Boundary Approximations, Effect of Forward Speed and Implementation of Genetic Algorithm in Parametric Rolling

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***Abstract*— This paper is the progressive research of the paper [1] titled "Stability of Offshore Barge Subjected to Parametric Rolling in Waves", and it deals with the boundary approximations for the instability zone of an offshore barge when subjected to parametric rolling in waves. The severity of the parametric rolling for the offshore barge is calculated by the mathematical modeling for solution of Mathieu's Differential equation using Matlab programming The frequencies prone to parametric roll resonance were identified and their threshold damping coefficient was then calculated. The susceptibility of parametric rolling including forward speed of ship was evaluated. Genetic Algorithm was implemented to find the most optimum angle of roll to enable us to determine the ratio of TCB to VCB for predefined upper limit of rolling**

Keywords*— *Parametric Rolling, Rolling, Hydrodynamic, Roll Resonance, Genetic Algorithm, Barge, Longitudinal Waves, Strip Theory, Forward Speed.

I. INTRODUCTION

Parametric roll may be defined as the spontaneous rolling motion of the ship moving in head or following seas that come about as a result of the dynamic instability of motion. The development of the parametric roll occurs under the conditions that the encounter angular frequency is approximately twice the roll angular frequency, the wavelength is equal to the ship length and the roll damping is insufficient to dissipate the parametric roll energy. Due to the unexpected nature of the motion as compared with synchronous roll in following or beam seas on smaller and finer ships, parametric roll is quite dangerous and unpredictable in real seas when multiple seas and swells coming from different directions. In head waves roll motion caused by direct wave excitation are not possible. Nevertheless, under certain conditions of encounter period, a rolling can be excited in head seas. The roll motion, once started, may grow to large amplitude limited by roll damping and, in extreme conditions, may result in danger to the ship or its contents. This phenomenon is referred to as "auto parametrically excited motion" which is usually shortened to "parametric motion".

The objective of the research paper is to predict the region of instability and subsequently approximation is made to find the frequencies for principal parametric roll resonance. Also, the effect of parametric rolling is studied when forward speed of the ship is considered.

A. Mathieu's Equation

The variation of GM with time may result in parametric resonance (Belenky, et al., 2004). To check whether this is possible, we transform the roll equation of motion to the form of Mathieu's equation in order to use the Ince-Strutt diagram to examine the properties of solutions. The Mathieu's equation [France, et al., 2001] can also be written as:

$$\frac{d^2\emptyset}{d\tau^2} + (\delta + \varepsilon\cos\tau)\emptyset = 0 \qquad (1)$$

Where,

$$\delta = \frac{{\omega_n}^2}{\omega^2}, \varepsilon = C\frac{{\omega_n}^2}{\omega^2} \qquad (2)$$

C is the fractional change of GM due to waves.

The above equation recognized as Mathieu Equation (France, et al., 2001) is seen to be a linear differential equation with a time varying restoring coefficient. The solutions of this equation has been studied extensively, are found to exhibit unstable behaviour at certain values of the frequency parameterδ. The shaded regions are stable corresponding to the (δ, ε) pairs for which parametric motion cannot exist. In an unstable region, an arbitrarily small disturbance will trigger an oscillatory motion that tends to increase indefinitely with time.

II. RESULTS

A. Modeling and Validation

Initially an offshore barge was modeled in ANSYS AQWA (Fig. 1) and the response [1] in the six degree of freedom was validated with a Journal Paper (Seung-Chul Lee et al, Analysis of motion response of barges in regular waves, 2012).

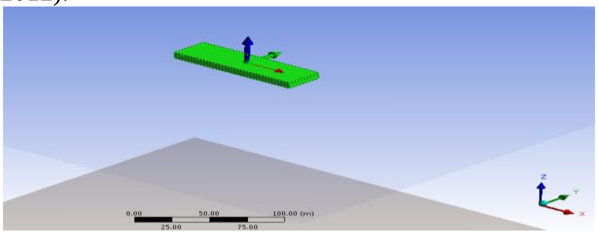

Fig 1. Barge modeled in ANSYS AQWA

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B. Solution of Mathieu's Differential Equation

Four cases [1] were studied to find out the stability using the graphical Ince-Strutt diagram. Table I and Table II represents stability of ship for different relationship between length of the wave and length of the ship respectively.

