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# Predictive Control and Stabilizing Effect Analysis of Controlled Passive Tank

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***Abstract* - Controlled passive tank is able to achieve a more perfect stabilizing effect by extending the natural period of water tank with opening/closing the air-valves in accordance with the variation tendency of ship's rolling. Two controlling parameters, which are most important, are the closing-time and closing time span. The determination of closing time span has a direct relation with the ship's real-time rolling period. By adopting wavelet neural network to predict the ship's rolling motion and real-time updating the closing time span of closing valves with the predicted values, meanwhile, real-time analysing the rolling power spectrum is applied before and after anti rolling according to the known input-output relation of anti-rolling tank model coupled with rolling. The paper shows this predictive control method which is more perfect than traditional anti rolling control effect and possess favourably practical value in engineering.**

***Index Terms – Controlled Passive Tank; Ship Rolling; Wavelet Neural Network .***

## I. INTRODUCTION

Roll motion affects the seakeeping performance of ships because of limiting the effectiveness of the crew and the operation of on- board equipment. In some cases, excessive roll motion can lead to cargo damage or cargo loss, passenger injury and, in extreme cases, capsize [1].

There are many types of roll stabilizer devices for ships, such as anti-rolling tank, weight stabilizer, fin stabilizer, and others. However, the most fin stabilizers systems can't effectively reduce the rolling motion of a ship sailing at low speed or for a ship at anchor. In contrast, the stabilizing effect of the anti-rolling tank does not depend on the forward speed of the ship, and it can be fitted to any type of ship operating at any speed. Anti-rolling tank is common and effective devices for reducing rolling of ships, and its usage expands quickly as the development of marine technology. The anti-rolling tank has three kinds including passive type, passive controlled type and activated type. In passive tanks, the fluid flows freely from side to side. The tank is dimensioned so that the tank fluid's natural period equals then actual roll period of the ship [2],in the presence of waves, however, the roll period is determined by the frequency of the waves, not the natural frequency in roll [3], the passive tanks are not as efficient a stabilizer over a wide wave frequency range. The activated tanks use up too much power to obtain beneficial reduction of the ship rolling motion over a wide range of speed and wave frequency, only the passive controlled tanks can satisfy the requirement, which have the advantages of passive tanks and passive controlled tanks .The passive controlled tank can control the flow in the tank through the air valve to extend the natural period of fluid artificially, which is necessary to maintain performance.

The optimization of hydrodynamics, control strategy, and structure design are all research aspects of the anti-rolling tank devices, within which the optimization of control strategy is key technology for passive controlled tank. Two control points are needed to solve for passive controlled tank, make the decision to close the valves, and determination of the closing time span of the valves. The control points have a direct relation with the ship's real-time rolling period, the roll period could be acquired by using natural period or statistical data of history record, but the complexity of the ship motion in different rough seas, ship roll period maybe fall away from the natural period, and using of the statistical data will be lagging behind the practical valve. Through predictive control, the real time and accuracy could be improved, for period prediction wavelet neural network is applied. The time series of ship motion have the characteristic of the correlation of time, the wavelet neural network prediction has certain advantages for dealing with nonlinear and uncertainty of the problems.

For best stabilizing effect, optimization analysis is an effective method to analyze the control parameters on the stabilizing effect. Stabilizing effect is control object of predictive control. Real time stabilizing effect analysis is able to keep the anti-rolling system running with the optimal control. In practice, there might be problems that sometimes the crew could not obviously sense the stabilizing effect while the anti-rolling stabilizer is running normally. So stabilizing effect analysis is also considered. Real-time analyzing the rolling power spectrum is applied before and after anti rolling according to the known input-output relation of anti-rolling tank model coupled with rolling.

## II. MATHEMATICAL MODEL

### *A. Sea Wave*

Simulating the sea environment is the first step to perform the analysis [4]. It is common to calculate the wave data using power spectral density (PSD) and simulate the wave height by superposition method, which is as in (1).

$$\zeta(t)=\sqrt{2}\sum_{i=1}^{\infty}\sqrt{\int_{\omega_{i-1}}^{\omega_i}S_{\zeta}(\omega)d\omega}\cos(\omega_i t+\varepsilon_i)\,. \tag{1}$$

Where ζ(t) is the wave height and S(ω) is its PSD, $\omega_i$ is the angular frequency of each harmonic wave, and $\varepsilon_i$ is the random phase.

