{\varphi 4} = \frac{F_{44}}{\cos\theta} \quad (10)$$

Calculation of roll amplitude

Roll amplitude can be given as

$$\varphi_a = \frac{F_{\varphi 4}}{\sqrt{[C_{44} - I_4\omega^2]^2 + (B_{44}\omega)^2}} \quad (11)$$

Where
φ_a = Roll amplitude

Roll displacement (φ)
The roll displacement is estimated using equation (12).

$$\varphi = \varphi_a \cos(\theta) \tag{12}$$

Roll velocity ($\dot{\varphi}$)
The roll velocity can be represented mathematically as

$$\dot{\varphi} = -\omega\varphi_a \sin\theta \tag{13}$$

Calculation of roll acceleration ($\ddot{\varphi}$)
The roll acceleration is given as

$$\ddot{\varphi} = -\omega^2\varphi_a \cos\theta \text{φ=-ω^2φ\_acosθ} \tag{14}$$

3.5.1 Wave motion in roll

Analyzing the single-degree-of-freedom of the ship roll motion effect due to wave using the roll acceleration, velocity, and displacement to determine roll effects as the vessel's position and depth at regular sea waves gives.

$$F_{\omega 4} = (I_4 + A_{44})\ddot{\varphi} + B_{44}\dot{\varphi} + C_{44}\varphi \tag{15}$$

Where
$F_{\omega 4}$ is the Vessel roll excitation force.

3.5.2 Roll RAO and Spectral

The roll RAO of the ship was analyzed to know the effect of roll response as it affects the vessel using equation (16).

$$RAO_4 = \frac{\varphi_a}{\zeta_a k} \tag{16}$$

Calculation of roll spectrum
To calculate the roll spectrum of the ship,

$$\boldsymbol{S}_{(\boldsymbol{\omega 4})} S_{(\omega 4)} = \left|\frac{\varphi_a}{\zeta_a \mathrm{k}}(\omega)\right|^2 . S_{(\omega)} \tag{17}$$

RESULTS AND DISCUSSION

Here we will consider the effect of U-tube tanks for minimizing roll damping by its stabilizing effects. The coupled roll damping response and the motion of the water in the tank are discussed. We will also discuss the stabilization effect of the U-tube tank with respect to the dimensions by varying some parameters such as the diameter of the tube sections, height of the water in the tank and the width of the tank.

4.1 Principal Particulars of the Vessels

The following parameters of the vessel in Table 1 are used in the design analysis of the U-tube.

Table 1: Parameters of the Vessel.

Particulars	Values	Units
Length of the vessel	350	m
Beam of the vessel	60	m
Depth of the vessel	32	m
Dead weight	240990	tonnes

The U- tube tank also has the following dimensions as shown in Figure 1 and is tabulated in Table.2 respectively.

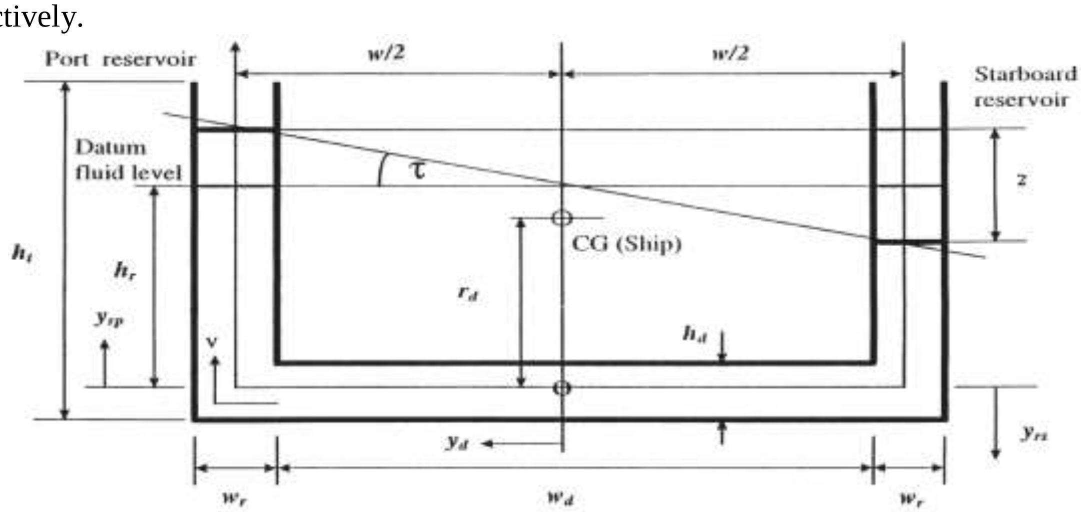

Figure 1: Cross section of a u- tube anti roll tank fitted to a vessel Source: (11).

Table 2: Particulars of the U-Tube anti roll tank.