TABLE I. STABILITY WHEN LENGTH OF WAVE IS FOUR TIMES LENGTH OF SHIP

	$L_w = 4L_{ship}$, $w_n = w$	$L_w = 4L_{ship}$, $w_n = 2w$
C (m)	1.0303	1.0303
d	0.94367	3.94
v	0.97226	4.06
Remarks	Stable	Stable

TABLE II. STABILITY WHEN LENGTH OF WAVE IS TWICE LENGTH OF SHIP

	$L_w = 2L_{ship}$, $w_n = w$	$L_w = 2L_{ship}$, $w_n = 2w$
C (m)	1.0426	1.0426
d	0.94367	4.515
v	0.9839	4.7075
Remarks	Stable	Un-Stable

For (d,v) pairs calculated for four different cases, it was plotted graphically on the Ince-Strutt diagram (Fig. 14.) and the region of instability was indicated. It can be seen that while for different (d,v) considered, they either lie in the shaded region or on the verge of shaded and in-shaded region except for one pair that was seen to lie outside the shaded region.

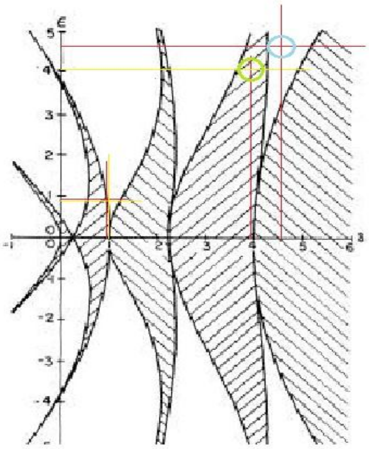

Fig 2. Ince-Strutt diagram

Usually parametric roll is profound when the natural roll frequency is twice the encountering wave frequency but in our analysis we got it when the natural roll frequency was 2.125 times the encountering wave frequency, which was almost near to the condition for parametric roll. This region of instability was further verified mathematically by substituting these values in the Mathieu's differential equation and solving them.

The Mathieu differential equation was finally solved in Matlab using ODE45 inbuilt function and following were the results that were obtained. The Mathieu's equation for the region of stability and instability were obtained from Table IX and was solved subsequently (Fig.15 and Fig. 16)

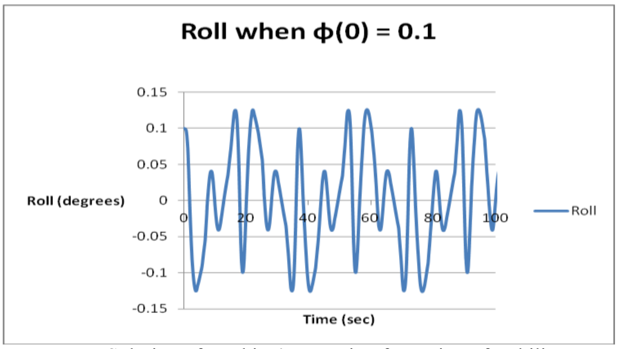

Fig 3. Solution of Mathieu's Equation for region of stability

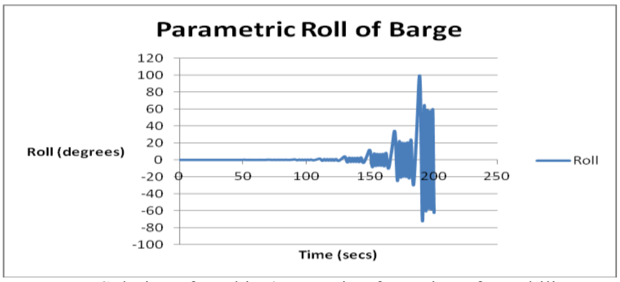

Fig 4. Solution of Mathieu's Equation for region of Instability

C. Boundary Approximations for Region of Instability

As the Ince-Strutt stability curve is plotted for different (δ, ϵ) pairs, an approximation is made to find out the frequencies for the principal parametric resonance. Both the linear and higher approximation was considered and the frequencies corresponding to parametric resonance were identified from the instability zone of the plot. Two cases were studied wherein the Length of the Wave is twice the length of the ship (case 1) and length of the wave is four times the length of the ship (case 2).

$$\delta_{b1} = \frac{1}{4} - \frac{\epsilon}{2} \quad (3)$$

$$\delta_{b2} = \frac{1}{4} + \frac{\epsilon}{2} \quad (4)$$

$$\delta_{b1} = \frac{1}{4} - \frac{\epsilon}{2} - \frac{\epsilon^2}{8} + \frac{\epsilon^3}{32} - \frac{1}{3} \cdot \frac{\epsilon^4}{128} \quad (5)$$

$$\delta_{b2} = \frac{1}{4} + \frac{\epsilon}{2} - \frac{\epsilon^2}{8} - \frac{\epsilon^3}{32} - \frac{1}{3} \cdot \frac{\epsilon^4}{128} \quad (6)$$

Equations (3) to (6) are linear and higher order approximations for the instability zone.