In practical, the long crested wave height of a fixed point on sea surface can be described as in (2).

$$\zeta(t)=\sum_{i=1}^{\infty}\zeta_{ai}\cos(\omega_i t+\varepsilon_i)\,. \tag{2}$$

Where $\zeta_{ai}$ is the wave height of each harmonic wave, and according to the ocean wave theory, $\varepsilon_i$ is a random number uniform distributed between 0 and 2π. In this paper, the P-M (Pierson – Moscowitz) single parameter PSD is used and shown as in (3).

$$S_\zeta(\omega)=\frac{A}{\omega^5}\exp(-\frac{B}{\omega^4})\,. \tag{3}$$

Where $A = 0.0081g^2$, $B = 3.12/(H_{1/3}^2)$, and $g$ is the acceleration of gravity, $H_{1/3}$ is the significant wave height.

In order to simulate the ship motion, it is necessary to consider the interaction between wave and ship body and transfer the wave height to effective wave slope $\alpha_1$ using (4).

$$\alpha_1=k_\varphi k\zeta(t)\,. \tag{4}$$

Where $k_\varphi$ is the ship body correction factor, $k$ is the wave number.

*B. Anti-rolling Tank Model Coupled With Rolling*

When the rolling angle of ship motion is relatively small, linear rolling theory can be used to analyze the rolling motion of ship. Thus, the linear function of ship rolling motion, shown as in (5), is obtained by integrating a variety of torques to which the ship is subjected in regular wave, according to the theory developed by Conolly.

$$(I_{44}+A_{44})\ddot\phi+N_u\dot\phi+C_{44}\phi=C_{44}\alpha_1\,. \tag{5}$$

Where $I_x$ and $\Delta I_x$ are the moment and additional moment respectively relative to the vertical axis which goes through the center of gravity of the ship, $2N_u$ is the damp moment of unit rolling angular velocity, $D$ is the ship displacement, and $h$ is the transverse metacenter height of ship.

When the anti-rolling tank is installed on the ship, it will generate a control moment $M_{stab}$ against the disturbance moment of wave. We now consider only the coupling between roll and flow in anti-rolling tank. Then equation(6) can be rewrite as in (7).

$$(I_{44}+A_{44})\ddot\phi+B_{44}\dot\phi+C_{44}\phi=C_{44}\alpha_1-M_{stab}\,. \tag{6}$$

The moment of fluid in anti-rolling tank can be calculated by (7), according to the rolling angle of ship.

$$M_{stab}=A_{4u}\ddot z_u+C_{4u}z_u\,. \tag{7}$$

And the linear equations of liquid motion and ship roll are as shown in (8). Definitions of parameters used in anti-rolling tank are in fig. 1.

$$A_{u4}\ddot\phi+C_{u4}\phi+A_{uu}\ddot z_u+B_{uu}\dot z_u+C_{uu}z_u=0\,. \tag{8}$$

Where:

$$A_{44}=0.105I_{44}$$

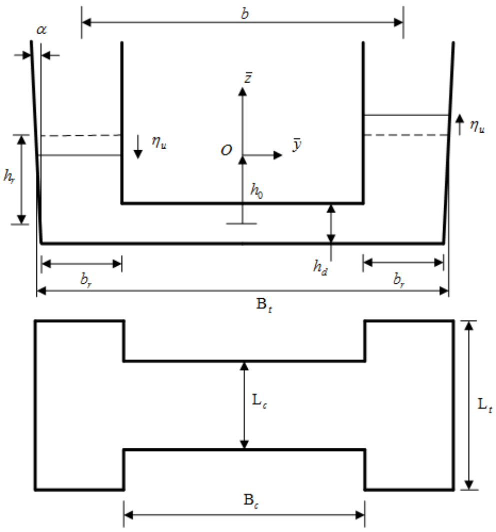



Fig.1 Definition of parameters used in anti-rolling tank

$$I_{44}=Mr^2{}_{44}$$
$$A_{uu}=\rho_l L_t b_r(2h_r+bb_r/h_d)$$
$$C_{uu}=2\rho_l L_t b_r g$$
$$A_{4u}=A_{u4}=\rho_l L_t b_r b(h_r+h_O)$$
$$C_{4u}=C_{u4}=\rho_l L_t b_r bg\,,\;B_{uu}=2\xi_u\sqrt{A_{uu}C_{uu}}$$
$$C_{44}=\rho g\nabla\overline{GM_T}$$
$$B_{44}=2\xi_4\sqrt{(I_{44}+A_{44})C_{44}}\,.$$

