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Influence of Variable Acceleration on Parametric Roll Motion of a Container Ship

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Abstract

Ship operators increase or decrease thrust force of ships to avoid parametric roll motion. These operations cause varying acceleration values. In this study, influence of variable acceleration and deceleration of ships on roll motion is investigated in longitudinal waves. The method which is referred as simple model is utilized for analysis. Simple Model is one degree of freedom nonlinear parametric roll motion equation which contains changing velocity and restoring moment in waves with respect to time. Ship velocities in waves are predicted by XFlow software for various thrust forces. Results indicate that variable acceleration has significant effect on parametric roll phenomenon.

Keywords: *Parametric Roll Motion, Longitudinal Waves, Nonlinearity.*

Konteyner Gemilerinde Değişken İvmenin Parametrik Yalpa Hareketi Üzerine Etkisi

Öz

Gemi operatörleri parametrik yalpa hareketinden kaçınmak için geminin itme kuvvetini azaltır veya arttırırlar. Bu operasyonlar değişken ivmelenme değerlerine neden olur. Bu çalışmada, boyuna dalgalarda değişen hızlanma ve hız kesme için değişen ivmelerin yalpa hareketi üzerindeki etkisi araştırılmıştır. Analiz için basit model olarak adlandırılmış olan metot kullanılmıştır. Basit model bir serbestlik dereceli lineer olmayan parametrik yalpa hareketi denklemidir. Bu denklemde zamanla değişen hız ve geri getirici moment terimi kullanılmaktadır. Dalgalar arasındaki hız değerleri farklı itme kuvveti değerleri için XFlow yazılımı kullanılarak belirlenmiştir. Sonuçlar, değişen ivmenin parametrik yalpa hareketi üzerinde belirgin bir etkisinin olduğunu göstermiştir.

Anahtar Kelimeler: *Parametrik Yalpa Hareketi, Boyuna Dalgalar, Lineer Olmama.*

1. Introduction

The first publications about parametrically excited roll motion appeared in 1930s and 1940s by Watanabe [1] and Kempf [2]. Roll motion of a ship in longitudinal waves have been studied by a number of researchers including Graff and Heckscher [3], Kerwin [4], Paulling and Rosenberg [5]. The first experimental observation of parametric roll phenomenon was done by Paulling et al [6]. Although its theoretical existence has been known for a long time, parametric roll phenomenon attracted a great deal of interest in recent years. In fifties only small ships, like fishing vessels were investigated related with this phenomenon. Nowadays there are examples of accidents with container vessels that cause significant damage to cargo and ship. For example in October 1998 the APL China experienced parametric roll resonance and lost more than sixty percent of its cargo [7]. In January 2003 Maersk Carolina encounters a storm at the Atlantic sea. In a few cycles the roll angle increased up to 47 degrees in head waves [8]. The casualties like CMV CHICAGO EXPRESS during typhoon "HAGUPIT" [9] led designers, researchers and regulatory authorities to initiate further research and investigations. Among these researchers: Spyrou [10], Neves and Rodrigues [11] and Bulian et al. [12] focused on nonlinear aspects and effects of changing tuning factors on parametric roll motion.

Variation of underwater ship geometry with respect to wave crest position has an important role on roll motion in longitudinal waves. In regular waves, the excitation is periodic with a finite period and certain ratios of encounter and natural frequencies. The most dangerous situation usually occurs in the first parametric resonance region in which wave length is approximately equal to the ship length at an encounter frequency twice that of the roll natural frequency. In this case, the variation of restoring moment causes the roll angle increase drastically unless other factors such as damping come into play. This particular state is called the parametric roll phenomenon. Controlling amplitude of roll motion is only possible by increasing damping, changing encounter angle or changing ship velocity. This study focuses on the variation of velocity. Roll motion of ships in longitudinal waves is generally investigated with constant velocity in previous studies. But ship velocity is not constant due to wave loads. Furthermore, ship operators increase or decrease thrust force of ships to avoid parametric roll motion. When combined with the waves in action, these operations result in variable acceleration.