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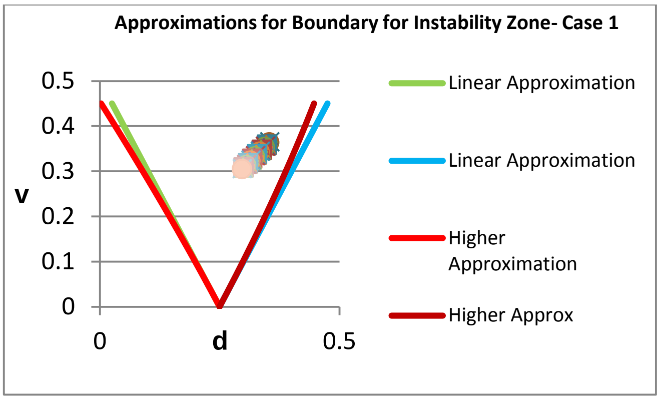

Fig 5. Instability Zone for Case 1

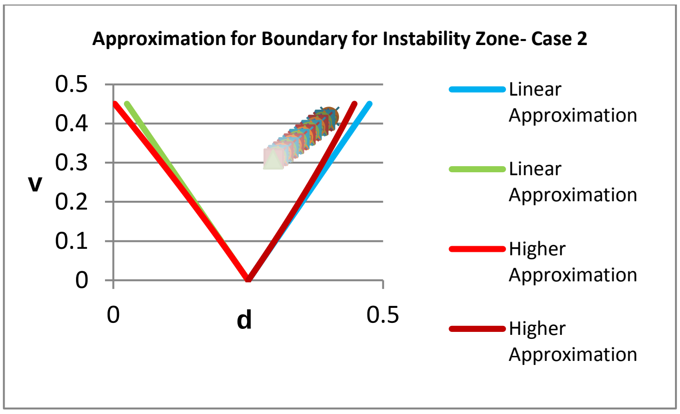

Fig 6. Instability Zone for Case 2

The frequencies from range 0.25 rad/sec to 1.25 rad/sec with a step increment of 0.002 were considered for the approximation. Figure 25 represents the instability zone for the condition when the length of the wave is twice the length of the ship, and the frequency varying from the range 1.012 rad/sec to 1.25 rad/sec were found to cause parametric resonance. Figure 26 represents the instability zone while the condition of the length of the wave is four times the length of the ship. It was observed that frequencies varying from 1.076 rad/sec to 1.25 rad/sec were susceptible to parametric resonance.

As the roll damping plays an important role in the development of parametric roll resonance, it can be said that if the loss of energy per cycle caused by roll damping is more than the gain in energy caused by the changing stability in longitudinal seas, then the parametric roll resonance will not develop and vice versa. There exists a threshold value which every frequency possesses. For all the frequencies which were lying in the instability zone of the first approximation, the threshold coefficient value was calculated and they were found to be positive definite.

D. Susceptibility of Parametric rolling Including Forward Speed

The offshore barge was analysed for the susceptibility to parametric rolling when it was subjected to a forward speed. The study of forward speed of the barge also illustrated the possibility of parametric rolling. The major factor in the study of parametric rolling along with forward speed is the encountering wave frequency. As mentioned before, one of the criteria for the occurrence of parametric rolling is when the encountering wave frequency is twice the natural roll frequency while the length of the wave is equal to the length of the ship.

Considering the barge forward speed as 10 knots and while the length of the wave is equal to the length of the ship.

$$\omega_w = \sqrt{\frac{2\pi g}{L_w}} \tag{8}$$

$$\omega_e = \omega_w + \frac{\omega_w^2 V}{g} \tag{9}$$

The ship speed for condition of parametric resonance is given by

$$V_{pr} = \frac{g(2\omega_m - \omega_w)}{\omega_w^2} \tag{10}$$

TABLE III. FORWARD SPEED OF SHIP

	ω_w	ω_e	V_{pr}
$L_w = L_{Ship}$	$0.555\ rad/sec$	$0.716\ rad/sec$	$-3.789\ m/s$

The calculated value of ω_e as 0.716 rad/sec is nearly equal to the natural roll frequency of the barge equal to be 0.69 rad/sec. The negative value of the ship speed is also an indication of susceptibility to parametric roll resonance. Hence it was validated that there is a possibility of parametric roll resonance when the ship travels forward with a speed of 10 knots while the length of the wave is equal to the length of the ship.

