A STUDY FOR THE SHIP SAFETY IN THE LARGE AMPLITUDE ROLLING

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ABSTRACT

In recent years, an accident of a container ship caused by the large amplitude rolling with parametric roll resonance has often occurred. From this background, the argument to revise the Intact Stability Code (IS Code) at the International Maritime Organization (IMO) has been made. This is very important in the stage of an initial design of a ship. On the other hand, it is very important for a ship operator to deal with the real time information of the state of the ship well.

A new assessment method of the ship safety in the large amplitude rolling by using the knowledge of Time Series Analysis is proposed in this study. Time varying coefficient auto regressive (TVAR) model is applied as the time series model. The model is useful to understand the change of the characteristic of the time series. In general, the model is used to estimate the instantaneous power spectrum based on the TVAR coefficient. Incidentally, the stability of stationary time series is judged by the roots of the characteristic equation with respect to the auto regressive (AR) operator. In this case, a system where the characteristic roots exist out of the unit circle is stable. This fact is extended into the time varying process. That is, the stability of time varying time series is judged by the roots of the characteristic equation of the TVAR coefficient. In this case, the TVAR coefficient can be successively estimated by using the algorithm of Kalman Filter, and the characteristic roots can be calculated by Newton-Raphson method. The goodness of the model is evaluated by using AIC (Akaike Information Criterion) with respect to the model. As the results, it is possible to judge the stability of time varying time series at real time.

The validation of the proposed procedure is performed by the analysis for the data of the experimental results which the parametric roll resonance was observed. We have confirmed that the large amplitude rolling occur when the characteristic roots move into the unit circle. Therefore, we can conclude that the proposed procedure is powerful tool for the judgment of the ship safety.

Keywords: Ship Safety, TVAR Modeling Procedure, Characteristic Roots

1. INTRODUCTION

It is very important that an intact stability is guaranteed at the time of the initial design of a ship. In 1998, in the North Pacific, a post-Panamax container ship occurred to heavy parametric roll resonance in head seas and suffered with extensive loss and damage to onboard containers. This accident forced us to revise the Intact Stability Code (IS Code) at the International Maritime Organization (IMO), and the various verification was carried out at IMO. In the SCAPE committee at the Japan Society of Naval Architects and Ocean Engineers in Japan, parametric roll resonance was verified by various approaches such as model test, numerical test, CFD, time series analysis, and so on, and intact stability criteria based on these outcomes were proposed by Japanese government (Umeda, N. 2007).

On the other hand, in the view of a ship operation, the viewpoint of prediction is important for the ship operator to keep the safety of ship in the large amplitude rolling caused by parametric roll resonance. That is, the ship operator has to get information on safety or danger with respect to the state of ship in from the present to the future. As a method to get their information, time series analysis with respect to the measured data of ship is very effective. In general the parametric roll resonance as a dynamics phenomenon is described by a non-linear motion equation, but in focus of the measured data the time series is possible to be considered as non-stationary time series with abruptly changing covariance structure. In this case, a methodology of time series analysis is effective to use Time Varying Auto Regressive (TVAR) modeling procedure and Time Varying Vector Auto Regressive (TVVAR) modeling procedure. From this viewpoint Iseki, T. (2007) implemented Time-Frequency Analysis based on TVAR and TVVAR modeling procedure, and devised the estimated instantaneous power spectra and higher order spectra, and concluded that their
procedure was the powerful tool of non-stationary time series analysis. Especially, the change of peak frequency in instantaneous power spectra was well expressed by their procedure. It is well known that a spectrum structure of stationary auto regressive process is characterized by characteristic roots of the Auto Regressive (AR) operator (Box, J.E.P. and Jenkins, G.M. 1970). When all characteristic roots are in the outside of the unit circle, the system is stable. The application of this fact to TVAR process it can suppose that it is characterized by characteristic roots of the TVAR operator. Therefore, when all characteristic roots in TVAR process are in the outside of the unit circle, we suppose that it is possible to judge that the time varying system is stable. The case where all characteristic roots are always in the outside of the unit circle is defined as stability, and except is defined as unstable.

In this study, unlike the approach (i.e. instantaneous power spectrum analysis) of Iseki, T. (2007) about TVAR process, we focused on characteristic roots of TVAR process and attempted to judge the ship safety in large amplitude rolling from the measured ship motions data based on the estimates of characteristic roots with time varying. And, we also attempted to implement instantaneous power spectrum analysis in order to check whether a phenomenon is parametric roll resonance as well as Iseki, T. (2007). We examined the characteristic of proposed procedure by using the data of model experiment conducted by Hashimoto, et al. (2005). And we compared the results of proposed procedure with the results of ordinary AR modeling procedure. This paper reports on some acquired knowledge.

