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Analysis of the Effects of Passive Free Surface Anti-Roll Tank for Roll Stabilization of a Cargo Ship

George S. Wilkinson*[1], Akandu Ezebuchi[2], Tamuno-dukobipi Daniel[3], Samson Nitonye[4]

Department of Marine Engineering, Rivers State University, Nkpolu-Oroworukwo, Port Harcourt, Nigeria

Abstract Excessive roll motion makes ships traveling on a seaway unstable, reduces safety, and adversely affects the performance of the crew and the health of passengers. It can also lead to machinery failures, cargo and hull damage, and possible capsizing. For more than a century the problem of ship roll has been investigated and certain devices have been developed to stabilize the roll motion of marine vessels and produce safer and more efficient working conditions on-board i.e. bilge keels, moving weight, water transfer in tanks, gyroscopes and external fins. Among the ship roll reduction devices presently in use, the passive anti-roll tanks have been the most successful due to their relative simplicity, lower cost and less maintenance. These devices have wide application in shipping, fishing, offshore oil and gas industry and the cruise transportation industry. The passive anti-roll tanks include free-surface tanks, U-tanks and free flooding tanks. However, in this paper only the performance of the free surface anti-tank stabilizing system of a cargo ship in beam seas was investigated. The work uses spectral analysis and other wave statistical methods to stimulate different wave energy spectrum for developed, developing, starting or young and decaying seas and the effectiveness of this anti-roll device in these sea states were determined. The results obtained from the study were used to validate the passive anti-roll tank as an effective roll reduction device for use on-board cargo ships.

Keywords Damping, Passive Anti-Roll Tank, Effectiveness, Spectral Energy, Roll Stabilization

1. Introduction

The motions of ships and the control of those motions have been the focal point of extensive research over the years. A ship in a seaway undergoes complex motions that may reduce the operational range andseakeeping capability of the ship. Among all these complex motions, roll motion is the most critical because it is the least damped by the sea, prone to dynamic magnification of its amplitude and therefore has the greatest risk of capsizing a vessel.

The use of partially filled tanks to stabilize roll motion of ships actually dated back to Froude [1] who tried to use water chambers in the upper part of a ship to stabilize its roll motion. Philip Watts [2] introduced the free surface anti-roll tank as a passive method of damping roll motions in 1885. He proposed a large, uniform cross sectional tank partially filled with water, placed across the breadth of the ship and located well above the center of gravity. Experimental investigation on rectangular tanks for damping of roll motion was conducted by Van den Bosch and Vugts [3]. From their study, they stated that one of the advantages of passive anti-roll tanks is their adaptability to various loading conditions at sea by changing the depth of water. The cardinal problem of the free surface anti-roll tank is the issue of sloshing, and several papers using various methods/techniques to model the sloshing phenomenon in rectangular tanks have been published i.e. shallow water wave theory – [4]; [5]; boundary element methods, [6]; [7] and [8], finite element methods, and Volume Fluid (VOF) method [9]. Extensive comparative studies on sloshing loads were carried out by [10] and [11]. Souto [12] investigated the

Smoothed Particle Hydrodynamics Technique. According to [13], despite the simplicity of the passive free surface tank, no adequate theory for predicting its performance has yet been developed.

However, [14] proposed a method to predict the statistics of ship response in a realistic seaway and used spectral methods to establish a relationship between the spectral density of ship response and ocean wave spectrum. Rayleigh's work [15] contributed immensely to the development of wave statistics, particularly in the probability distributions of energy, wavelength, period and wave height.

This present work attempts to establish the effectiveness of passive anti-roll tanks in the stabilization of the roll motion of a cargo ship in realistic seas using spectral methods.

2. Materials and Methods

Modeling Free Surface Anti-Roll Using Standard Wave Spectral Models

These are idealized wave spectra models used for the prediction of the characteristics of real wave energy spectrum. Two of the most common ones used in the design of offshore structure are the Pierson-Moskowitz (PM) and JONSWAP spectrum.

