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NUMERICAL-EXPERIMENTAL MODELING OF A PLANNING VESSEL'S DYNAMICS IN REGULAR WAVES

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ABSTRACT

In this paper, movements of a high speed craft with flight body have been studied both experimentally and numerically. The aim of these studies are to compare the results obtained from experimental models and test results from the numerical equation solving by couple vertical motion and longitudinal rolling using Savitsky method. The most important issue in numerical modeling of ship flight is determining the conditions of constant motion and the ship's trim. Comparing the results showed that despite the uncertainty of moving conditions, the corresponding results in the range are not different from each other. Using advanced numerical methods would obtain to better estimation of movement of the vessels, especially in higher speeds.

Key words: Ship motion - High speed craft - time domain

1. INTRODUCTION

Prediction of vessel motion in waves resulted in plan operations and implementation of ship research is always considered. Therefore vessels' movement's investigations are considered in design process.

Movement of a ship at sea with regard to issues such as maximum speed of the ship in the waves, voluntary slowdown due to increased forces on the float and involuntary slowdown due to added resistance, ships' route optimization in order to reduce transport time, fuel consumption and overall cost and increase safety of vessels based on existing criteria (calculated acceleration, the occurrence slamming, stuff conditions on deck etc), is very important. The first work in this field, based on Strip theory lay out, to obtain coefficients of the equations of ship's motion.

Each of these methods, mentioned above, have their limitations and conditions. Numerical methods, although depended on the experimental results, but with acceptable accuracy and their low cost, are their benefits. Research in this area based on two general potential theories, ([1] Strip theory and [2] boundary element methods) and complete form of equations Navier – Stokes equations (such as RANS (Reynolds Averaged Navier-Stokes Equations ([2]).

The main topic in numerical modeling of the ship is determination of its status (heave and pitch motion) during the test procedure. This position can be identified with trim and depression level of ship in water. It should be noted that changing ship's speed leads to change into these two variables.

In this research Savitsky method and relationships used to calculate movements and resistance of flying vessels in linear mode, and resistance movements float is calculated.

The experimental model conducted with the dimensions shown in table (2), and a constant wave velocity and amplitude of various wavelengths is examined. The aim of this study is investigation on ship motions affected by input wave profile. Tensile tests have been conducted in Basin of Sharif University of Technology.

Both experimental and numerical methods are in good agreement ship's movement's prediction. Experimental methods, used of testing a similar model, in smaller size.

Therefore, here numerical and experimental study of a ship with high speed movements and its interaction with waves has been studied, however this categorize High Speed Crafts.

Movement of vessels at sea can be clearly estimated in three categories. First, estimation of sea environment (wave spectrum). Second, calculating ship's response (ship's motion spectrum) and last ship's movement criteria in the sea and their efficiency. Accuracy in modeling of environment where ship interferes with is necessary. Appropriate assumptions and the efficiency of ship (three) motion based on the criteria, have significant effect on the results.

2. EXPERIMENTAL MODELING

Tensile test were conducted using regular waves in the Marine Engineering Research Center, Sharif University of Technology. This laboratory is equipped with a traction system and the wave generator produced regular, which is able to produce both regular and random waves. Basin is 2.5 meters wide, 24 meters long and 1.5 meters height.

For this study a laboratory model of a High Speed Craft of 70 centimeters long is used. Profile test model is shown in Table (2).

2.1 Model experiment with waves

2.1.1 The effects of wave lengths on ship movement

To investigate the effect of wave length on ship's movement, ship moved with Froude number equal to 2.250 and constant amplitude 1cm used with range of wavelengths equal to 1.7 meters until 2 meters.