2. AUTO REGRESSIVE MODELING PROCEDURE

2.1 AR model

According to Box, J.E.P. and Jenkins, G.M. (1970), assume that the observed discrete data \( y(1), \ldots, y(N) \) is stationary process, it is described by the following AR expression:

\[
y(n) = \sum_{j=1}^{m} a_j \cdot y(n-j) + w(n), \tag{1}\]

where \( a_j \ (j=1, \ldots, m) \) is an AR coefficients of a lag \( j \), \( m \) is the order of the model and \( w(n) \) is assumed to be a Gaussian zero-mean uncorrelated sequence with unknown variance \( \sigma^2 \).

In this case, when the roots (i.e. \( z(=r \cdot \exp(i\theta)) \)) of characteristic equation with respect to AR operator expressed by the following Eq. (2) are in the outside of the unit circle, the system is stationary process.

\[
a(B) = 1 - \sum_{j=1}^{m} a_j \cdot B^j = 0. \tag{2}\]

In Eq. (2), \( B \) is a backward operator defined by \( B \cdot y(n) = y(n-1) \).

In this case, the characteristic roots in Eq. (2) can be calculated by Newton-Raphson method (Akaike, H., et al. 1979)).

2.2 ESTIMATION OF AR COEFFICIENTS

The autocovariance function \( \hat{C}_j (j=0, \ldots, m) \) of m-th order AR model expressed by Eq. (1) satisfy the following Yule-Walker equation (Box, J.E.P. and Jenkins, G.M. 1970):

\[
\begin{align*}
C_0 &= \sum_{j=1}^{m} a_j \cdot C_j + \sigma^2 \tag{3} \\
\hat{C}_j &= \hat{C}_0 \cdot \hat{C}_j 
\end{align*}
\]

In case of the discrete data \( y(1), \ldots, y(N) \) is obtained, we can calculate the sample autocovariance function \( \hat{C}_j (j=0, \ldots, m) \), and we substitute the calculations for Eq. (4) and can obtain the following equation which makes AR coefficients \( a_j \ (j=1, \ldots, m) \) an unknown number:

\[
\begin{bmatrix}
\hat{C}_0 \\
\hat{C}_1 \\
\vdots \\
\hat{C}_{m-1}
\end{bmatrix}
\begin{bmatrix}
\begin{bmatrix}
\hat{a}_1 \\
\hat{a}_2 \\
\vdots \\
\hat{a}_m
\end{bmatrix}
\end{bmatrix}
= 
\begin{bmatrix}
\hat{C}_1 \\
\hat{C}_2 \\
\vdots \\
\hat{C}_m
\end{bmatrix}
\tag{5}
\]

As the solutions of Eq. (5) we can obtain the estimates \( \hat{a}_j \ (j=1, \ldots, m) \) of AR coefficients. And by using Eq. (3), the estimates \( \hat{\sigma}^2 \) of variance \( \sigma^2 \) is given by

\[
\hat{\sigma}^2 = \hat{C}_0 - \sum_{j=1}^{m} \hat{a}_j \cdot \hat{C}_j. \tag{6}
\]

The unknown coefficients \( a_j \ (j=1, \ldots, m) \) can be efficiently calculated by the Levinson-Durbin method. And
the optimum value of the model order \( m \) can be evaluated by the minimizing the following Akaike Information Criterion (AIC) (Akaike, H. 1973):

\[
AIC(m) = N \log 2\pi \hat{\sigma}^2 + 1) + \frac{2m}{2N} - \frac{1}{2} \]

(7)

Generally, this model selection method is called MAICE (Minimum AIC Estimation) method.

### 2.3 Estimation of power spectrum

In order to estimate the power spectrum of an AR process, we apply the following relation of the power spectrum \( P_y(f) \) and \( P_w(f) \) of a stationary stochastic process \( y(n) \) and \( w(n) \) with an input-output relation of linear system:

\[
P_y(f) = |A(f)|^2 \cdot P_w(f),
\]

(8)

where \( A(f) \) is the frequency response function.