The INTERING anti-rolling tank use valves at the two reservoir to realize control of tank. When the ship rolls with period larger than the uncoupled natural period for the liquid motion in the tank, the valves are alternatively opened and closed. When the valves are closed on either the port or the starboard side, it nearly halt the liquid motion in the tank. We start by analyzing the case where the port chamber is equal to atmospheric pressure $P_a$, and $p(0)$ changes with time according to the pressure in the closed air chamber. According to the conservation of mass for the air chamber, and using a Taylor expansion.

$$p(l)-p(0)=p_a-p_a\left(\frac{h_c}{h_c+z_u-z_{u0}}\right)^{\kappa}\approx\frac{P_a\kappa}{h_c}(z_u-z_{u0})\,. \tag{9}$$

With one closed chamber , equation (8) can be as:

$$A_{u4}\ddot\phi+C_{u4}\phi+A_{uu}\ddot z_u+B_{uu}\dot z_u+(C_{uu}+\frac{P_a\kappa\cdot L_t b_r}{h_c})z_u=\frac{P_a\kappa\cdot L_t b_r}{h_c}z_{u0}\,. \tag{10}$$

## III. Control Method Of Anti-Rolling Tank

The roll period is determined by the frequency of the waves, not the natural frequency in roll [3].Therefore, active control is necessary to maintain performance. Active tanks operate in a similar manner to their passive counterparts, but they incorporate a control system which modifies the period of the tank to match the actual ship roll period, and can also ensure optimal phase difference. Control can be achieved by adjusting the air that flows from one reservoir to the other by means of an air duct.

In passive controlled tanks, the valves switch control should be modeled to analyze [6].Two control parameters are involved in valve control of passive controlled tank. When make the decision to close the valves, and how long is closing time span of the closing time of the valves.

Ship motion coupled anti-rolling tank is coupled mutually. When the phase between ships roll angle and water level in the tanks keeps in order, the stabilizing effect is best. The information of roll angle, roll angular velocity, water level or water velocity in the connection duct is used to control air valves opened or closed. The signals of roll angle and water velocity are used to control air valves. Actually, the ship motion is stochastic process, the roll period is mainly determined by the frequency of wave, the roll period should be analyzed real time through clocking the time between the moment that the roll angle is zero and the moment that the roll angle has reached its maximum.

When it has been decided that the valves will be closed during a certain wave, the point in time of closing the valves must be determined, the point is marked by a maximum water level in one of the wing tanks, This moment can be found easily, by keeping track of the water volume of the wing tanks.

To open the valves again, The water can flow to the other wing tank, the valves should be opened when the ship is clearly rightening .The goal is to lengthen the natural period of the anti rolling tank to the roll period of the wave, if the closed valves were able to keep the water at the same level, we can calculate the optimal closing time period as follows. At the moment the valves are closed, At the moment the valves are closed, the ship has a certain roll velocity $\dot{\phi}_x(t_{close})$ , the ship's roll velocity will get larger until the roll angle is zero at stage3 ,Around this point in time the ship rolls with maximum roll velocity $(\dot{\phi}_{x\max})$ .After that the velocity decreases and will reach the valve $\dot{\phi}_x(t_{close})$ again ,at this point in time we should open the valve if the same water level are maintained. This principle is discussed under presume regular seas:

$$\phi(t) = A\sin(\frac{2\pi}{T}t) . \tag{11}$$

Where : $A$ is the amplitude ,$T$ is the rolling period.

The closing time span is given by:

$$\Delta t_{close} = \frac{1}{2}(T - T_{ART}) . \tag{12}$$

The roll velocity at the opening and closing time point can be calculate as:

$$\begin{aligned}\dot{\phi}(t_{close}) &= \dot{\phi}(t_{roll=0} - \frac{1}{2}\Delta t_{optimal}) \\ &= A\frac{2\pi}{T}\cos(\frac{1}{2\pi}(1-\frac{T_{ART}}{T})) .\end{aligned} \tag{13}$$

In reality , expect the valves should be closed somewhat longer than the optimal closing period calculated above, the roll velocity we calculated is a factor of the maximal roll velocity $A\omega$, this factor is equal to $cos(\frac{1}{2})(1-\frac{T_{ART}}{T}))$, the valves are opened if the roll velocity satisfies.