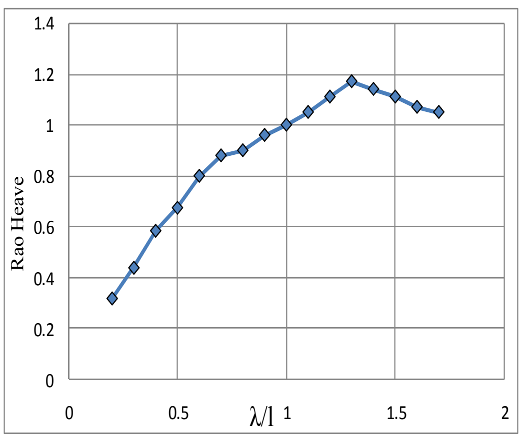

Figure 1: Experimental study on the effects of wavelength on ship's heave motion, Froude number is equal to 2.250

Experiments showed that heave motion increased as, wavelength increases. In small wavelengths heave tends toward zero. Obviously that is due to reduction in wavelength, the water wills moves slowly. In calm water heave motion tends toward zero. Waves with larger wavelengths, range of heave motion tends towards one, it is resulted because of the alignment of the ship's and wave moves.

In experimental study, showed that pitch movement increases as wavelength increases. In small wavelengths pitch tends to zero.

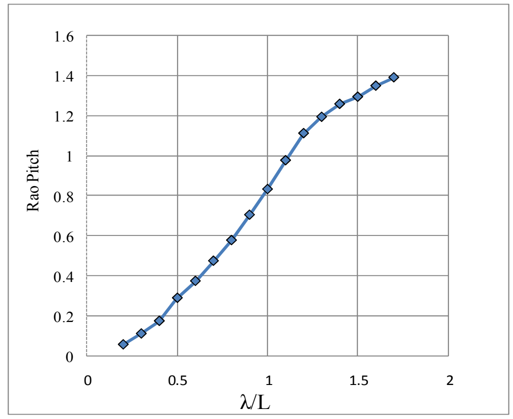

Figure 2: Effect of wavelength on the ship's pitch movement, Froude number is equal to 2.250

2.1.2 Effects of waves' amplitude on ship's movement

To study effects of wave amplitude on ship's movement, ship moved with constant velocity of 2 meters per second, wavelength varied between 1till 2 centimeters used.

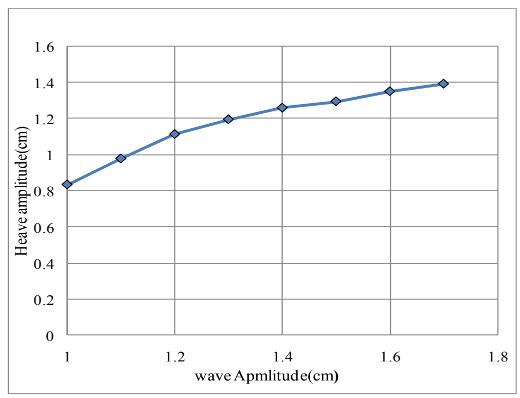

Figure 3: Experimental study on the effects of wavelengths on ship's heave, Froude number is equal to 2.25

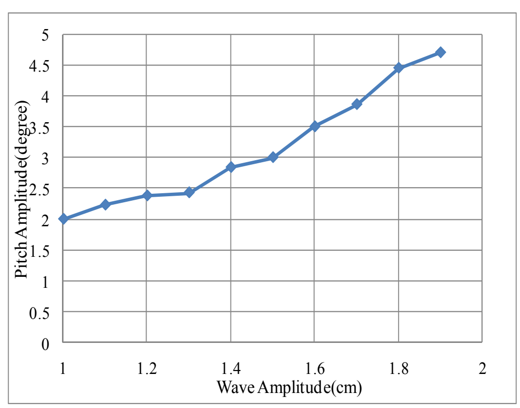

Figure 4: Experimental study on the effects of wavelengths on ship's pitch, Froude number is equal to 2.25

3. EQUATIONS OF MOTION

First it is necessary to declare coordinate (x, y, z) which do not fluctuate with the ship. This coordinate systemic moving with the same speed as vessel is moving. When the ship is located in a stable position, the coordinate origin is considered on center of gravity of the ship. Z axis is vertical and its positive direction is upward. X axis is horizontal and the positive direction is toward the heel. Movement is time dependent and is shown with η_k , for example η_3 means the vertical movement of centroid and η_5 is longitudinal rolling in terms of radians. Angles of trim τ and pitch are positive, if the prow comes up. Longitudinal and transverse centers of gravity respectively are showed by lcg and vcg.