Simple Model was solved by numerical method in time domain and approximate analytic method in frequency domain for various conditions. Choosing solution method being numerical or analytical has great influence. A numerical simulation usually starts from one particular initial condition that lies in a particular domain of attraction. We are not able to estimate other steady state solutions without changing the initial condition. In brief, numerical methods are inadequate to give a global picture of the response curve and bifurcations involved in the phenomenon. However, an analytical approach is usually able to give such a global picture in a very fast and quite accurate way.

XFlow software is based on mesh free approach: Lattice Boltzmann Method. In the last two decades, the Lattice Boltzmann method (LBM) was used as a tool for modeling the Navier-Stokes equations and simulating complex fluid flows. LBM is based on microscopic models and mesoscopic kinetic equations. The Lattice Boltzmann method [13, 14, 15] was originated from Ludwig Boltzmann's kinetic theory of gases. The fundamental idea is that gases or fluids can be imagined as consisting of a large number of small particles moving randomly. The exchange of momentum and energy is achieved through particle streaming and billiard-like particle collision. Validation of XFlow software for hydrodynamic properties of a sailing yacht can be found in [16].

2. Simple Model

Simple model is based on one degree of freedom parametric roll motion equation which includes ship velocity, heave and pitch effects by means of time in restoring moment variation [17, 18]. Restoring moment is also excitation moment in head waves. Heave and pitch effects are taken into account by analytical restoring moment term related with time and instant roll angle. Surge effect is taken into account by changing encounter frequency in other word changing ship velocity which is determined by XFlow software (LBM).

In general, the equation of roll motion in regular longitudinal waves can be written as follows:

$$(I_{xx} + \delta I_{xx})\ddot{\phi} + B(\dot{\phi}, \phi) + \Delta GZ(\phi, t) = 0 \qquad (1)$$

Where $(I_{xx} + \delta I_{xx})$ is moment of inertia, ϕ is roll angle, $B(\dot{\phi}, \phi)$ is damping function and $\Delta GZ(\phi, t)$ is restoring function. Eq. (1) may be re-written as;

$$\ddot{\phi} + b(\dot{\phi}, \phi) + \frac{\omega_0^{\,2}}{GM_0} GZ(\phi, t) = 0 \qquad (2)$$

Here, ω_0 is roll natural frequency, GM_0 is the metacentric height for calm sea and $b(\dot{\phi}, \phi) = \dfrac{B(\dot{\phi}, \phi)}{I_{xx} + \delta I_{xx}}$ is the damping term.

Variation of restoring moment surface with respect to time and instantaneous roll angle for various wave crest positions can be determined by a standard stability program as given in Figure 1. In this study, restoring moment surface was predicted by only wave crest and wave trough restoring moment levers for practicality and capability of solution in frequency domain. Pesman and Taylan show that the simplification does not affect the results in acceptable accuracy [18]. Analytic restoring moment surface utilized in roll motion equation is given in Figure 2. Restoring moment curves were calculated in free trim condition.

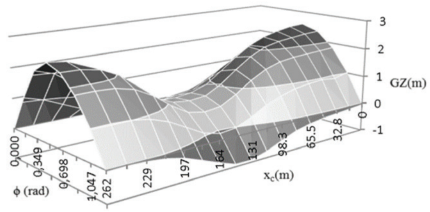

Figure 1. *Restoring Moment Variation*

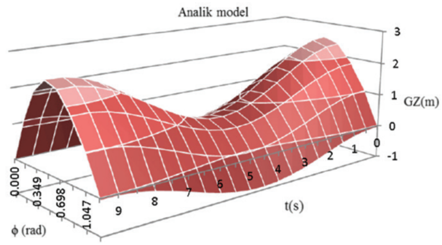

Figure 2. *Analytic Restoring Moment Surface*

In Eq. 2, $GZ(\phi, t)$ is approximated by the following expression [17]. Restoring moment variation is modeled by only wave crest and wave trough restoring moment curves.