Modified Pierson-Moskowitz (MPM) Spectrum

For prediction of responses of marine vessels and offshore structures in open sea, the International Ship and Offshore Structures Congress (ISSC) and the International Towing Tank Conference (ITTC), have recommended the use of a modified version of the PM - spectrum

$$S\phi(\omega) = \frac{124}{TZ\,4} Hs^2 \omega -^5 \exp.\left[-\frac{496}{TZ4}\omega^{-4}\right] \quad (1)$$

Where:

Hs = Significant wave height; ω = Wave frequency; Tz. = Mean zero up-crossing period

JONSWAP Spectrum

The JONSWAP spectrum is an empirical formulation that defines the distribution of energy with frequency within the ocean. It was developed for long crested limited fetch waves to describe developing sea states or conditions.

The underlying equation is:

$$S\phi(\omega) = \alpha Hs^2\, Tp^{-4}\, \omega^{-5}\exp\left[-\beta(Tp.\omega)^{-4}\right]\gamma^a \quad (2)$$

Where:

α = alpha = Intensity of the spectra = $5.061(\frac{\omega p}{2\pi})^4 H^2 s\,[1 - 0.287 \,\mathrm{Log}\gamma]$;

Hs = ζ = Significant Amplitude; γ = gamma = Peak enhancement factor= 3.3; β= beta = Shape factor = 1.25;

Tp = Wave Peak Period = 1.41 Tz

Prediction of Spectral Energy for Roll Damping

Wave energy imparted to an un-stabilized ship minus that imparted when stabilized should be equal to the energy used for damping - (Law of the Conservation of Energy).

(E-damping) = (E-ship with tank) – (E-ship without tank) (4)

(E-damping) = (E-stabilized Ship) - (E- Un-stabilized Ship) (5)

(E-damping) = ($\rho g A_2$) stabilized ship - ($\rho g A_1$) un-stabilized ship (6)

Where A_1 = Area under un-stabilized ship curve

A_2 = Area under stabilized ship curve

(E-damping) = $\rho g(A_2 - A_1)$ (7)

= ρg ($m_o$stabilized - $m_o$un-stabilized)

= Energy required for stabilization (For a particular spectral condition)

(E-damping) ≅Energy Dissipated by the Anti-roll Tank (8)

From energy balance approach: Energy Dissipated by the anti-roll tank = (E-damping) + tank Losses i.e. frictional losses, noise energy losses, heat energy losses etc.

Effectiveness of Passive Free Surface Tank for the Different Seas

Stabilizer Effectiveness (% Roll Reduction) = $[\frac{\rho.g.Mo.unstabilised - \rho.g.Mo.stabilised}{\rho.g.Mo.unstabilised}] x \ \frac{100}{1}$ (9)

$=[\frac{Peak\ S\phi(\omega)unstabilised - Peak\ S\phi(\omega)stabilised}{Peak\ S\phi(\omega)unstabilised}]$ x 100

Efficiency of Tank = $[1 - \frac{Hrms..stabilised}{Hrms.unstabilised}] \ x \ \frac{100}{1}$ (10)

Principles of Operation of Passive Anti-Roll Tanks

A passive free surface anti-roll tank is a large partially filled open channel type roll damping system that is usually placed across the full beam of a vessel high above the ships center of gravity. Its shape, size and internal geometry allow the liquid inside to slosh from side to side in response to the roll motion of the ship.