It was re-evaluated to find the exact ship speed when the encountering wave frequency is 0.69 rad/sec. On back substituting, it was found out that when the ship travels with a speed of 8 knots under the same condition of wave length as that of ship length, there is high parametric roll resonance.

The next step was to find a wavelength when the encountering wave frequency was twice that of the natural roll frequency.

$$\omega_w = \frac{1}{2V_s} \cdot \left(-g + \sqrt{g^2 + 8V_s\omega_m g}\right) \tag{11}$$

$$L_w = \frac{2\pi g}{\omega_w^2} \tag{12}$$

On calculating,

$$\omega_w = 0.365\ rad/sec. \tag{13}$$

Therefore,

$$L_w = 460\ m \tag{14}$$

Thereby,

$$L_w = 2.3\ L_{ship} \tag{15}$$

We see that when the length of the wave is almost twice the wave of the ship, we have another possibility of parametric rolling.

E. Study of Parametric Rolling considering Damping

The Mathieu's equation of damping was solved by incorporating the unstable region values that were calculated before, the equation becomes as

$$\frac{d^2\emptyset}{d\tau^2} + 0.21548\frac{d\emptyset}{d\tau} + (4.515 + 4.7075\cos(0.7t))\emptyset = 0 \quad (16)$$

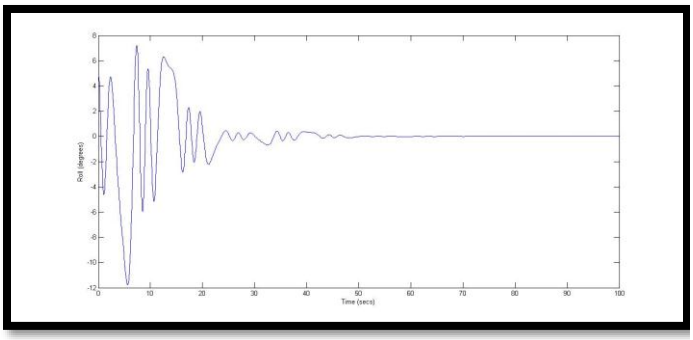

Fig 7. Solution by Matlab ODE 45 Solver

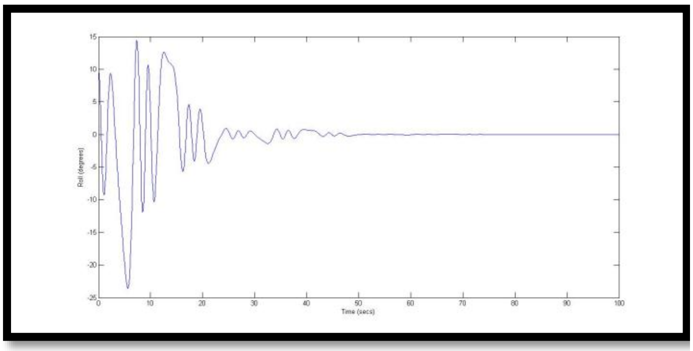

Fig 8. Solution by Matlab ODE 45 Solver

Fig. 7 and Fig. 8 are the graphical solution of Mathieu's equation with 5% damping with the initial condition as 5 degrees and 10 degrees respectively

F. Estimation of Optimum Conditions for Parametric Rolling with Genetic Algorithm

In the cases [1] that have been considered before for finding the susceptibility of parametric rolling, we have considered the initial angle of roll as 0.01degrees or 0.1degrees, and the rolling of the barge was seen to be predominantly dependent on the initial angle of roll. So it can be further easily said that the rolling of the barge depends on the initial angle of roll considered and the plot of rolling versus time also manifests itself as the initial angle of rolling is chosen.

In this study of parametric rolling, a program was developed in Matlab to find the most optimum value of rolling using genetic algorithm. The basic objective of developing the program was to find the most optimum value of initial rolling and also bringing the parametric rolling phenomenon to a controlled environment.

In GA, the population is defined to be the collection of individuals. A population is a generation that undergoes under changes to produce new generation. Like nature, GAs has also collection of several members to make population healthy. A chromosome that is a collection of genes is correspondence to individual of population. Each individual chromosome represents a possible solution to the optimization problem. The dimension of the GA refers to the dimension of the search space which equals the number of genes in each chromosome.

In the program developed, the differential equation for the parametric rolling of instable region was solved by ODE45 solver; however this differential equation was incorporated in the genetic algorithm. A population of size 10, generations of 20, crosses over rate of 0.75 and population initial range varying from 0 to 1.5 was selected.