$$GZ(\phi, t) = \sum_{n=1}^{N} \left(m_{2n-1} + k_{2n-1}\cos(\omega_e t)\right)\phi^{2n-1} \qquad (3)$$

The coefficients "m" and "k" in Eq. (3) are obtained from polynomials fitted to righting lever curves in wave crest and wave trough conditions.

$$m_{2n-1} = \frac{c_{2n-1,trough} + c_{2n-1,crest}}{2} \qquad (4)$$

$$k_{2n-1} = \frac{c_{2n-1,trough} - c_{2n-1,crest}}{2} \qquad (5)$$

In Eq. (4) and (5), "$c_{2n-1,crest}$ and $c_{2n-1,trough}$" show the coefficients of polynomials fitted to restoring lever curves in wave trough and wave crest conditions, respectively and ω_e is the encounter frequency. In this work, seventh degree polynomials are utilized for developing the restoring lever surfaces. Variable damping functions are utilized by a number of researchers as indicated in [17, 19]. Equation (6) is a cubic nonlinear damping function but it also represents quadratic nonlinear damping function by choosing and represents linear damping function by choosing $\delta = \beta = 0$ [17, 19]. In this study, constant linear damping term was utilized for steady state solution of Simple Model (μ=0.05, β=0, δ=0). Quadratic nonlinear damping function was utilized for time domain solution of Simple Model. Linear and nonlinear damping coefficients of quadratic nonlinear damping function were calculated for each time step in time domain solution. Coefficients of the damping function are addressed by Ikeda, Himeno and Tanaka [20].

$$b(\phi, \dot{\phi}) = 2\mu\dot{\phi} + \beta\dot{\phi}|\dot{\phi}| + \delta\dot{\phi}^3 \quad (6)$$

Substitution of Eq. (6) and Eq. (3) in Eq. (2) leads to the following differential equation:

$$\ddot{\phi} + 2\mu\dot{\phi} + \beta\dot{\phi}|\dot{\phi}| + \delta\dot{\phi} + \omega_0^2 \frac{\left(\sum_{n=1}^{N}(m_{2n-1} + k_{2n-1}\cos(\omega_e t))\phi\right)^{2n-1}}{GM_0} = 0 \quad (7)$$

Variation of ship velocity with respect to time depends on ship resistance: ship mass, added mass, thrust of propellers, ship motions with their damping effects and excitation term due to waves. In this study, variation of velocity determined by XFlow software which can handle 6 DOF ship motion problems in waves with mesh free Lattice Boltzmann Method.

Encounter frequency with respect to time is written as follows. V(t) is variation of ship velocity in following equation.

$$\omega_e(t) = \omega_w + \frac{\omega_w^2}{g} V(t) \quad (8)$$

Equation (7) was solved by Krylov Bogoliubov Averaging Method in frequency domain [21] and Dormand-Prince Method in time domain [22].

3. Validation of Simple Model and XFlow Software

Simple Model was tested in [17] for various ship forms and wave conditions. One of these ship forms is a Ro-Ro whose experimental tests were carried out at the towing tank of DINMA [23].The experiments were carried out for 3 DOF (heave, pitch and roll) [23].This sample ship has no bilge keels and appendages. The wave length and wave height were chosen as 130 m and 4.4 m, respectively. Steady-state results of Simple Model were compared with experimental results in Figure 3. It is observed that experimental results and simple model results are in good agreement.

