MODELING FLAT PENDULUM AND SIMULATING ITS VALIDATION AT THE PENDULUM-FLAT PONTOON MODEL SEA WAVE ELECTRIC GENERATOR APPLICATION

Ardi Noerpamoengkas[1], Harus Laksana Guntur[2] dan Zamrisyaf SY[3]
Department of Mechanical Engineering, Adhi Tama Surabaya Institute of Technology[1]
Department of Mechanical Engineering, Sepuluh Nopember Institute of Technology[2]
Research and Development Division, State Electricity Company[3]
Email: ardinoerpamoengkas@gmail.com[1]

Abstrak

Indonesia memiliki potensi pengembangan sumber daya kelautan yang sangat besar karena Indonesia adalah negara kepulauan terbesar di dunia. Salah satu potensi tersebut adalah potensi energi dari gelombang laut. Penelitian dalam pengembangan energi dari laut tersebut adalah pemodelan pendulum datar pada aplikasi pembangkit listrik tenaga gelombang laut sistem pendulum-ponton datar. Pada model ini, gelombang laut akan membuat miring ponton datar kemudian memutar pendulum untuk dikonversikan ke dalam energi listrik oleh generator. Sistem pendulum datar yang digunakan adalah penyederhaaan pembangkit listrik tenaga gelombang laut sistem pendulum-ponton datar dan merupakan model pendulum baru dan belum pernah ada studi tentang responnya. Model simulasi respon pendulum datar non linear yang telah dibuat akan divalidasi dengan model simulasi numerik hasil linearisasi. Validasi memperhatikan error periode respon pendulum antara kedua model pada sudut simpangan yang kecil. Penyelesaian numerik non linear dan hasil linearisasi dari respon perputaran pendulum disimulasikan dengan bantuan *toolbox* Simulink *software* MATLAB.

Kata Kunci: pembangkit listrik tenaga gelombang laut, pendulum datar, simulasi, solusi non linear.

Abstract

Indonesia has plenty of sea potential resources because Indonesia has the biggest group of archipelago in the world. One of sea potential resources is sea wave potential energy. Its development has reached flat pendulum model at the pendulum-flat pontoon model sea wave electric generator. In this model, the sea wave will incline the flat pontoon. Which in turn, it will rotate the pendulum and be converted into electricity with the generator. Flat pendulum is simplified system of pendulum-flat pontoon model sea wave electric generator, and new pendulum model never being researched before. Non linear flat pendulum response model's checked with linearization result of numeric simulation model. The validation's concerned to pendulum respond period error of those two models at very small angular displacement. Non linear numeric solution and linearization result of flat pendulum respond are simulated by using Simulink toolbox of MATLAB software.

Keywords: *sea wave electric generator, flat pendulum, simulation, non linear solution.*

1. Introduction

Indonesia has the potential of marine resources. One of marine resources is the ocean wave potential energy. Ocean wave potential energy development can solve the problem of electrical energy as an archipelagic country. There are still many islands or remote areas in Indonesia that need electricity power supply so they require special policy, such as the provision of electrical energy. This development can strengthen the self-sufficient of the Indonesian nation in terms of new and renewable energy technologies, and face the issue of global warming. It is developing technology of Sea Wave Electric Power Generation with Pontoon Flat-Pendulum model.

Pendulum mechanism is used for harvesting energy from rotating structures with stationary coil and magnet built-in pendulum, Dirk *et al* [1], mass and generator built-in double pendulum, Tzern *et al* [2], and weighted-pendulum-type electronic generator placed at a rotating wheel, Wang *et al* [3]. Sea wave power generator with the different rotating pendulum type is also considered. It is supposed to be set at the center of a smaller circular surface of a floating body without sliding.

This rotating structure is placed vertically relative to water surface, Masashi *et al* [4]. These mechanisms are different with pendulum-flat pontoon model sea wave generator mechanism.