The program selects an arbitrary value from the population initial range and then proceeds to modify it and finally displays the most optimum value as the initial roll angle. In the program, the objective function was written such that the parametric roll does not exceed 30 degrees and the initial roll angle displayed would be such that the maximum angle of 30 degrees is nearly obtained within a time interval of 200 seconds.

TABLE IV. Optimum Initial Roll using GA

Optimum Initial Angle of Roll (degrees)	TCB/VCB
0.1670	686.175
0.1996	574.103
0.1751	654.432
0.1621	706.917
0.1686	679.66
0.1795	638.390
0.1649	649.913
0.1577	726.641
0.1648	695.335
0.1526	750.926

The program was run for ample number of times as the GA always displays a new value as and when it is freshly run. The best possible 10 values that the program gave for restricting a parametric roll up to 30 degrees are tabulated in table IV. With these values, the ratio of transverse center of buoyancy to vertical center of buoyancy was calculated (TCB/VCB). With this ratio, it illustrates us how the center of buoyancy changes and what ratio should be kept in consideration so as to limit the maximum parametric roll of 30 degrees for the barge under the same wave conditions of 5 sec to 25 sec waves.

As the program has been run for an offshore barge of length 100 m and width 30.5m, the range of TCB/VCB ratio should be between 574.103 to 750.926 so as to have a controlled parametric roll of 30 degrees.

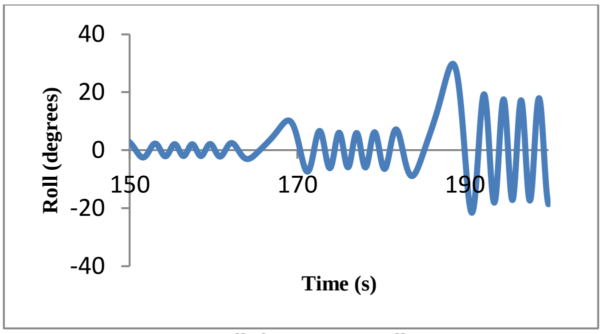

Fig 9. Controlled Parametric Rolling, 30 Degrees

Fig. 9 illustrates the controlled parametric rolling for 30 degrees angle of parametric roll. The time series under observation was from 150 seconds to 200 seconds.

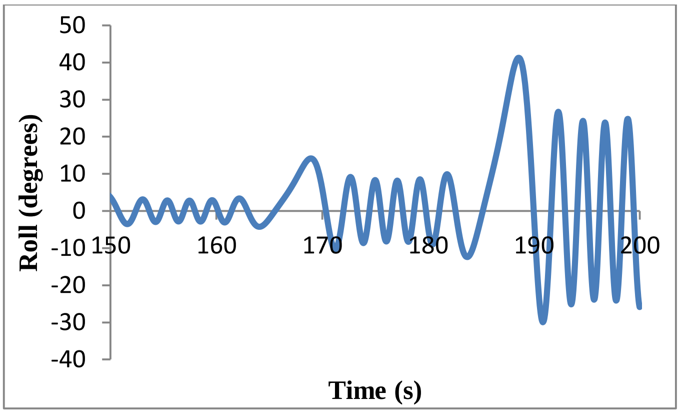

Fig 10. Controlled Parametric Rolling, 40 Degrees

It was worked out to find the center of buoyancy ratio for controlled parametric rolling for 40 degrees and the result obtained was 493.926. Fig 10 shows the controlled parametric roll for 40 degrees. Hence we can say that if the designer is provided with the ratio and the initial condition, he can have the vague idea of the possible angle of parametric roll.

G. Matlab Runs

The following is the coding used in Matlab for genetic algorithm. A function run and funsys2 was defined respectively to enable effective running in the solver.

```
function run()
global GAflag Yv
GAflag=0;
options =
gaoptimset('PopulationSize',10,'Generations',20,'Crosso
verFraction',0.75,'PopInitRange',[0;1.5]);
X=ga(@objective,1,options);
GAflag=1;
J=objective(X)
end
function J=objective(X)
global GAflag Yv
in=X;
tic
[tv,Yv]=ode45('funsys2',[100 200],[0;in]);
J=(max(Yv(:,2))-30)^2;
toc
if GAflag
X
plot(tv,Yv(:,2))
end
end
```

III. CONCLUSIONS

The region of first instability and their threshold coefficient for frequencies that were prone to principal parametric resonance were observed. The criteria for parametric rolling with the forward ship speed were found respectively.

An important contribution was the implementation of genetic algorithm to calculate the most optimum angle of roll. This optimum angle of roll was used to find the ratio of TCB to VCB for predefined parametric roll angle. This would help to keep parametric rolling within limits or enable controlled parametric rolling.

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