In this case, the AR process is the response of linear system which considers white noise as an input, so \( A(f) \) is given by

\[
A(f) = \frac{1}{1 - \sum_{j=1}^{N} a_j \cdot \exp(-i2\pi f j)},
\]

(9)

where \( i \) is the imaginary unit. And the power spectrum \( P_w(f) \) of white noise \( w(n) \) is given by

\[
P_w(f) = \sigma^2 \left( -1/2 \leq f \leq 1/2 \right).
\]

(10)

Therefore based on Eq. (8), Eq. (9) and Eq. (10) the power spectrum \( P_y(f) \) of the AR process is given by

\[
P_y(f) = \frac{\sigma^2}{1 - \sum_{j=1}^{N} a_j \cdot \exp(-i2\pi f j)}}.
\]

(11)

Note that the Fourier transformation of \( A(f) \) can be efficiently calculated by the Goertzel method (Hamming, R. W. 1962).

### 3. Time Varying Auto Regressive Modeling Procedure

#### 3.1 TVAR model

According to Kitagawa, G, and Gersh, W. (1996), the generic TVAR model of the observed discrete data \( y(1), \ldots, y(N) \) is given by

\[
y(n) = \sum_{j=1}^{m} a_j(n) \cdot y(n-j) + w(n), \tag{12}
\]

where \( a_j(n) \) \( (j = 1, \ldots, m) \) are a TVAR coefficients and are assumed to change “gradually” with time and \( w(n) \) is assumed to be a normally distributed white noise sequence with perhaps an instantaneous variance \( \sigma^2(w) \).

In order to apply the concept of an AR modeling procedure to a TVAR modeling procedure, suppose that the characteristic equation with respect to TVAR operator

\[
a_j(B) \cdot 1 - \sum_{j=1}^{m} a_j(n) \cdot B^j = 0, \tag{13}
\]

where \( B \) is a backward operator defined by \( B \cdot y(n) = y(n-1) \).

Then, in case of the roots \( i.e. z(n) = r(n) \cdot \exp[i\theta(n)] \) of characteristic equation with respect to TVAR operator expressed by the following Eq. (13) are in the outside of the unit circle, we consider that the system is stable and safety as well as a ordinary AR process. And, in this case, the characteristic roots in Eq. (13) can be calculated by Newton-Raphson method (Hamming, R. W. 1962) as well as the AR modeling procedure.

#### 3.2 ESTIMATION OF TVAR COEFFICIENTS

Since these are \( m \times N \) AR coefficients in Eq. (12), an attempt to fit the parameters by the least squares method or any other ordinary means to the \( N \) observations \( y(1), \ldots, y(N) \), will yield poor parameter estimates. To solve this difficulty, it is assumed that the unknown TVAR coefficients are random variables and a Gaussian distribution. That is, it is introduced that the following stochastically perturbed difference equation constraint model

\[
\Delta \hat{a}_j(n) = v_j(n), \tag{14}
\]

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where \(v_j(n) = (v_1(n), \ldots, v_m(n))^T\) denotes the \(m\)-th order Gaussian white noise sequence with mean zero and covariance matrix \(Q\), which is supposed here to be a diagonal matrix with diagonal values \(\sigma^2\). \(\Delta\) is the difference operator at time stamp \(n\) and defined by
\[
\Delta a_n = a(n) - a(n-1),
\]
and \(k\) is the order of difference operator and is 1 or 2 in this study.

In order to estimate efficiently unknown TV AR coefficients, the following state space representation is introduced regarding Eq. (12) and (15) as a system model and an observation model.
\[
x(n) = Fx(n-1) + Gv(n)
\]
\[
y(n) = H(n)x(n) + \varepsilon(n)
\]
In Eq. (16) and (17), \(F\) and \(G\) is respectively the \(km \times km\) and the \(km \times m\) matrix, \(H(n)\) and \(x(n)\) is the \(km\) vector, and these notations can be written as follows:
\[
F = \begin{bmatrix} F^{(k)} & \cdots & F^{(i)} \\ \vdots & \ddots & \vdots \\ F^{(i)} & \cdots & F^{(1)} \end{bmatrix} = I_m \otimes F^{(i)}, \quad F^{(i)} = \begin{bmatrix} 2 & -1 \\ 1 & 0 \end{bmatrix},
\]
\[
G = \begin{bmatrix} G^{(k)} & \cdots & G^{(i)} \\ \vdots & \ddots & \vdots \\ G^{(i)} & \cdots & G^{(1)} \end{bmatrix} = I_m \otimes G^{(i)}, \quad G^{(i)} = \begin{bmatrix} 1 \\ 0 \end{bmatrix},
\]
\[
H(n) = (y(n-1), \ldots, y(n-m)) \otimes H^{(i)}(n), \quad H^{(i)}(n) = \begin{bmatrix} 1 & 0 \end{bmatrix},
\]
\[
x(n) = \begin{bmatrix} (a_1(n), \ldots, a_m(n))^T \\ (a_1(n), a_1(n-1), \ldots, a_m(n), a_{m1}(n-1))^T \end{bmatrix}, \quad k = 1
\]
\[
Q = \begin{bmatrix} \sigma^2 & \cdots & \sigma^2 \\ \vdots & \ddots & \vdots \\ \sigma^2 & \cdots & \sigma^2 \end{bmatrix},
\]
where \(I_m\) is the \(m \times m\) identity matrix, notation \(T\) denotes the transpose of a vector and \(\otimes\) denotes the Kronecker product.