Sea Wave Electric Power Generation System with Pendulum - Flat Pontoon model is one of the works of Mr. Zamrisyaf SY from Research and Development Division of State Electricity Company. Sea Wave Electric Generator with Pendulum Mechanism's been Mr. Zamrisyaf's Patent since 2010, patent number P.00200200854. In Phase I Work Reports, Studies Modeling and Simulation of Sea Wave Power Generation - bollocks System (PLTGL - SB) the cooperation between Research and Development Division of State Electricity Company and the Research and Social Dedication of Sepuluh Nopember Institute of Technology in 2010, conducted research on the shape PLTGL - SB-enhanced using the pontoon as the basis for the movement of the pendulum. Pontoon is placed horizontally above the sea water level. Ocean waves will make the flat pontoon oblique. The slope of this flat pontoon cause the pendulum rotate.

Flat pontoon which tends to move random or irregular is caused by irregular sea wave. Flat pontoon movement affects the velocity of the pendulum above them. Currently, there is no study about the pendulum movement response.

It is necessary to further study about the response of this new pendulum model. Issues to be discussed in this research include modeling the flat pendulum system to obtain non-linear pendulum response, validating the model with the results of the linear flat pendulum response, and analyzing influences of input variants to pendulum response.

2. Research Procedure

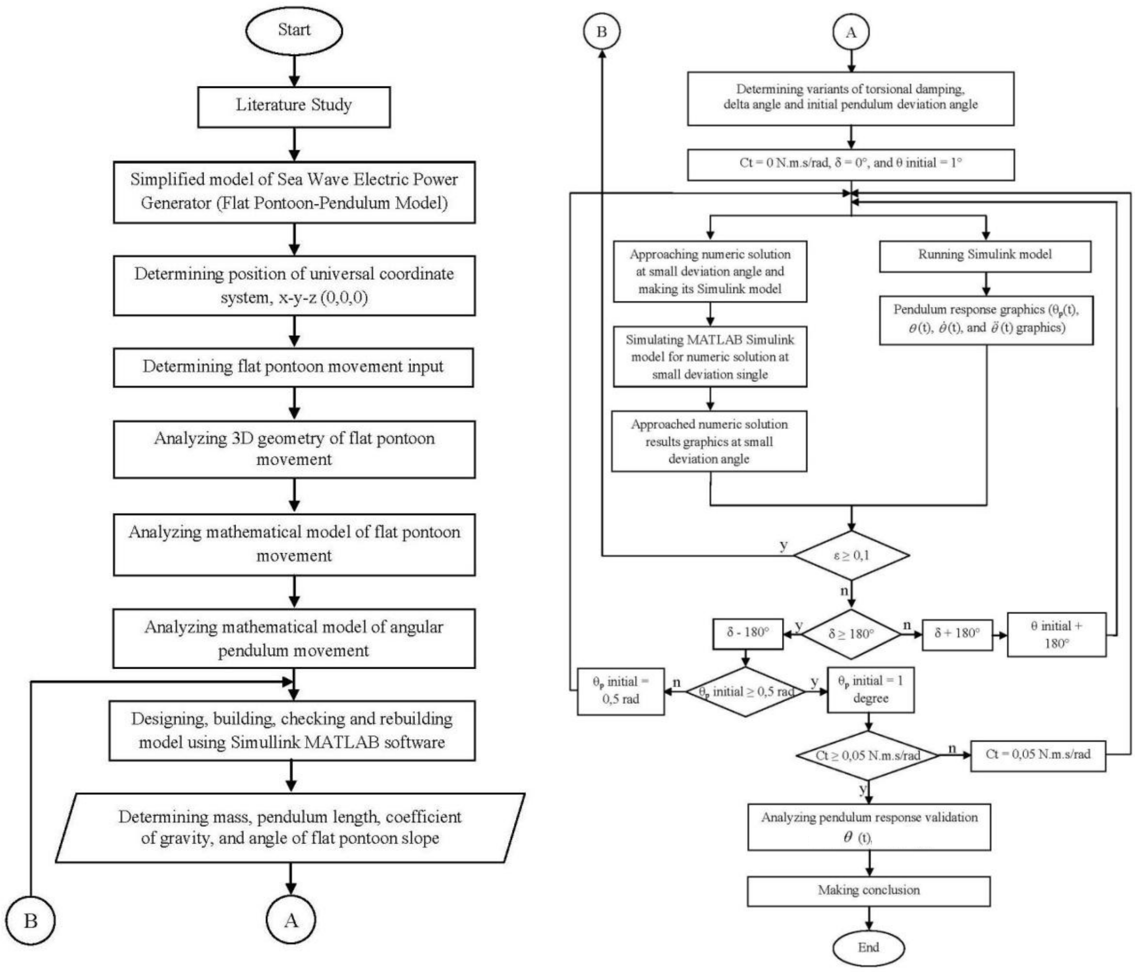

Figure 1. Research procedure flowchart.

This research was begun by gathering and studying many related literature. Pendulum-flat pontoon model sea wave electric power generator was simplified that become center pivoted flat pendulum. Simplified flat pendulum was given a determined universal coordinate system, x-y-z (0,0,0). Flat pendulum movement input was determined. 