Linear couple equations of ship's heave and pitch motions is considered:

$$(M+A_{33})\frac{d^2\eta_3}{dt^2}+B_{33}\frac{d\eta_3}{dt}+C_{33}\eta_3+A_{35}\frac{d^2\eta_5}{dt^2}+B_{35}\frac{d\eta_5}{dt}+C_{35}\eta_5=F_3 \quad (1)$$

$$A_{53}\frac{d^2\eta_3}{dt^2}+B_{53}\frac{d\eta_3}{dt}+C_{53}\eta_3+(I_{55}+A_{55})\frac{d^2\eta_5}{dt^2}+B_{55}\frac{d\eta_5}{dt}+C_{55}\eta_5=F_5 \quad (2)$$

M is mass of ship and I_{55} is moment of inertia in pitch movement, considering defined coordinate system. (A_{jk}) is added mass. (B_{jk}) and (C_{jk}) are Damping and restoring coefficient respectively. They all will be provided, in following part of descriptions. Damping force is due to body lift and restoring coefficients are due to changes in buoyancy force.

3.1 Moment and restoring force

Linear restoring coefficients in heave and pitch motions calculated by using the following equation:

$$C_{jk}=-\left.\frac{\partial F_j^{\,c}}{\partial \eta_k}\right|_0 \qquad j,k=3,5 \quad (3)$$

Here, zero means the static equilibrium position in this case $\eta_3=\eta_5=0$.

Savitsky approach is used to define center of pressure, lift force and drag. [4]

$$C_{L\beta}=C_{L0}+0.0065\beta C_{L0}^{\,0.6} \quad (4)$$

$$C_{L0}=\tau_{\deg}^{1.1}0.012\lambda_W^{0.5}=(\frac{180}{\pi})^{1.1}\tau^{1.1}0.012\lambda_W^{0.5} \quad (5)$$

Where:

C_{L0} = Coefficient of lift force with angle of dead rise at zero

L_k = wetted length of keel

C_L = lift force coefficient

L_c = wetted length of Chine

F_{L0} = lift force at angle of dead rise zero

L_p = center of pressure

F_L = lift force

U = Ship velocity

λ_w = Average wetted ratio of length to width

L = length of ship

$\tau_{\deg}$ = angle of trim in planning level in term of degrees

vcg , lcg = position of the center of gravity

τ = angle of trim in planning level in terms of radians

F_{nv} = Volumetric Froude number (without speed)

B = width of planning level

U = Ship velocity

It should be mentioned, that in the term of Froude number of the width parameter is used instead of length of the ship. The reason is the constant ratio of width to instead length the ship. For example, wetted length of keel before solving equilibrium equations related the vertical force and trim's moment at a specified speed, is unknown.

Equation 4 in the range of $2^\circ \le \tau_{\deg} \le 15^\circ$ and $\lambda_w \le 4$ is correct and usable. In figure 5 geometry of the ship's body and angles τ and β are specified. Average ratio of wetted length to width (λ_w) is equal to $0.5\,(L_K + L_C)/B$. L_K and L_C, are wetted length of keel and Chine, respectively. In Savitsky approach body form is assumed to be prismatic, also deadrise angle is assumed to be constant through the length of the ship.

According to the Savitsky equation, when the trim angle approaches to zero, the value of the lift force tends to zero. Implication of trim angle here is the same as role of the rake angle in hydrofoil. It also revealed that the lift force decreases with increasing in deadrise angle.