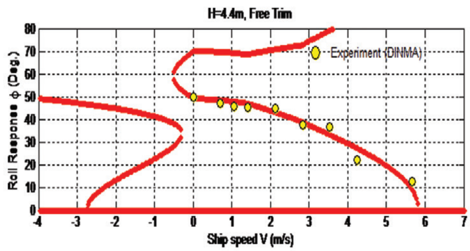

Figure 3. *Comparison of Simple Model and Experimental Results [17]*

Validation of XFlow software for hydrodynamic properties of a sailing yacht can be found in [16]. Validation of XFlow software was also performed for roll decay test of a combatant ship form (Model 5512) at design speed [24]. Roll decay experiments of combatant ship form were realized with collaboration of IIHR, INSEAN and DTMB. Validation case is detailed in [25]. Results given in Figure 4 indicate that XFlow software is a usable tool for analyzing ship motions.

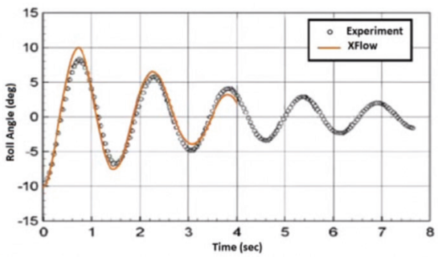

Figure 4. Comparison of XFlow and Experimental Results [24]

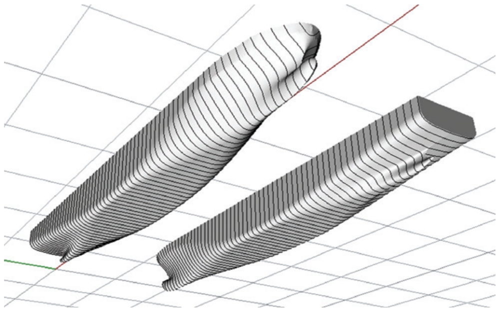

Figure 5. *Form of DTC Container Ship*

4. Sample Ship and XFlow Simulations

In this study Duisburg Test Case (DTC) container form was used. Duisburg Test Case (DTC) is a hull design of a modern 14000 TEU post-panamax container carrier, developed at the Institute of Ship Technology, Ocean Engineering and Transport Systems (ISMT) [26]. DTC is a single-screw vessel with a bulbous bow, large bow flare, large stern overhang and a transom. Figure 5 shows hull form of the vessel. Main dimensions of sample ship and its scaled model are given in Table 1.

Table 1. *Main Dimensions of DTC Container Ship*

	Ship	Model (1/59.407)
Length between perpendicular (LBP):	355 m	5.976 m
Breadth (B):	51 m	0.859 m
Draught (T):	14.5 m	0.244 m
Vertical position of gravity (KG):	23.68 m	0.3986 m
Roll gyration radius (k_{xx}):	20.25 m	0.2109 m
Roll Natural Period:	3.536 s	3.536 s
Block coefficient (C_B) :	0.661	0.661
Speed ratio of ship and model (Vship/Vmodel):	7.707	

In this study, IGES file of scaled DTC hull form was utilized [26]. Environment of XFlow software was set up as free surface model and initial conditions were selected as water channel. The most dangerous situation usually occurs in the first parametric resonance region in which wave length is approximately equal to the ship length at an encounter frequency twice that of the roll natural frequency. In this study, wave length was chosen equal to the model length and wave height was chosen 1/30 of the model length. Progressive wave boundary condition was set up with linear wave theory. Length, frequency and amplitude of wave are selected 5.976 m, 0.511 Hz and 0.1 m, respectively. All constrains were chosen free, so model has capability of 6 DOF motion. In this study, simulation time was chosen 10 s and time step was chosen 0.01 s. Resolution was set up with adaptive refinement algorithm: resolved scale was chosen 0.2 m and target resolved scale was chosen 0.025 m as shown in Figure 6. In simulation, 40 N, 70 N and 140 N thrust forces were utilized in local coordinate system at initial condition: zero model velocity and 5° heel angle for acceleration. Zero force and 40 N reverse force were utilized at initial conditions: 1 m/s model velocity, 5° and 42° heel angle for deceleration of ship speed.

Simulations and calculations were made for 7 different conditions. These conditions are given in Table 2. Variation of restoring moment values of scaled model with respect to heel angle in wave crest, wave trough and still water are given in Figure 7.