It is well known that Kalman filter is effective in the state estimation of the linear state space representation expressed by Eq. (16) and (17). The formulas are as follows:

**Prediction [Time Update]**
\[
x_{\phi,1} = F_en_{\phi,1-1},
\]
\[
V_{\phi,1} = F_{\phi,1-1}F_{\phi,1-1}^T + GQ_{\phi,1-1}G_{\phi,1-1}^T.
\]
We assume that the initial conditions \(x_{\phi,0}\) and \(V_{\phi,0}\) are given.

**Filter [Measurement Update]**
\[
K_s = V_{\phi,1-1}H_{\phi,1-1}^T(H_{\phi,1-1}V_{\phi,1-1}H_{\phi,1-1}^T + R_s)^{-1},
\]
\[
x_{\phi} = x_{\phi,1-1} + K_s(y(n) - H_sx_{\phi,1-1}),
\]
\[
V_{\phi,1} = (I - K_sH_s)V_{\phi,1-1}.
\]
Using the outputs of the Kalman filter, the smoothed state \(x_s\) given the entire set of observations \(y(N)\) is given by the fixed interval smoother:
\[
A_s = V_{\phi,1}F_s^T V_{\phi,1}^{-1},
\]
\[
x_{\phi} = x_{\phi,1} + A_s(x_{\phi,1} - x_{\phi,1-1}),
\]
\[
V_{\phi,1} = V_{\phi,1} + A_sV_{\phi,1} A_s^T.
\]
In this case, suppose that the variance \(\sigma^2(n)\) of observation noise \(\varepsilon(n)\) is constant it can be made the reduction of the dimension of parameters, and the state estimation can be efficiently implemented. And the optimum value of the model order \(m\) can be obtained by the minimizing the following Akaike Information Criterion (AIC) (Kitagawa, G. and Gersch, W. 1996):
\[
AIC(m) = N \log 2\pi\sigma^2 + \sum_{n=1}^{N} \log \tilde{d}_{\phi,1-1} + 2
\]

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where $\tilde{d}_{n-1}$ is the covariance matrix of the conditional distribution of $y(n)$ given the distribution at time stamp $n-1$.

### 3.3 Estimation of Instantaneous Power Spectrum

After fitting the TVAR model to the time series and evaluation of TVAR coefficients, the instantaneous power spectrum can be estimated by the similar concept to the ordinary AR modeling procedure. That is, definition of the instantaneous power spectrum $P_s(f)$ at time stamp $n$ can be written by

$$
P_s(f) = \frac{\sigma^2}{1 - \sum_{j=1}^{\infty} a_j \cdot \exp[-i2\pi f j]}, \quad \frac{1}{2} \leq f \leq \frac{1}{2}.
$$

(22)

Note that the variance $\sigma^2$ in Eq. (22) which evaluated by using MAICE method is different notation in Eq. (21).

### 4. Analysis and Discussion

In this section, we examined the characteristic of proposed procedure by using the data of free running model experiments conducted by Hashimoto, H. et al. (2005) and shown the effectiveness of the proposed procedure as a new assessment method of ship safety from comparison with the AR modeling procedure.