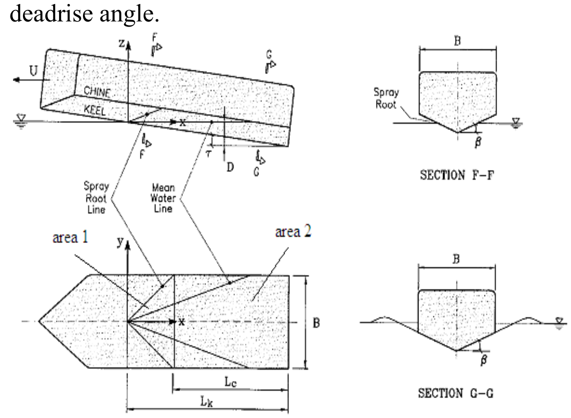

Figure 5: Coordinate (x, y, z) and parameters used in calculations related to a planning, charter vessel Savitsky 1964

The L $_P$ is the distance along the keel of the ship till heel (transom) to the center of pressure due to hydrodynamic forces. In equation (5) and (6) force and moment caused by hydrodynamic lift. Also in this equation the effect of hydrostatic forces and the production of surface waves are also considered. [4]

$$\frac{L_p}{\lambda_w B} = 0.75 - \frac{1}{5.21(\frac{F_{n_B}}{\lambda_w})^2 + 2.39} \quad (6)$$

Horizontal and vertical distance between the highest local pressure point applied and ship keel are respectively equal to Vt + Z $_{max}$ and C = (Vt + Z $_{max}$) / tan β. The fact that Vt = xτ would lead to a function of x axis, thus it is demonstrated that flow separation from the chine starts at x = x $_S$ = L $_K$ - L $_C$ which would be calculated by the following equation:

$$\frac{B}{2} = (1+\frac{Z_{max}}{Vt})\frac{tV}{\tan\beta} = (1+\frac{Z_{max}}{Vt})\frac{x_s\tau}{\tan\beta} \quad (7)$$

Table 1: The amount calculated parameters of $\frac{Z_{max}}{Vt}$ for a wedge with constant vertical velocity V impacted to the water surface [7].

$\frac{Z_{max}}{Vt}$	τ
0.5695	4 º
0.5623	7.5 º
0.5556	10º
0.5361	15 º
0.5087	20 º
0. 4709	25 º

Also it is necessary to declare how λ_w changes with η_3 and η_5 :

$$L_k = L_{cg} + \frac{V_{cg}}{\tan(\tau+\eta_5)} - \frac{Z_{wl}+\eta_3}{\sin(\tau+\eta_5)} \quad (8)$$

Using equation 7 and replacement for τ , $\tau+\eta_5$ there is:

$$L_c = L_k - x_s = L_k - \frac{0.5\tan\beta}{(1+\frac{Z_{max}}{Vt})(\tau+\eta_5)} \quad (9)$$

Value of $\lambda_w = 0/5\,(L_K + L_C)/B$ is calculated at any time by using equations (8) and (9).

Using equations (5) and (6) to the amount of vertical static force to, the results are as follows:

$$\frac{C_{33}}{0.5\rho U^2 B^2} = -B\left.\frac{\partial C_{L\beta}}{\partial \eta_3}\right|_0 = -B\left.\frac{\partial C_{L0}}{\partial \eta_3}\right|_0 \left[1-0.0039\beta C_{L0}^{-0.4}\right] \quad (10)$$

$$\frac{C_{35}}{0.5\rho U^2 B^2} = -B\left.\frac{\partial C_{L\beta}}{\partial \eta_5}\right|_0 = -B\left.\frac{\partial C_{L0}}{\partial \eta_5}\right|_0 \left[1-0.0039\beta C_{L0}^{-0.4}\right] \quad (11)$$

Pitch moment around COG can be expressed as follows:

$$\frac{F_5^c}{0.5\rho U^2 B^3} = (\frac{L_p}{B} - \frac{L_{cg}}{B})C_{L\beta} \quad (12)$$

The L $_P$ value is achieved by using the equation 6. Therefore:

$$\frac{C_{53}}{0.5\rho U^2 B^2} = -\left[\frac{1}{B}\frac{\partial L_P}{\partial \lambda_\omega}B\frac{\partial \lambda_\omega}{\partial \eta_3}C_{L\beta} + (\frac{L_P}{B} - \frac{L_{cg}}{B})B\frac{\partial C_{L\beta}}{\partial \eta_3}\right]_0 \quad (13)$$

$$\frac{C_{55}}{0.5\rho U^2 B^3} = -\left[\frac{1}{B}\frac{\partial L_P}{\partial \lambda_\omega}B\frac{\partial \lambda_\omega}{\partial \eta_5}C_{L\beta} + (\frac{L_P}{B} - \frac{L_{cg}}{B})B\frac{\partial C_{L\beta}}{\partial \eta_5}\right]_0 \quad (14)$$