U-tube tank particular	Values	Units
Water height	2.7	M
Radius of the pipe diameter	0.25	M
Width of the tank	3.54	M

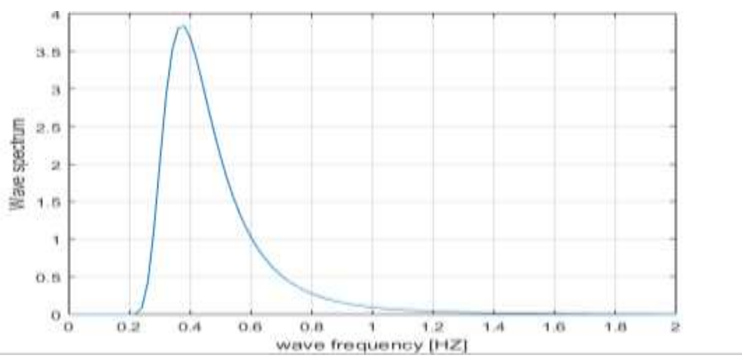

Figure 2; Wave spectrum versus frequency

The highest wave height in Nigerian sea is 4m. From Figure 2, it can be seen that the wave spectrum increases from a frequency of 0.2 Hz and reduces at a frequency of 0.3 Hz until it reaches a frequency of 2 Hz. From the figure it can be seen that change in frequency determines the wave height spectrum.

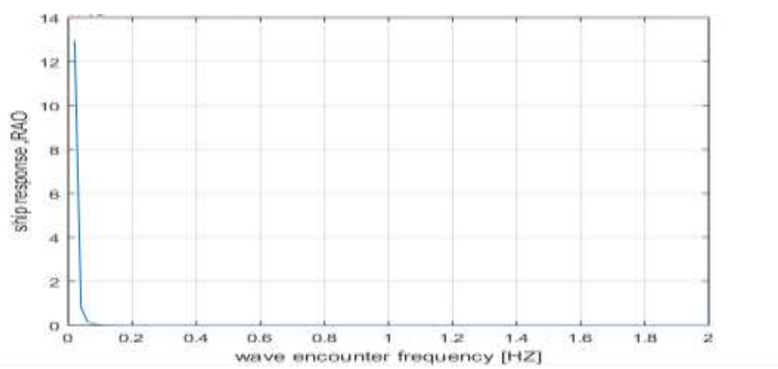

Figure 3: Ship roll RAO versus frequency

Figure 3 shows that the worst motion of the ship (motions close to the resonant frequency) coupled easily into motion of the stabilizer. When the tank is turned off, RAO reaches a peak value of 12 at a frequency of 0.1 Hz and as the wave encounters increase in frequency, the RAO remains constant at the value of 0. The response of the corresponding tank and the vessel tends to go out of phase by 90 degrees as the tank acts as an absorber through its damping effects by the restoring moments it provides to the vessel along its motion in seaway. Some characteristics of the tank with respect to the natural frequency with regards to the U-tube diameter, water level in the tank and the width of the tank are shown Figure 4 and Figure 5 respectively.

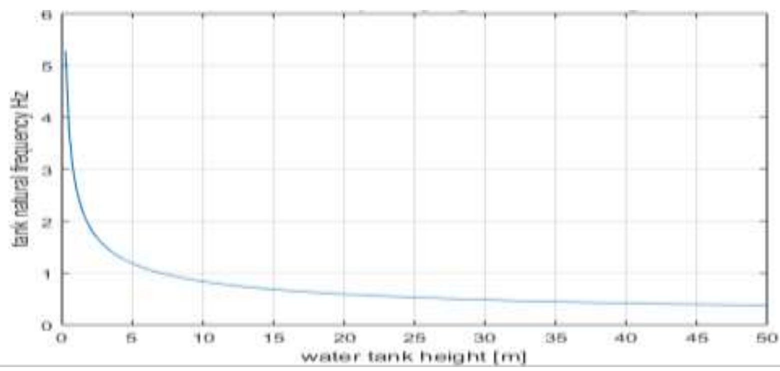

Figure 4: Variation of the tank natural frequency against the water tank height in the U-tube tank

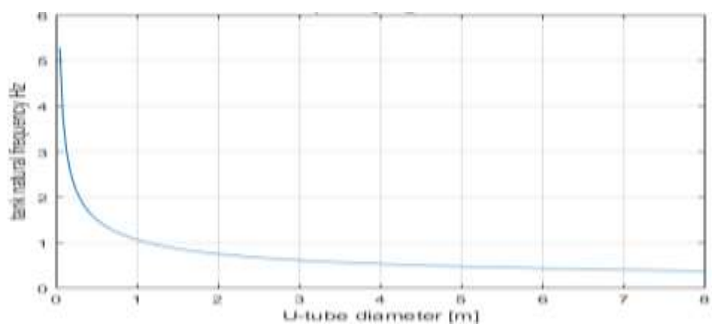

Figure 5: The variation of the tank natural frequency against the pipe diameter of the U-tube tank

The regular changes of natural frequency of waves during vessel movement at seaway is a common experience and it is more obvious for tankers and cargo ships where there is a fluctuating exchange of load between the port and starboard sides of the vessel.

Since the optimal effect of the stabilizer is obtained at approximately $w_t = w_s$, it is important to change the tank frequency to be close to w_s where the natural frequency of the tank as shown in the graphical representations of Figures 4 and 5 is a function of the tank parameters and its variations. From Figure 5, it can be seen that the highest sensitivity of the natural frequency of the tank is at a diameter of 0.016 m and frequency of 5.34 Hz and a similar sensitivity with a height of water tank is obtained at 1.24 m.

CONCLUSIONS

The design of U-tube tank into the vessel successfully reduces the roll motion of the vessel which has considerably reduced the effect of sea sickness on crew members. Roll motion have been considered relatively easy to control and a lot of work have been put into damping the effects ranging from surface tanks to controlled passive tanks. The U-tube tank possess some advantages over other types of installations as it is relatively less expensive to install, easy to maintain and has shown to considerably cushion the effects of rolling.

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