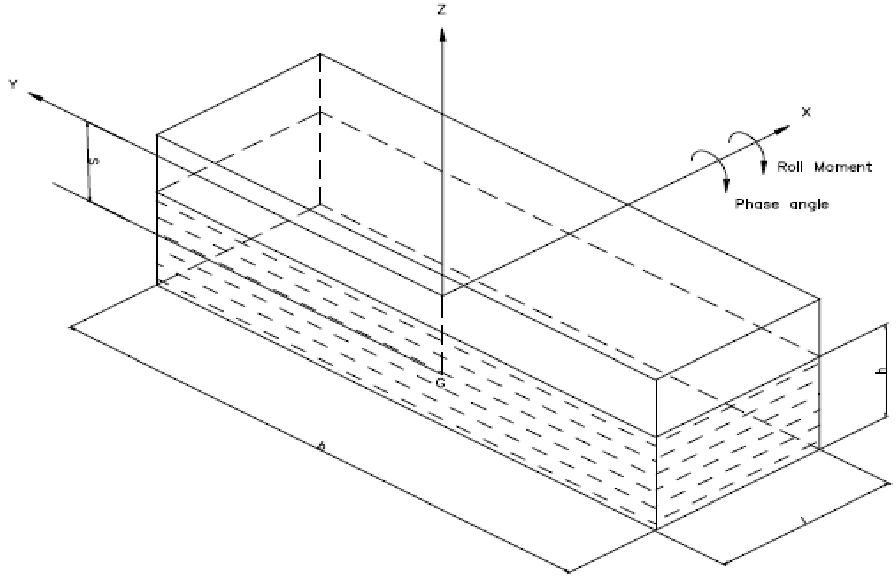

Figure 1: Free Surface Type Anti Roll Tank Geometry and Dimensions

The Spectral Energy Method

This study employed an energy approach to evaluate the performance of the free surface anti-roll tank in an irregular sea. The basic principle involved in stabilizing a rolling ship requires that, the wave energy responsible for the excitation of the motion be expended or dissipated by a mechanism fitted on it(in this case a tank). From energy point of view, the energy imparted to the ship by the waves is transferred to the tank and dissipated which result in reducing the amplitude of the ship, thereby stabilizing its roll motion.

Wave Energy Spectrum and Spectral Moments

The zeroth moment, m_o represents the variance of the spectrum or water surface elevation

In general, $m_n = \int_0^\infty \omega^n S\phi(\omega)\, d\omega$ (11)

Where n is any positive integer 0,1,2,3…

Mean Period (Tp) $=2n\sqrt{\frac{m2}{m4}}$ (12)

Mean Zero Crossing Period (T) = $2n\sqrt{\frac{m2}{m0}}$ (13)

Different Sea Conditions

A sea state is the overall condition of the surface of a large body of water which results from the combined effects of wind-generated waves, swells, and currents. The different states of a ship operating in a realistic seaway can be described as fully developed, developing, decaying and young or starting. The typical energy spectra for these seas are presented below:

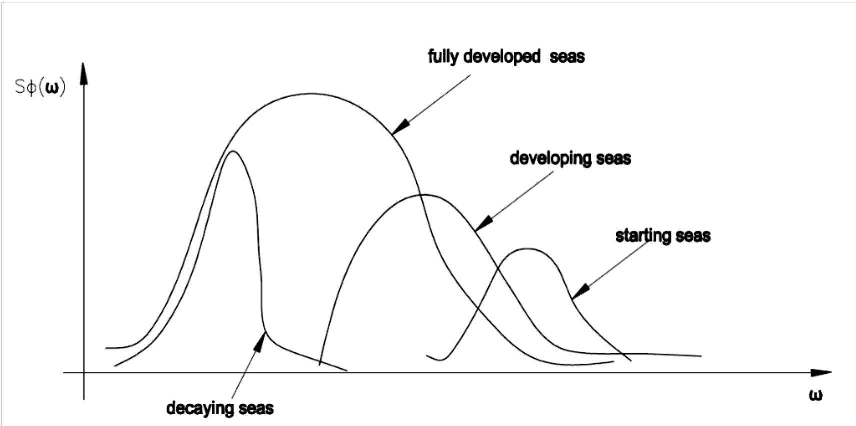

Figure 2: Typical Wave Spectra for Different Seas [16]

Performance of Free Surface Anti-Roll Tanks – Case Study

Table 1: Significant Roll Amplitude [3]

	Measured $\phi_{\phi 1/3}$ **Degrees**	**Calculated** $\phi_{a 1/3}$ **Degrees**
Ship without tank		
Spectrum 1	8.66 (0.151 rad)	9.19
Spectrum 2	10.99 (0.192 rad)	13.92
Ship with tank		
Spectrum 1	3.56 (0.0621 rad)	3.69
Spectrum 2	5.85 (0.1021 rad)	5.71

Given the following Data for the model of C_B-0.70 and a scale of 1:50

Generic Cargo Ship with the following details:

L_{PP} = 152.40 m; B = 21.77 m D = 13.54 m d_{mid} = 8.71 m

∇_{mid} = 20228m^3 Tϕ = 14.52 s

3. Results

Modified Pierson Moskowitz (MPM)

Using the following periods to simulate the wave energy spectra

Case 1: Tz = 8 s; Case 2: Tz = 12.4 s

Case 3: Tz = 20 s Case 4: Tz = 33 s

The idealized Modified Pierson Moskowitz spectral formulation was used to obtain the wave spectral density of the different wind seas of spectrum 1, when the ship had no anti-roll tank in operation (Table 2) and the graphs of the energy spectra is presented in Fig. 3 below;