$$\dot{\phi}_x(t_{open}) = \cos(\frac{1}{2}\pi(1-\frac{T_{ART}}{T}))\dot{\phi}_{x\max} . \tag{14}$$

Roll period could be acquired by using two methods, one kind is to use natural period, another kind is to use roll after for statistical data of history record, but because of the complexity of the ship motion in different rough seas, ship roll period maybe fall away from the natural period, and using of the statistical data will be lagging behind the practical valve. Through prediction of ship period, the real time and accuracy could be improved. The time series of ship motion has the characteristic of the correlation of time, the wavelet neural network prediction has certain advantages for dealing with nonlinear and uncertainty of the problems.

Wavelet neural networks combine the theory of wavelets and neural networks into one. A wavelet neural network generally consists of a feed-forward neural network, with one hidden layer, whose activation functions are drawn from an orthonormal wavelet family. One application of wavelet neural networks is that of function estimation. Given a series of observed values of a function, a wavelet network can be trained to learn the composition of that function, and hence calculate an expected value for a given input.

In Fig.2, $X_1$, $X_2$....,$X_k$ is input parameters of neural network, and $Y_1$, $Y_2$....,$X_m$ is prediction output parameters of neural network, $\omega_{ij}$ and $\omega_{jk}$ is weight coefficients of wavelet neural network. When input series is $x_i$ ($i$=1,2,…,$k$), output calculation formula of hidden layer is as in (15).

$$h(j) = h_j\left[\frac{\sum_{i=1}^{k}\omega_{ij}x_i - b_j}{a_j}\right] \quad j = 1,2,\cdots,l . \tag{15}$$

Where, $h(j)$ is output value of node $j$, $b_j$ is translation factor , $a_j$ is magnification factor, $h_j$ is wavelet function.

The Morlet wavelet function is used as calculation formula in (16).

$$y = \cos(1.75x)e^{-x^2/2} . \tag{16}$$

The calculation formula of output layer is as in (17).

$$y(k) = \sum_{i=1}^{l}\omega_{ik}h(i) \quad k = 1,2,\cdots,m . \tag{17}$$

Where, $h(i)$ is hidden layer node of output. $l$ is number of hidden layer nodes. $m$ is number of output nodes.

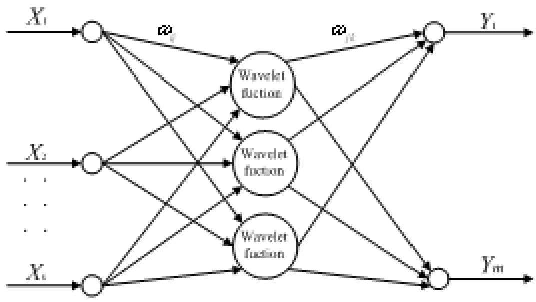



Fig.2 Structure of a wavelet neural network.

The rectification procedure of wavelet neural network is as below, The error of prediction networks is as in (18).

$$e = \sum_{k=1}^{m} yn(k) - y(k) . \tag{18}$$

According to error, to rectify the weighs of neurons and coefficients of wavelet function.

$$\begin{aligned} \omega_{n,k(i+1)} &= \omega_{n,k}^{(i)} + \Delta\omega_{n,k}(i+1) + k*(\omega_{n,k}(i) - \omega_{n,k}(i-1)) \\ a_{k(i+1)} &= a_k(i) + \Delta a_k(i+1) + k*(a_k(i) - a_k(i-1)) \\ b_{k(i+1)} &= b_k(i) + \Delta b_k(i+1) + k*(b_k(i) - b_k(i-1)) . \end{aligned} \tag{19}$$

Where , $\Delta\omega_{n,k}^{(i+1)}$, $\Delta a_k^{(i+1)}$, $\Delta b_k^{(i+1)}$ is calculated through prediction error.

$$\begin{aligned} \Delta\omega_{n,k}^{(i+1)} &= -\eta \frac{\partial e}{\partial \omega_{n,k}^{(i)}} \\ \Delta a_k^{(i+1)} &= -\eta \frac{\partial e}{\partial a_k^{(i)}} \\ \Delta b_k^{(i+1)} &= -\eta \frac{\partial e}{\partial b_k^{(i)}} . \end{aligned} \tag{20}$$

The weights are adjusted in accordance to a learning algorithm in response to some classified training data, with the state of the network converging to the correct one. The perception is thus make to learn from experience.