#### Table 1: Principal perpendiculars of the post-Panamax container ship

<table>
<thead>
<tr>
<th>Items</th>
<th>Ship</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between perpendiculars: L</td>
<td>238.8m</td>
<td>2.838m</td>
</tr>
<tr>
<td>Breadth: B</td>
<td>42.8m</td>
<td>0.428m</td>
</tr>
<tr>
<td>Depth: D</td>
<td>24.0m</td>
<td>0.24m</td>
</tr>
<tr>
<td>Draft at F.P.: $T_f$</td>
<td>14.0m</td>
<td>0.14m</td>
</tr>
<tr>
<td>Mean draft: $T$</td>
<td>14.0m</td>
<td>0.14m</td>
</tr>
<tr>
<td>Draft at A.P.: $T_a$</td>
<td>14.0m</td>
<td>0.14m</td>
</tr>
<tr>
<td>Block coefficient: $C_b$</td>
<td>0.630</td>
<td>0.630</td>
</tr>
<tr>
<td>Pitch radius of gyration: $K_{yy}/L$</td>
<td>0.239</td>
<td>0.258</td>
</tr>
<tr>
<td>Longitudinal position of center of</td>
<td>5.74m</td>
<td>0.00574m</td>
</tr>
<tr>
<td>Metacentric height: GM</td>
<td>1.08m</td>
<td>0.0106m</td>
</tr>
<tr>
<td>Natural roll period: $T_{\omega}$</td>
<td>30.3 s</td>
<td>3.20 s</td>
</tr>
<tr>
<td>Natural pitch period: $T_{\phi}$</td>
<td>0.86</td>
<td></td>
</tr>
</tbody>
</table>

Source: Hashimoto, H. et al. 2005

#### 4.1 Results of experiment in regular waves

We analyzed the data which parametric rolling was observed and which parametric rolling was not observed in the experiment in regular waves. Fig. 1 shows the analyzed results of the data which parametric rolling is observed. And Fig. 2 shows the analyzed results of the data which parametric rolling is not observed. Viewing downward, these figures respectively show the measured time series, the estimated power spectrum and the characteristic roots based on the AR modeling procedure, the estimated instantaneous power spectrum based on the TVAR modeling procedure and the maximum values of the absolute values of the characteristic roots based on the TVAR modeling procedure. Note that results of characteristic roots are shown by the inverse number to simplify the expression for figures, and indicate the maximum values of the absolute values at each time stamp and so in case of characteristic roots are in the inside of the unit circle is stable.

In Fig. 1 (a) the characteristic of measured time series is different covariance at from 0 second to about 30 second and after about 30 second. In Fig. 1 (b) results of the AR modeling procedure, it can be seen that the peak of power spectrum exists on the natural frequency 0.32(Hz) and the 3 times frequency 0.96(Hz) of natural frequency and characteristic roots exist on about the unit circle. Results show the characteristic of frequency domain with respect to parametric roll resonance well. However, it is noted that information with respect to changing characteristics of time series can not obtain in this procedure. Therefore, our purpose which is the real time judgments of the ship safety is not satisfy. On the other hand, as is apparent in Fig. 1 (c) and (d), we can conform that results of the proposed procedure i.e. the TVAR modeling procedure extract information with respect to changing characteristics of time series well. That is, it can be seen that in Fig. 1 (c) the peak of power spectrum exists on the natural frequency 0.32(Hz) and the 3 times frequency 0.96(Hz) of natural frequency, the power of spectrum is increasing with increase of the covariance of measured time series in Fig. 1 (a) and in Fig. 1 (d) the maximum values of characteristic roots are abruptly moving to
outside of the unit circle after 25 second at which the covariance of measured time series increases and exist on about the unit circle after 50 second because the measured time series becomes the stable motion in the large amplitude after 50 second.

In Fig. 2 (a) the characteristic of measured time series is that in spite of the fact that the covariance is about constant, the time series is nonlinear. In Fig. 2 (b) results of the AR modeling procedure, it can be seen that of although the power is weak, many peaks exist, and characteristic roots by which the spectrum structure are characterized exist on about the unit circle. Note that the estimates based on the AR modeling procedure with respect to the nonlinear time series is not effective in general. On the other hand, we can conform that in Fig. 2(c) the peak of power spectrum is changing from the natural frequency 0.32(Hz) to the 2 times frequency 0.64(Hz) of natural frequency with time and in Fig. 2 (d) the maximum values of characteristic roots are moving to outside of the unit circle around 10 and 50 second at which the covariance of measured time series somewhat becomes large. In this case, although as a result motion has not grown to be large amplitude, we can consider that the large amplitude rolling occurs when some action is added to the system because the characteristic roots are moving to outside of the unit circle. It means that the unstable state is inherent in the inside of the system.