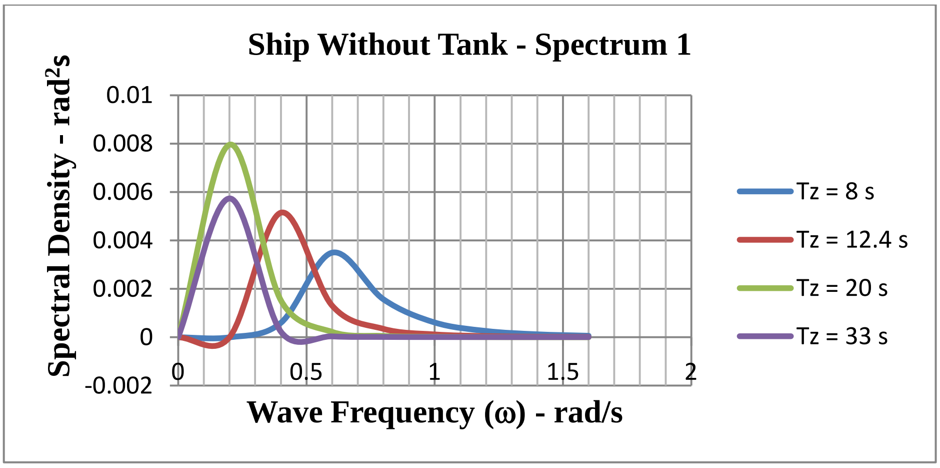

Figure 3: MPM Wave Energy Spectra for Different Seas - Spectrum 1 (Ship Without. Tank)

Table 2: MPM Spectral Densities of the Different Seas over Wave Frequencies- Spectrum 1 (Ship Without. Tank)

ω	Sϕ(ω)1	Sϕ(ω)2	Sϕ(ω)3	Sϕ(ω)4
0	0	0	0	0
0.2	2.92E-33	7.55E-07	0.007955	0.005736
0.4	0.000595	0.005146	0.001529	0.000229
0.6	0.003487	0.001308	0.000222	3.06E-05
0.8	0.001567	0.000347	5.35E-05	7.27E-06
1.0	0.000612	0.000117	1.76E-05	2.38E-06
1.2	0.000262	4.76E-05	7.09E-06	9.58E-07
1.4	0.000124	2.21E-05	3.28E-06	4.43E-07
1.6	6.46E-05	1.14E-05	1.68E-06	2.27E-07

The wave spectral densities of the different wind seas of spectrum 1 when the ship had anti-roll tank in operation are shown in (Table 3) and the graphs of the energy spectra are presented in Fig. 4 below;

Table 3: MPM Spectral Densities of the Different Seas over Wave Frequencies - Spectrum 1 (Ship With. Tank)

ω	Sϕ(ω)1	Sϕ(ω)2	Sϕ(ω)3	Sϕ(ω)4
0	0	0	0	0
0.2	4.93E-34	1.28E-07	0.001346	0.001
0.4	0.000101	0.00087	0.000259	4.00E-05
0.6	0.00059	0.000221	3.75E-05	5.00E-06
0.8	0.000265	5.86E-05	9.05E-06	1.00E-06
1.0	0.000103	1.98E-05	2.98E-06	4.00E-07
1.2	4.43E-05	8.05E-06	1.20E-06	2.00E-07
1.4	2.10E-05	3.74E-06	5.55E-07	7.00E-08
1.6	1.09E-05	1.92E-06	2.85E-07	4.00E-08