## IV. Analysis Of Stabilizing Effect And Simulation

### A. *Spectral Analysis of Ship Rolling Angle*

PSD Estimation of Ship Rolling Angle with anti-rolling tank, multitaper method (MTM) is used to estimate the PSD of ship rolling angle while the control system is running.

PSD of Wave Slope. According to random process theory[7], relationship as in (21) exists between the PSD of ship rolling angle $S_\phi(\omega)$ and the PSD of wave slope $S_{\alpha 1}(\omega)$ .

$$S_\phi(\omega) = \left|G_c(\omega)\right|^2 S_{\alpha 1}(\omega) . \tag{21}$$

It shows that the frequency response of simplified model is almost the same as original model when the frequency of input signal is below 10 Hz. Thus, the PSD of wave slope $S_{\alpha 1}(\omega)$ is obtained, shown as（22）.

$$S_{\alpha 1} = S_\phi(\omega) / \left|G_c(\omega)\right| . \tag{22}$$

PSD of Ship Rolling Angle without anti-rolling tank. According to equation(6）and equation(10), the PSD of ship rolling angle while anti-rolling tanks not running is obtained by (23).

$$S_{\phi NF}(\omega) = \left| G_\phi(\omega) \right|^2 S_{\alpha 1}(\omega) = \frac{\left| G_\phi(\omega) \right|^2}{\left| G_c(\omega) \right|^2} S_\phi(\omega) . \tag{23}$$

### B. *Definition of Stabilizing Effect*

Before the analysis of the stabilizing effect, the ship rolling angle should be obtained in the first place. The feedback signal of anti-rolling tank system is the rolling angular velocity. It is assumed that the ship rolling angle is obtained either by integrating the feedback signal, or by using another angular sensor. Thus, the PSD of ship rolling angle $S_\phi(\omega)$ is obtained by spectra analysis. Then the PSD of wave slope $S_{\alpha 1}(\omega)$ can be got using (21) and random process theory, as the rolling motion of ship subjecting to long crested waves can be regarded as a stationary random process. At last, the PSD of ship rolling angle without anti-rolling tank $S_{\phi NF}(\omega)$ is obtained using (23) and random process theory.

With regard to a certain sea condition, the variance of ship rolling angle reflects the rolling condition. Therefore, the stabilizing effect can be defined as the ratio between the variance of ship rolling angle with and without anti-rolling tank running. According to random process theory, the variance of ship rolling angle can be obtained by integrating the PSD of ship rolling angle, shown in (24).

$$E[\phi^2] = \frac{1}{2\pi} \int_{-\infty}^{+\infty} S_\phi(\omega) d\omega . \tag{24}$$

Thus, stabilizing effect is described as equation(25). Where *SE* is the stabilizing effect.

$$SE = \frac{E[\phi^2]}{E[{\phi_{NF}}^2]} = \int_{-\infty}^{+\infty} \frac{S_\phi(\omega)}{S_{\phi NF}(\omega)} d\omega . \tag{25}$$

And the another expression of stabilizing effect:

$$SE_1 = 1 - \frac{1}{SE} . \tag{26}$$

### C. *Roll Period Prediction and Simulation*

In order to get the analysis data and test the method used, a simulation model is developed using MATLAB/Simulink[8] based on mathematical model described in section above, shown as Fig. 3. The upper right part of Fig. 3 is used for simulating the ship rolling motion without anti-rolling tank, so the contrast can be made to judge part of Fig. 3 is used for simulating the ship rolling motion without anti-rolling tank, so the contrast can be made to judge the accuracy of the estimated PSD of ship rolling angle without anti-rolling tank.

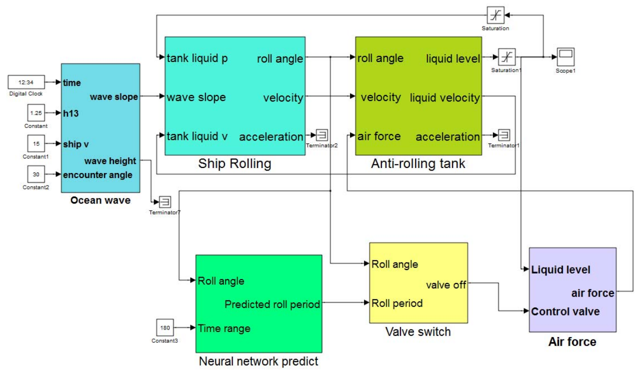
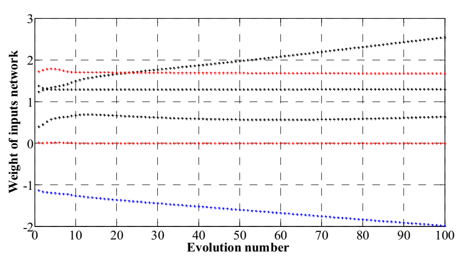