3.2 Added mass in heave and pitch motions

Calculations related to the added mass are based on the Strip theory. Therefore, added mass coefficient in the case of two-dimensional heave, α_{33} for the wedge, is an important parameter for High Speed Craft prismatic body. Analytical methods for calculating α_{33} have been presented by many researchers. Faltinsen approach is one of them: [5]

$$a_{33} = \rho d^2 K = \frac{\rho d^2}{\tan(\beta)}\left[\frac{\pi}{\sin(\beta)}\frac{\Gamma(1.5-\frac{\beta}{\pi})}{\Gamma^2(1-\frac{\beta}{\pi})\Gamma(0.5+\frac{\beta}{\pi})} - 1\right] \quad (15)$$

Here d is the mug equal to 0.5 b tan β , and b is the wedge width. Γ is gamma function.

For part of the body that x_s, since there chine is wetted, based on topic presented before equation (7) the amount mug is written as follows:

$$d = C(t)\tan(\beta) = (1+\frac{Z_{max}}{Vt})x\,\tau \quad (16)$$

Total amount of heave added mass is calculated as followings:

$$A_{33}{}^{1} = \int_0^{x_s} a_{33}{}^{1} dx = \rho K (1 + \frac{Z_{max}}{Vt})^2 \tau^2 \int_0^{x_s} x^2 dx \qquad (17)$$

K according to equation (15) and x $_s$ according to equation 7 is defined as follows:

$$x_s = \frac{B}{2} \frac{\tan(\beta)}{(1 + \frac{Z_{max}}{Vt})\tau} \qquad (18)$$

Value of $\left(1 + \frac{\tan\beta}{Vt}\right)$ for different deadrise angles from Table 1 is derived. After integration these results achieved:

$$\frac{A_{33}{}^{1}}{\rho B^3} = \frac{K}{24} \frac{\tan^3(\beta)}{(1 + \frac{Z_{max}}{Vt})\tau} \qquad (19)$$

Added mass coupled heave and pitch is calculated as:

$$A_{35}{}^{1} = A_{53}{}^{1} = \int_0^{x_s} (x - x_G) a_{33}{}^{1} dx = -\rho K \int_0^{x_s} d^2 (x - x_G) dx \qquad (20)$$

$$x_G = L_K - L_{cg} ,$$

$$\frac{A_{35}{}^{1}}{\rho B^4} = \frac{A_{53}{}^{1}}{\rho B^4} = \frac{A_{33}{}^{1}}{\rho B^3} \frac{x_G}{B} - \frac{K}{64} \frac{\tan^4(\beta)}{(1 + \frac{Z_{max}}{Vt})^2 \tau^2}$$

That added mass pitch is calculated as followings:

$$A_{55}{}^{1} = \int_0^{x_s} (x - x_G)^2 a_{33}{}^{1} dx = -\rho K \int_0^{x_s} d^2 (x - x_G)^2 dx \qquad (21)$$

$$\frac{A_{55}^{(1)}}{\rho B^5} = \frac{K}{160} \frac{\tan^5\beta}{(1 + \frac{Z_{max}}{Vt})^3 \tau^3} - \frac{K}{32} \frac{X_G}{B} \frac{\tan^4\beta}{(1 + \frac{Z_{max}}{Vt})^2 \tau^2} + (\frac{X_G}{B})^2 \frac{A_{33}^{(1)}}{\rho B^3}$$