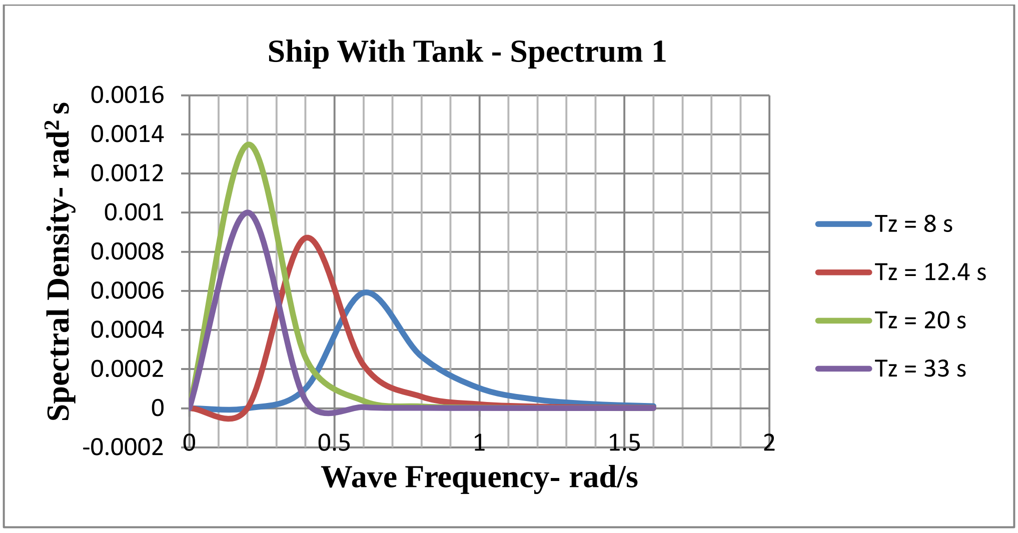

Figure 4: MPM Wave Energy Spectra for Different Seas – Spectrum 1 (Ship With. Tank)

JONSWAP Spectrum Spectral Analysis. - Spectrum 1 (Ship Without. Tank)

Wave spectra of an equivalent JONSWAP sea state: Tz = 8 s, 12.4 s, 20 s, 33 s is simulated

The idealized JONSWAP spectral formulation was used to obtain the wave spectral density of the different wind seas of spectrum 1 when the ship had no anti-roll tank in operation (Table 4) and the graphs of the energy spectra is presented in Fig. 5 below;

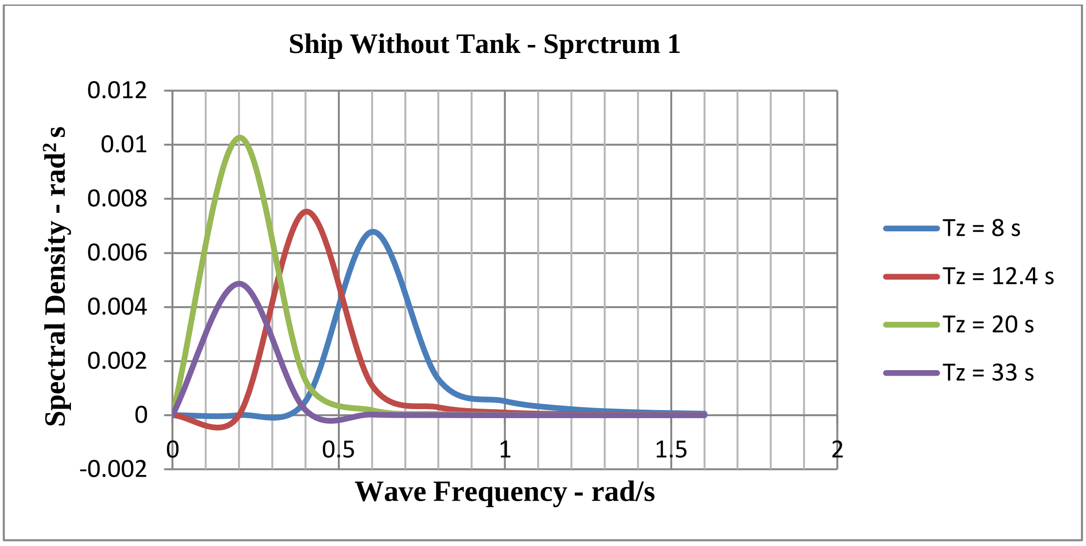

Figure 5: JONSWAP Wave Energy Spectra for Different Seas – Spectrum 1 (Ship Without. Tank)

Table 4: JONSWAP Spectral Densities of the Different Seas over Wave Frequencies – Spectrum 1 (Ship Without. Tank)