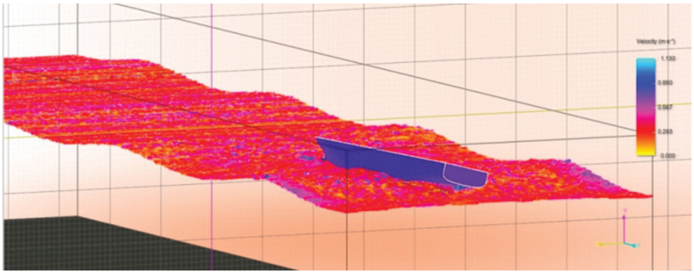

Figure 6. *Domain Structure of Simulation*

Table 2. *Simulation and Calculation Conditions*

	Initial velocity (m/s)	Initial roll angle (deg.)	Thrust force (Newton)
Condition 1	0 m/s	5°	40 N Forward
Condition 2	0 m/s	5°	70 N Forward
Condition 3	0 m/s	5°	140 N Forward
Condition 4	1 m/s	5°	Zero force
Condition 5	1 m/s	5°	40 N Reverse
Condition 6	1 m/s	42°	Zero force
Condition 7	1 m/s	42°	40 N Reverse

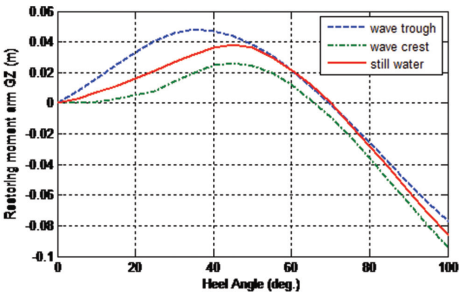

Figure 7. *Variation of Restoring Moment Values of Scaled Model*

5. Results

Roll amplitudes with respect to constant model velocities were determined by solving nonlinear parametric roll motion equation (Simple Model) with averaging method in frequency domain (Figure 8). The reason why parametric roll motion equation is solved in frequency domain by approximate analytic method is capability of detecting bifurcations globally. Nonlinear parametric roll motion equation was also solved by numerical method (Dormand-Prince Method) in time domain as shown in Figure 8.

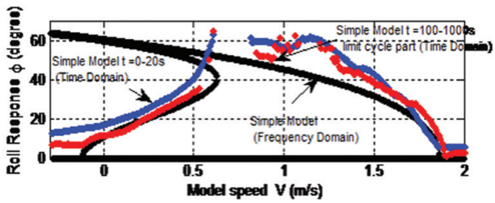

Figure 8. *Results of Roll Response with respect to Model Velocity*

In Figure 8, black color represents frequency domain approximate solution; blue color represents time domain numeric solution in time between 0 to 20 s, and red color represents limit cycle part of time domain numeric solution (100 to 1000 s). Results show that there is a fold bifurcation at amplitudes between 40° and 60° where model velocities are less than 0.62 m/s. Frequency domain results in other word steady state results given in Figure 8 were used for comparison of different conditions given in Table 2.

Variations of velocities obtained by XFlow software were given in Figure 9 and Figure 10 for acceleration and deceleration respectively.

Time domain results were rearranged with respect to model velocity and plotted on frequency domain (steady state solution) results to present influence of

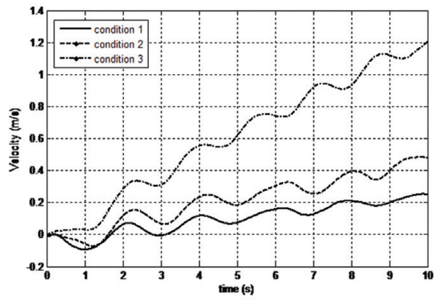

Figure 9. *Variation of Velocities with respect to Time (Acceleration)*

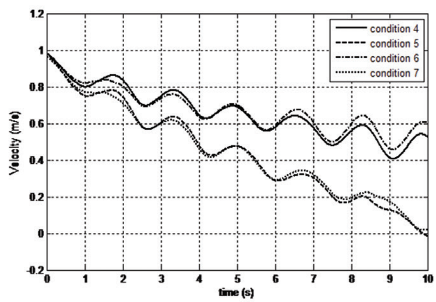

Figure 10. *Variation of Velocities with respect to Time (Deceleration)*

variable acceleration and deceleration on parametric roll motion more clearly in Figure 11-17.