4.2 Results of experiment in irregular waves

We analyzed the data which parametric rolling was observed and which parametric rolling was not observed in the experiment in irregular waves. In this case, the judgment of parametric roll resonance is done by the TVAR modeling procedure. Fig. 3 shows the analyzed results of the data which parametric rolling is observed. And Fig. 4 shows the analyzed results of the data which parametric rolling is not observed. Viewing downward, these figures respectively show the measured time series, the estimated power spectrum and characteristic roots based on the AR modeling procedure, the estimated instantaneous power spectrum based on the TVAR modeling procedure and the maximum values of the absolute values of the characteristic roots based on the TVAR modeling procedure as well as Fig. 1 and Fig.2.

In Fig. 3 (a) the characteristic of measured time series, unlike the time series of regular waves, is to change the amplitude and the phase with time. In Fig. 3 (b) results of the AR modeling procedure, it can be seen that the peak of power spectrum exists on the natural frequency 0.32(Hz) and characteristic roots exist in the unit circle. From results, parametric roll resonance can not be judged clearly. On the other hand, as is apparent in Fig. 3 (c), we can clearly judge that the phenomenon is parametric roll resonance by using the TVAR modeling procedure because the peak of instantaneous power spectrum exist on the 3 times frequency 0.96(Hz) of natural frequency. And we can conform that in Fig. 3 (d) the maximum values of characteristic roots are moving to outside of the unit circle around from 50 to 80 second and from 100 to 160 second at which the covariance of measured time series becomes large. In this case, it is considered that the stable state and the unstable state are intermingled in the system. By the above consideration, we need to focus the experimental conditions, that is, the course keeping of ship in the free running model experiment is implemented by PID control. So, according to PARK, J. S. et al. (2000), ship's autopilots which apply AR modeling procedure can reduce the roll motion because the rolling is considered as the manipulated value. These systems control the controlled variable i.e. the rudder as there are the characteristic roots out the unit circle, and as the result the ship motions (especially Yawing and Rolling) are considerably reduced. Therefore, it is considered that autopilots of this type may be able to prevent the large amplitude rolling.

From Fig. 4 (a) it can be seen that the maximum value of measured time series is over 10 degrees to one side, and so it can be considered that this data is the large amplitude rolling. Results of the TVAR modeling procedure in Fig. 4 (c) show good agreement with results of the AR modeling procedure in Fig. 4 (b). Therefore, in this case, we can judge that the phenomenon is not parametric roll resonance. Thus, note that the large amplitude rolling is not necessarily caused by parametric roll resonance.

5. CONCLUSION

In this study, we focused on characteristic roots of TVAR process and attempted to judge the ship safety in large amplitude rolling from the measured ship motions data based on the estimates of characteristic roots with time varying. We examined the characteristic of proposed procedure by using the data of free running model experiments conducted by Hashimoto, H. et al. (2005). In addition we also attempted to implement instantaneous power spectrum analysis in order to check whether a phenomenon is parametric roll resonance. The results may be summarized as follows:

(a) TVAR modeling procedure is effective in order to check whether a phenomenon is parametric roll resonance. That is, it is possible to judge parametric roll resonance by examination with respect to the peak frequency of estimated instantaneous power spectrum.
(b) In experiment in regular waves, in case of parametric rolling was observed, characteristic roots move to unstable domain when the time series is abruptly growing.

c) In experiment in regular waves, in case of parametric rolling was not observed, although the time series is not growing in a large amplitude rolling, characteristic roots move to unstable domain and it can be considered that the unstable state is inherent in the inside of the system.

d) In experiment in irregular waves, in case judged as parametric rolling, characteristic roots move to unstable domain when the time series is growing.

e) The large amplitude rolling is not necessarily caused by parametric roll resonance.

(f) TVAR modeling procedure is effective to judge the ship safety in the large amplitude rolling as discussed above. Therefore, we conclude that the proposed procedure is powerful tool for the judgment of the ship safety.

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7. REFERENCES


Fig. 1 Results in parametric roll resonance (Regular waves)

(a) Measured time series
(b) Power spectrum and Characteristic roots
(c) Instantaneous power spectrum
(d) Maximum values of the absolute values of the characteristic roots

Fig. 2 Results in no parametric roll resonance (Regular waves)

(a) Measured time series
(b) Power spectrum and Characteristic roots
(c) Instantaneous power spectrum

(d) Maximum values of the absolute values of the characteristic roots

Fig. 3 Results in parametric roll resonance
(Irregular waves)

(a) Measured time series

(b) Power spectrum and Characteristic roots

(d) Maximum values of the absolute values of the characteristic roots

Fig. 4 Results in no parametric roll resonance
(Irregular waves)