ω	Sϕ(ω)1	Sϕ(ω)2	Sϕ(ω)3	Sϕ(ω)4
0	0	0	0	0
0.2	3.96E-33	6.93E-07	1.03E-02	4.86E-03
0.4	5.18E-04	7.53E-03	1.29E-03	1.94E-04
0.6	6.78E-03	1.11E-03	1.88E-04	2.59E-05
0.8	1.33E-03	2.93E-04	4.53E-05	6.15E-06
1.0	5.18E-04	9.91E-05	1.49E-05	2.02E-06
1.2	2.21E-04	4.02E-05	6.00E-06	8.10E-07
1.4	1.05E-04	1.87E-05	2.78E-06	3.75E-07
1.6	5.47E-05	9.62E-06	1.42E-06	1.92E-07

Spectral Analysis - Spectrum 1 - Ship With. Tank

Table 5 below shows the spectral densities of the different seas of spectrum 1 when the ship had anti-roll tank in operation using JONSWAP spectral formulations and the graphs of the energy spectra is presented in Fig 6.

Table 5: JONSWAP Spectral Densities of the Different Seas over Wave Frequencies – Spectrum 1 (Ship With. Tank)

ω	Sϕ(ω)1	Sϕ(ω)2	Sϕ(ω)3	Sϕ(ω)4
0	0	0	0	0
0.2	6.70E-34	1.17E-07	1.74E-03	8.22E-04
0.4	8.77E-05	1.27E-03	2.19E-04	3.28E-05
0.6	1.15E-03	1.87E-04	3.17E-05	4.37E-06
0.8	2.25E-04	4.96E-05	7.66E-06	1.04E-06
1.0	8.76E-05	1.68E-05	2.52E-06	3.41E-07
1.2	3.74E-05	6.81E-06	1.01E-06	1.37E-07
1.4	1.78E-05	3.16E-06	4.70E-07	6.34E-08
1.6	9.25E-06	1.63E-06	2.41E-07	3.25E-08

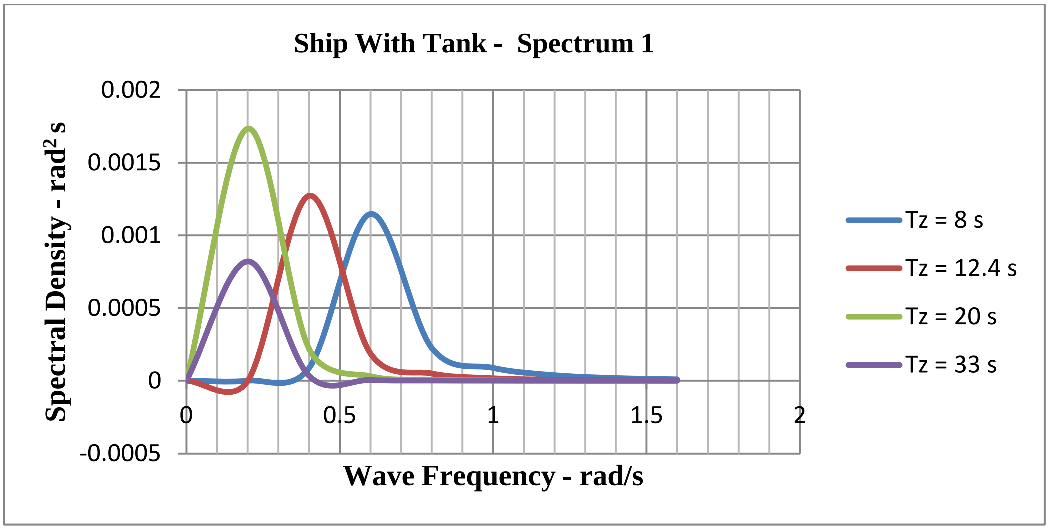

Figure 6: JONSWAP Wave Energy Spectra for Different Seas Spectrum 1 (Ship With. Tank)

Comparison of MPM and JONSWAP Spectrum 1– Ship without tank

Table 6 shows the spectral densities of the developed sea for JONSWAP and Modified Pierson Moskowitz for comparison, while Fig. 7 is their wave energy spectra.