Fig. 3 Simulation model based on MATLAB/Simulink

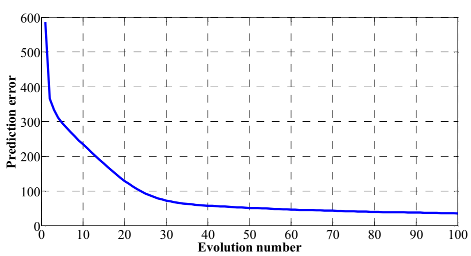
The training of wavelet neural network is as shown in Fig.4. Weights and predictive error are convergent. The weights are used for predictive control. Fig.5 are result of prediction and ship rolling period of simulation, the error of prediction is small which could satisfy the requirement of control systems.

Simulation of ship rolling motion under wave scale six is made, and the following sections are the analysing results of stabilizing effect.

According to (26), the stabilizing effect is calculated , for convenience,the express of percent is used. The ship rolling reduction scale is represented through stabilizing effect.



(a) Variation of Weights



(b) Prediction error of neural network

Fig. 4 Training of wavelet neural network

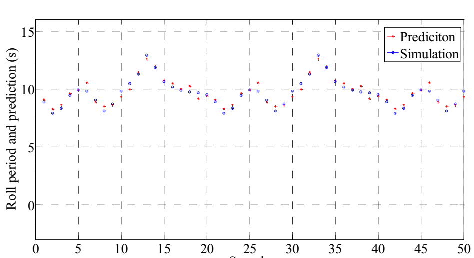


Fig. 5 Real time simulation and period prediction

Fig.6 is the curves of ship rolling and ship rolling coupled with passive anti rolling tank. The stabilizing effect is 47.96%. Fig.7 is curves of ship rolling coupled with passive controlled tank, the stabilizing effect is 59.26%. The parameters of closing time span is constant ,which relate to natural period of ship. Fig.8 is the curves of ship rolling coupled with passive control tank, the parameter of closing time span is obtained through prediction, the stabilizing effect is 67.97%. Comparison between Fig.7 and Fig.8 , the stabilizing effect enhance 8.71% because of period prediction.