Figure 11 was generated for condition 1: 0 m/s initial velocity, 5° initial roll angle and 40 N thrust force. Results of roll motion with 40 N thrust force deviated from steady state solution. Maximum angle of roll oscillation increased from 5° to 30°. Roll motion of accelerated model was attracted by fold bifurcation part of steady state solution.

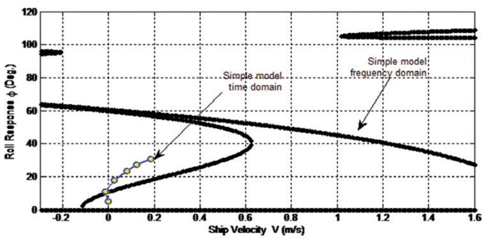

Figure 11. *Acceleration from 0 Ship Velocity with 40 N Thrust Force (condition 1, initial angle: 5°)*

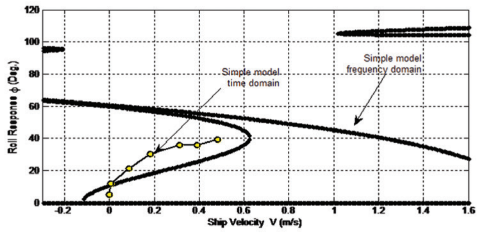

Figure 12. *Acceleration from 0 Ship Velocity with 70 N Thrust Force (condition 2, initial angle: 5°)*

Figure 12 was generated for condition 2: 0 m/s initial velocity, 5° initial roll angle and 70 N thrust force. It is observed that roll motion of accelerated model was also affected by fold bifurcation, but stable part of steady state solution prevents amplitudes from increment.

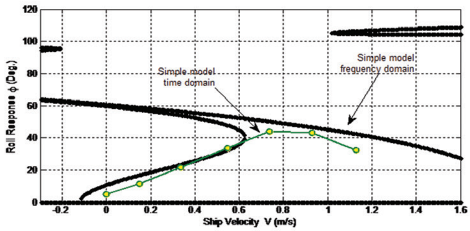

Figure 13. *Acceleration from 0 Ship Velocity with 140 N Thrust Force (condition 3, initial angle: 5°)*

In Figure 13, 140 N thrust force was utilized. Initial values of ship velocity and roll angle are 0 m/s and 5° respectively. Velocity of model increases to 1.1 m/s in 10 seconds and maximum roll amplitudes increase from 5° to 45° in 10 seconds. Increment of thrust force in other word

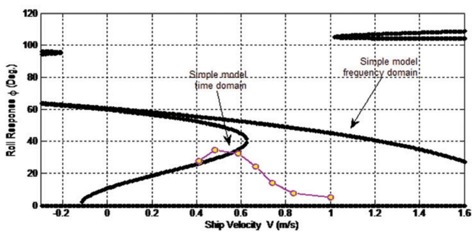

Figure 14. *Deceleration from 1 m/s Ship Velocity with Zero Thrust Force (condition 4, initial angle: 5°)*

acceleration prevents roll amplitudes from attraction of fold bifurcation unlike condition 1 and condition 2. It should be noted that 140 N thrust force is great in real: it was chosen to show effect of acceleration.