Table 6: Comparative values of spectral densities of the developed seas for JONSWAP and Modified Pierson Moskowitz

ω	Sϕ(ω)3 JONSWAP	Sϕ(ω)3 Modified Pierson Moskowitz
0	0	0
0.2	1.03E-02	0.007955
0.4	1.29E-03	0.001529
0.6	1.88E-04	0.000222
0.8	4.53E-05	5.35E-05
1.0	1.49E-05	1.76E-05
1.2	6.00E-06	7.09E-06
1.4	2.78E-06	3.28E-06
1.6	1.42E-06	1.68E-06

Table 7: Summary of Results –Passive Free Surface Anti-Roll Tank

Summary of Results		
Spectral Parameter	**Modified Pierson Moskowitz Spectral Model (MPM)**	**Jonswap Spectral Model**
SPECTRUM 1		
Anti-Roll Tank Effectiveness		
Developed Sea	83.14 %	83.11 %
Developing Sea	83.11 %	83.13 %
Decaying Sea	82.58 %	83.09 %
Young Sea	83.14 %	83.18 %
ART Efficiency (%)	59.00 %	58.97 %
Spectral Energy Dissipated by ART	20.05 KJ/rad^2	24.90 KJ/rad^2
SPECTRUM 2		
Anti-Roll Tank Effectiveness		
Developed Sea	71.75 %	71.69 %
Developing Sea	71.75 %	71.80 %

Decaying Sea	71.70 %	71.75 %
Young Sea	71.70 %	71.71 %
ART Efficiency (%)	46.71 %	46.68 %
Spectral Energy Dissipated by ART	28.0 KJ/rad^2	34.6 KJ/rad^2

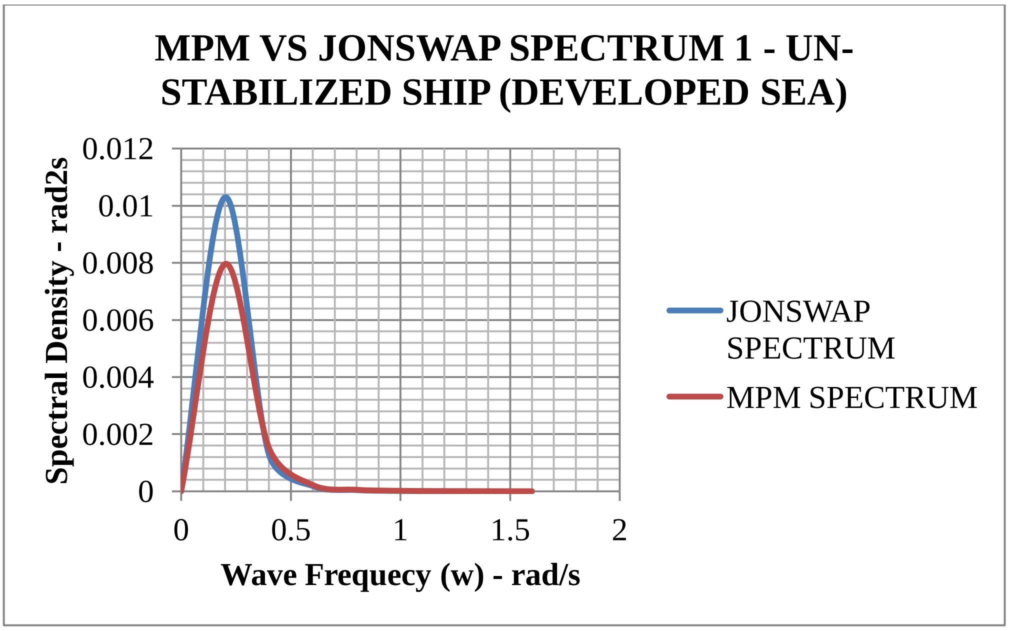

Figure 7: Comparison of Peak Energy Spectra of the Two Wave Models for Developed Sea

4. Discussion

The discussion of the findings of the study is summarized as follows;

- The resonance frequencies of the different wave energy spectra were observed to be the same in both wave models i.e. Modified Pierson Moskowitz and JONSWAP
- It was observed that the effectiveness and efficiency of the device in any given spectrum was observed to be essentially the same for both spectral models.(see Table 7)
- The computed spectral energy dissipated by the free surface tank for the two spectral conditions (spectrum 1 and 2) indicates that the anti-roll tank expends more energy for damping roll in JONSWAP seas than the Modified Pierson Moskowitz (MPM).With further experimental investigation and validation, this finding can be generalized. (see Table 7)
- Comparison of the wave energy spectra of the different seas of both spectral models of (spectrum 1 and 2), reveal that those of the JONSWAP spectrum are steeper than the Modified Pierson Moskowitz in all the sea states.(see Fig. 7)
- Finally, the study used spectral analysis with some simplifying assumptions to predict the energy dissipated by the free surface anti-roll tank of a ship in irregular beam sea, and based on the results obtained it is recommended that further studies be carried out in this area.