B) For the part of the wetted chine body d equals to:

$$d = \frac{B}{2} \tan\beta$$

In mass added phrase integration from x $_s$ till L_K, consequently:

$$\frac{A_{33}^{(2)}}{\rho B^3} = C_1 \frac{\pi L_C}{8B}$$

$$\frac{A_{55}^{(2)}}{\rho B^4} = \frac{A_{53}^{(2)}}{\rho B^4} = -C_1 \frac{\pi}{16} \left[(\frac{L_K}{B})^2 - (\frac{X_S}{B})^2 \right] + \frac{X_G}{B} \frac{A_{33}^{(2)}}{\rho B^3}$$

$$\frac{A_{55}^{(2)}}{\rho B^5} = C_1 \frac{\pi}{24} \left[(\frac{L_K}{B})^3 - (\frac{X_S}{B})^3 \right] - C_1 \frac{\pi}{8} (\frac{X_G}{B}) \left[(\frac{L_K}{B})^2 - (\frac{X_S}{B})^2 \right] + (\frac{X_G}{B})^2 \frac{A_{33}^{(2)}}{\rho B^3}$$

3.3 Damping in heave and pitch

In this part damping induced by body lift and heave velocity are considered. Calculations are based on empirical equation of Savitsky. This equation includes the hydrostatic part is, and only need to lift part of the hydrodynamic force and moment. For this purpose the equations (5) and (6) presented is using C $_{L0}$ and L $_P$.

Because of the speed heave, attack angle (trim) will be changed:

$$\alpha = \tau = \frac{V}{U} = \frac{-d\eta_3}{dt} / U \qquad (22)$$

Angle of attack with lift force is:

$$F_3 = \frac{\rho}{2} U^2 B^2 C_{L\beta} \qquad (23)$$

When force term moves to left side of the equations, damping coefficient, B_{33} is expressed as follows:

The velocity acts heave also cause pitch-moment around COG.Value of this moment by using equation (6) when the considered $Fn_B \to \infty$, is calculated. That will be result in:

$$F_5 = F_3 (L_P - L_{cg}) = F_3 (0.75 \lambda_W B - L_{cg}) \qquad (24)$$

Here, F_3 vertical force at a time when $Fn_B \to \infty$ is considered. When this moment transfers to the left side of equations of motion, coefficient damping, B_{53}, is expressed as follows:

$$\frac{B_{53}}{B_{33} B} = 0.75 \lambda_W - \frac{L_{cg}}{B} \qquad (25)$$

Therefore, using simplified analytical calculations following results rose:

$$B_{55} = U x_T^2 a_{33}(x_T) \qquad (26)$$

$$B_{35} = -U A_{33} - U x_T a_{33}(x_T)$$

3.4 Wave-induced force

To evaluate and analyze wave induced force, ship movement out of water surface is neglected; otherwise it is necessary to consider slamming forces. Computation of slamming force of the ship body at any given moment would be very difficult and complicated.

3.4.1 Froude-Krilof force

When motions due to waves are considered, it is necessary to apply wave force on the right side of equation (1) and (2). And left side of the equations remains unchanged. Assume that wave steepness is small thus linear wave theory can be applied. Therefore, the wavelength λ is considered great enough. This calculation is assumed to be easier to lead. Collision wave height at any given moment is expressed as followings:

$$\zeta = \zeta_a \sin(\omega_e t - kx) \qquad (27)$$

Here $\omega_e = \omega_0 + kU$ is collision frequency, ω_0 is wave frequency in coordinate system which is connected to the earth, and $k = \frac{2\pi}{\lambda} = \frac{w_0^2}{g}$ is wave number.

Consequently vertical Froude-Krilof force is equal to:

$$F_3^{FK} = C_{33}\zeta_a \sin\omega_e t + C_{35}k\,\zeta_a \cos\omega_e t \qquad (28)$$

And Froude-Krilof pitch moment is equal to:

$$F_5^{FK} = C_{53}\zeta_a \sin\omega_e t + C_{55}k\,\zeta_a \cos\omega_e t \qquad (29)$$

3.4.2 Diffraction force

In calculations related to Froude-Krilof force, effect of terms of velocity and waves' acceleration did not considered. These effects are considered in diffraction force calculations. In the first step the velocity potential function should be estimated with the velocity potential function of input waves, the flow around the body is zero. Then pressure and force on the body is calculated.