Influence of deceleration is presented in Figure 14-17. Figure 15 was generated for condition 4: 1 m/s initial velocity, 5° initial roll angle and zero thrust force. Velocity of model decreases from 1 m/s to 0.4 m/s in 10 seconds. Maximum roll angles of decelerated model increase from 5° to 35° in 10 seconds. It is observed that maximum roll angles increase from trivial unstable part to stable non-trivial part of steady state solution.

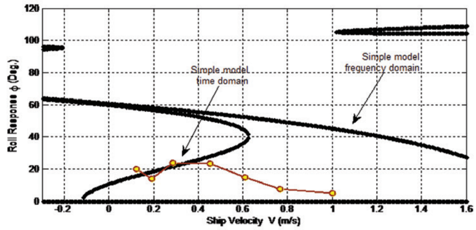

***Figure 15.** Deceleration from 1 m/s Ship Velocity with 40 N Thrust Force (condition 5, initial angle: 5°)*

Figure 15 was generated for condition 5: 1 m/s initial velocity, 5° initial roll angle and 40 N reverse thrust force. Velocity of model decreases from 1 m/s to 0.1 m/s in 10 seconds and maximum roll angles of decelerated model increase from 5° to approximate 25° in 10 seconds. Results of Simple Model are adapting to results of steady state solution at velocities less than 0.3 m/s as condition 4.

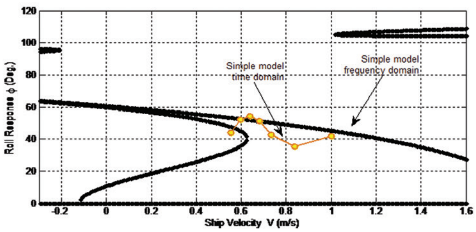

***Figure 16.** Deceleration from 1 m/s Ship Velocity with Zero Thrust Force (condition 6, initial angle: 42°)*

In condition 6 and 7, initial value of roll angles were selected as 42°. In Figure 16, it is observed that roll motion oscillation attracted by fold bifurcation at model velocities between 0.7 m/s and 0.6 m/s and reached 55°. Amplitude of oscillation decreased from 50° to 44° at model velocities less than 0.6 m/s to stable part of steady state solution.

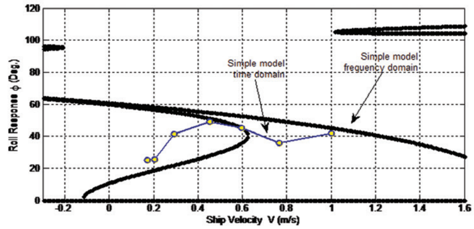

***Figure 17.** Deceleration from 1 m/s Ship Velocity with 40 N Thrust Force (condition 5, initial angle: 42°)*

In Figure 17, it is observed that amplitude of roll motion attracted by steady state solution and decreased to 20° at 0.2 m/s model velocity. But roll motion is also affected by fold bifurcation at speeds between 0.6 m/s and 0.3 m/s, and roll angles reached 50° at this zone.

6. Conclusion

Increasing or decreasing thrust force of a ship is an important tool for operator to avoid parametric roll motion. Difference between initial and executed thrust forces cause acceleration. Magnitude of acceleration depends on magnitude of thrust force (Figure 10 - Figure 11). The oscillation of acceleration values due to waves can be considered additional parametric excitation. Roll motion phenomenon in longitudinal waves is generally investigated with constant velocity in previous studies. This work focuses on how the existence of acceleration acts on parametric roll motion, unlike other studies. Results are indicated that acceleration can cause increment of roll amplitudes unexpectedly. Most important result of this work is, getting away from attraction of fold bifurcation is possible by passing fold bifurcation region rapidly, otherwise attractor of fold bifurcation leads to drastically increasing amplitudes. Especially, intensity of deceleration can be increased with reverse thrust force for events like condition 4 and 5.

If analysis of parametric roll motion of a ship is made by regarding deceleration, this can be useful for operators of ship. This study was not supported by experiments: researches of acceleration in longitudinal waves shall be made experimentally in further studies.

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