5. Conclusion

The aim of this paper was to investigate the performance of the free surface anti-roll tanks inthe reduction of roll motion of cargo ships, and based on the findings it is concluded as follows; The ship recorded significant roll reduction at resonance or peak frequencies of the different wave spectra but achieved moderate reductions at higher frequencies.

1) The free surface anti-roll tank’s effectiveness and efficiency is consistent (the same) for the different wind seas in a particular sea spectrum.

2) Increase of the significant amplitude of the vessel in waves reduces the effectiveness and efficiency of the anti-roll tank.
3) For the best stabilization of the vessel, thetank-fluid moment of the tank should always be in phase with the frequency of the wave excitation force. This ensures that the resulting moment always acts in the opposite direction of the wave excitation force, which naturally leads to roll reduction.
4) The results of the study clearly show that passive free surface anti-roll tanks offer good solution to excessive roll motion problems of marine vessels traveling in realistic seas.

References

[1]. Froude, W (1861). , the Rolling of Ships. Trans. *Inst. Naval Architects*, Vol. 2, pp.180-229.

[2]. Watts, P. (1885). The Use of Water Chambers for Reducing the Rolling of Ships at Sea. *Trans. I.N.A*, pp. 30.

[3]. Van Den Bosch J.J. &Vugts, J.H.(1966). On Roll Damping by Free-Surface Tanks. *Trans. RINA*, pp. 345–361.

[4]. Verhagen, J.H.G., & Van Wijngaarden, L. (1965). Non-Linear Oscillations of Fluid in a Container. J. Fluid Mechanics, 22 (4), pp. 737–751.

[5]. Armenio, V., Francescutto, A., &La Rocca, M. (1996).On the Roll Motion of a Ship with Partially Filled Unbaffledand Baffled Tanks – Part 2: Numerical and Experimental Analysis, *International Journal of Offshore and Polar Engineering*, 6(4).

[6]. Liu, Z., & Huang, Y. (1994). A New Method for Large Amplitude Sloshing Problems, pages *Journal of sound and Vibration*, 175(2), 185-195

[7]. Zhong, Z., Falzarano, J.M., & Fithen, R.M. (1998). A Numerical Study of U-Tube Passive Anti-Rolling Tanks.*Proceedings of the Eight International Offshore and Polar Engineering Conference*, Montreal, Canada, 3, 504–513.

[8]. Popov, G., Sankar, S., & Sankar, T.S. (1993). Dynamics of Liquid Sloshing in Baffled and Compartmented Road Containers. *Journal of Fluid Structures*. 7 (7), 803–821.

[9]. Celebi, M.S., Akyildiz, H. (2002). Nonlinear Modeling of Liquid Sloshing in a Moving Rectangular Tank. *Journal of Ocean Engineering*, 29 (12), 1527–1553.

[10]. Cariou, A., & Casella, G. (1999). Liquid Sloshing in Ship Tanks: a Comparative Study of Numerical Simulation. *Marine Structures*. Vol 12 (3), pp. 183–198.

[11]. Sames, P.C., Marcouly, D., & Schellin, T.E. (2002).Sloshing in Rectangular and Cylindrical Tanks. *Journal of Ship Research*, 46 (3), pp. 186–200.

[12]. Souto, I., Perez, R., & Zamora, R. (2004). Simulation of Anti-Roll Tank and Sloshing Type Problems With Smoothed Particle Hydrodynamics. *Ocean Engineering* 31, 1169-1192

[13]. Lloyd, A.R. (1989): *Seakeeping: Ship Behaviour in Rough Weather*, Ellis Horwood Limited, Chichester, West Sussex, UK.

[14]. St Denis, M., & Pierson, W. J. (1953). On the Motions of Ships in Confused Seas. *SNAME Transaction*, New York.

[15]. Longuet-Higgins M. S. (1952). On the Statistical Distribution of the Heights of Sea Waves. *Journal of Marine Research*. 9(3), 245–266

[16]. Techet, A.H. (2005). Ocean Waves. MIT Ocean Engineering. Massachusetts Institute of Technology, U.S.A.