$$F_3 = F_{3s}\zeta_a \sin\omega_e t + F_{3c}\zeta_a \cos\omega_e t \qquad (30)$$

$$F_5 = F_{5s}\zeta_a \sin\omega_e t + F_{5c}\zeta_a \cos\omega_e t \qquad (31)$$

Here F_{jc} and F_{js} are expressed in terms of adding mass (A_{jk}), damping coefficients (B_{jk}) and restoring coefficients (C_{jk}):

$$F_{3s} = C_{33} - A_{33}\omega_0\omega_e + B_{35}^{D}\omega_0 k$$
$$F_{3c} = C_{35}k - A_{35}\omega_0\omega_e k + B_{33}^{D}\omega_0$$

$$F_{5s} = C_{53} - A_{53}\omega_0\omega_e - B_{55}^{D}\omega_0 k$$
$$F_{5c} = C_{55}k - A_{55}\omega_0\omega_e k + B_{53}^{D}\omega_0$$

Based on linear theory $B_{33}^{D} = B_{33}$ and $B_{53}^{D} = B_{53}$. Also:

$$B_{35}^{D} = B_{35} + UA_{33} \qquad (33)$$

$$B_{55}^{D} = B_{35} + UA_{35}$$

After replacement of coefficients and input parameters in the equation of motion and solve the basic equation in time t, domain motions of ship's heave and pitch comes by adding ship's mug term and range of heave motion. New mug will be developed. The same procedure is applied to derived new trim term.

Using new mug and trim as input for the program leads to change in coefficients, as well as changes in the stable force of motion. Solving this new equation in time t + dt leads to new range of heave and pitch. Adding this value to the previous mug and trim, would lead to new mug and trim. The latter comes as input for next time; this procedure continues doing until convergence of the answers. Figure (6) shows model output of the test model. Input parameters of the program are the following:

Table 2: Model inputs for the test program in the experimental tests

U	ship speed (m / s)	7
B	ship width (m)	0.15
L	ship length (m)	1
Lcg	Longitudinal center of gravity position (m)	0.20
Vcg	Center of gravity height (m)	
M	Ship mass (kg)	2
β	Deadrise angle	20
□	Amplitude (m)	0.01
T	Period (sec)	2.250
μ	Angle of wave approach to the ship	180

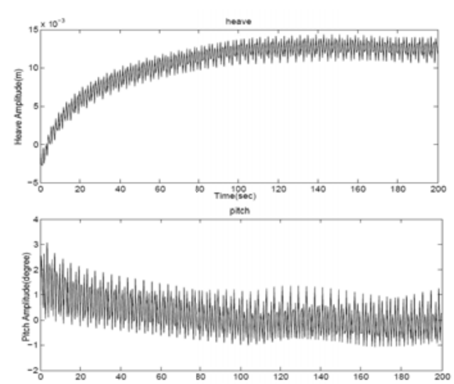

Figure 6: Model output results with characteristics of Table 2

4. COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS:

4.1 Comparison between the results of with variable amplitude

In this section, numerical and experimental results for the model mentioned in the case compared with each other. Here the ship's velocity and input wavelength are constant and amplitude of the waves is varied. Comparing the results of ship's movement, heave and pitch respectively give figures 7 and 8. It shows that with increment range of input waves amplitude, ship's movement mode changes from linear one, nonlinear. Indeed the numerical solution assumed in linear mode. Consequently difference between numerical and experimental results increases as it goes up. This difference increment shows up in heave and pitch motion (Figure 7) when they reach 1.5 in the range. As the range value goes up, this difference moves up either. Before data range reach 1.5 there is a good agreement between experimental and numerical results.

4.2 Comparison between the results with variable wavelength

In this section, numerical and experimental results for the model mentioned in the case compared with each other. Here the ship's velocity and input wavelength are constant and amplitude of the waves is varied. Comparing the results of ship's movement, heave and pitch respectively give figures 9 and 10. Consequently difference between numerical and experimental results decreases as wave length goes up. This difference decrement shows up in heave motion (Figure 9) but in pitch motion, with increment in wave length differences between numerical and experimental results show up (Figure 10). Before wavelength before reaches 1.5m experimental results and numerical in pitch movement show a good agreement.