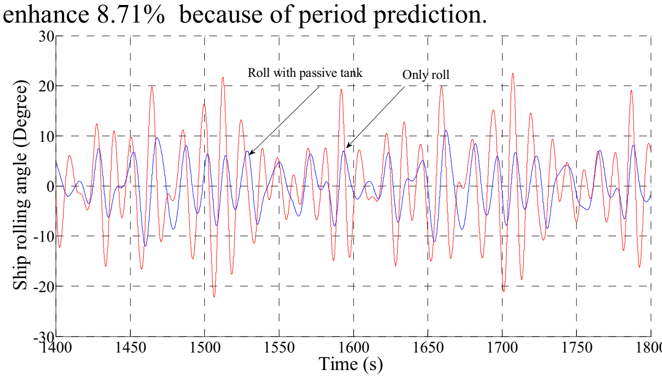


Fig.6 Ship rolling and coupled with passive anti-rolling tank

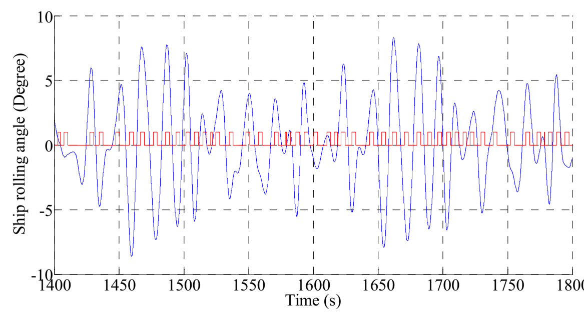


Fig.7 Constant closing closing time span used by passive controlled tank

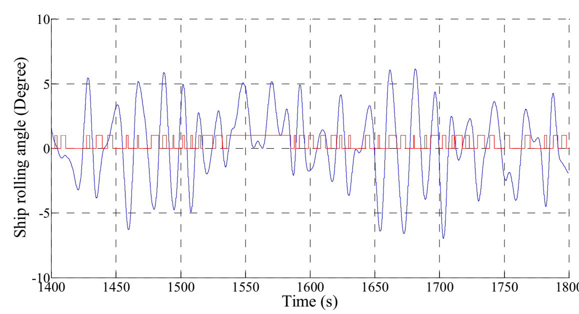


Fig. 8 Predictive control used by passive controlled tank

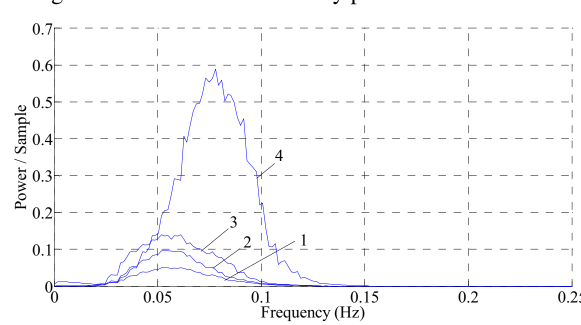


Fig. 9 PSD of ship rolling angle

### *D. Estimation Result of Ship Rolling Angle PSD without anti-rolling tank*

The PSD of ship rolling angle while anti-rolling tank is not running is obtained using (23), shown as Fig. 9.

The figure shows the PSD of ship rolling angle without anti-rolling tank which is obtained directly by spectra analysis of ship rolling angle data generated by the ship rolling model without anti-rolling tank. This figure shows that the PSD calculated by equation (23) well matches the actual PSD of ship rolling angle if anti-rolling tank is not running.

The curve 4 is only ship roll, the curve 3 is ship rolling with passive anti-rolling tank, the curve and curve 1 is ship rolling with passive controlled tank. The closing time span of curve 2 is constant and the closing time span of curve 1 is obtained through period predictive.

## V. CONCLUSION

Roll period prediction can improve the stabilizing effect dramatically, especially in irregular wave.

In Practice Applications, training and control should be synchronizing in time, the influences of different ship load , ship speed ,ship heading and so on could be considered.

Simulation result illustrates period prediction make proper closing time span according to actual ship roll motion. Compared with fixed closing time span stabilizing effect can enhance 10%-20% ,but for accurate control weights of neural networks should be trained through making use of abundance data and the algorithm of wavelet neural network also has room for improvement. Later research different influence of disturbed factor will be considered for example wind different encounter angle .etc Analysis results show that spectra analysis is an efficient way to accurately estimate the stabilizing effect of anti-rolling tank.

## REFERENCES


[1] Beck, R.F., Cummins, W.E., Dalzell, J.F., Mandel, P., Webster, W.C. “Motion in waves,” Principles of Naval Architecture, vol. 3, pp. 1–187, 1989.

[2] Lloyd, A.R., Seakeeping: Ship Behaviour in Rough Weather:ARJM Lloyd, 1998.

[3] Nayfeh, A.H., Mook, D.T., 1995. Nonlinear Oscillations. John Wiley & Sons, Inc..

[4] Theresa Kleefsman. Numerical Simulation of Ship Motion Stabilization by an Activated U-tube Anti-Roll Tank [D]. Groningen: Department of Mathematics, University of Groningen, 2000.

[5] Hongzhang Jin and XL Yao (2001). "The Principles of Ship Control", pub. by Harbin Engineering University Press.

[6] Faltinsen, O.M., Timokha, A.N.. “Sloshing,” Cambridge University Press, 2009.

[7] Cihua Liu (2008). "Stochastic Processes 4th Ed.". pub. by Huazhong University of Science and Technology Press.

[8] Dingyu Xue (2000). "Design and Analysis of Feedback Control System", pub. by Tsinghua University Press.

[9] E.F.G. Van Daalen. Anti-roll Tank Simulations With A Volume Of Fluid(VOF) Based Navier-Stokes Solver.[]. The National Academy of Science(2001)457-473.

[10] Zhong, Z, Falzarano, J., and Fithen, R. A Numerical Study Of U-Tube Passive Anti-Rolling Tanks [R].1998.

[11] Stigter C. The performance of U-tanks as a passive anti-rolling device. International shipbuilding progress. Vol. 13, No. 114, 1922(8). pp249~275