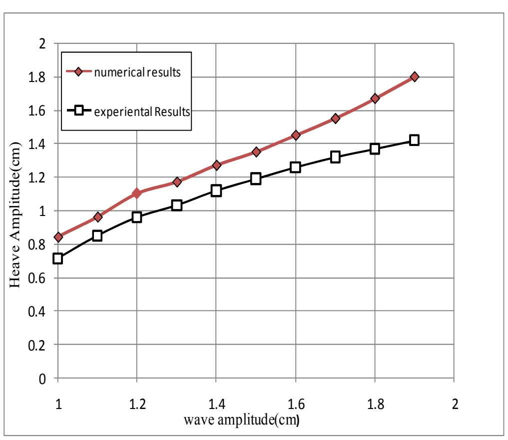

Figure 7: Comparison between the results of ship's heave motion with the conditions mentioned in Table 2

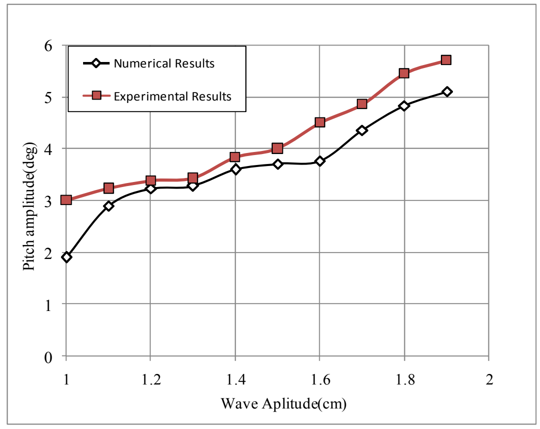

Figure 8: Comparison between the results of ship's pitch motion with the conditions mentioned in Table 2

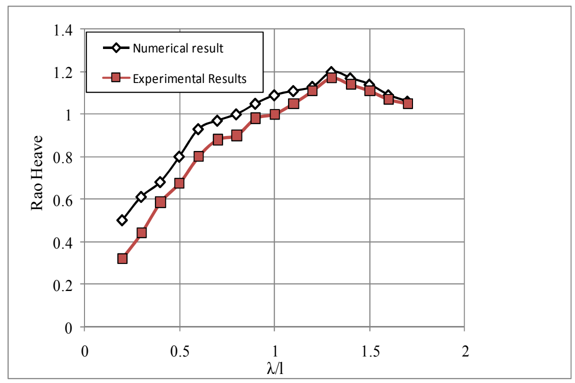

Figure 9: Comparison between the results of ship's heave motion with the conditions mentioned in Table 2

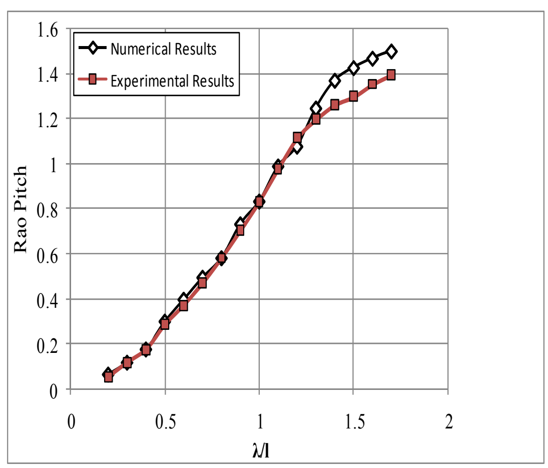

Figure 10: Comparison between the results of ship's pitch motion with the conditions mentioned

5. CONCLUSION

Comparisons of experimental and numerical results show that numerical solution are in acceptable range and better results can be obtained by using more accurate models and equations. Therefore, this issue is important in the ship's design procedure. Obviously, this point should be noted that numerical results for solving linear mode are acceptable (numerical assumption). Increasing speed would lead to nonlinear circumstances such as slamming, wet deck surface and etc. Increasing the scope of wave lengths, it is not recommended to use this numerical method.

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