3D geometry and mathematical model of flat pontoon motion movement were analyzed. Then, mathematical model of angular pendulum movement was analyzed. After analyzing all of mathematical model requirement, the next processes were designing, building, checking, and rebuilding model by using Simulink MATLAB software. Determining set value of pendulum mass, pendulum length, coefficient of gravity and angle of flat pontoon slope, and variant value of torsional damping, delta angle (explained at the next discussion) and initial pendulum deviation angle are required for running Simulink model.

The first variant value of torsional damping, delta angle and initial pendulum deviation angle were 0 N.m.s/rad, 0°, and 1°. Then, these values were being input of linear and non linear pendulum response Simulink model. If response period error's more than 0,1, it's required to check and rebuild Simulink model. If response period error's less than 0,1, the process's continued to repeat running model with the variant value of delta angle, theta pendulum angle, and torsional damping. Each running model results must have been analyzed, and then made its conclusions.

3. Concept and Theory

The first thing to do in this research is simplifying pendulum-flat pontoon model sea wave electric power generator. Actually, this electric power generator has complicated shape and dimension. It's only studying and analyzing the effect of flat pontoon movement against pendulum response. It's necessary to simplify this model. Flat pontoon become flat, thin, and circle plate. Pendulum can rotate freely, and been center pivoted at this plate.

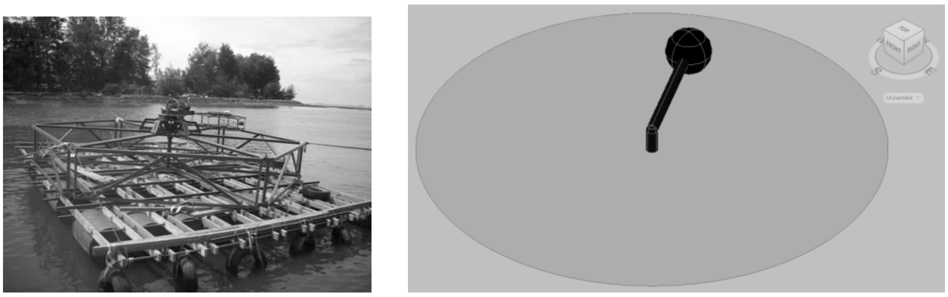

Figure 2. Simplifying of pendulum-flat pontoon sea wave electric power generator. The left figure is the real picture of pendulum-flat pontoon sea wave electric power generator. the right one is its simplifying model, pendulum and flat plate.

Universal coordinate system's given at simplified model to support 3D geometric analysis of flat plate movement. This UCS's fix and not able to transform against universe. It's placed at the center of flat plate.

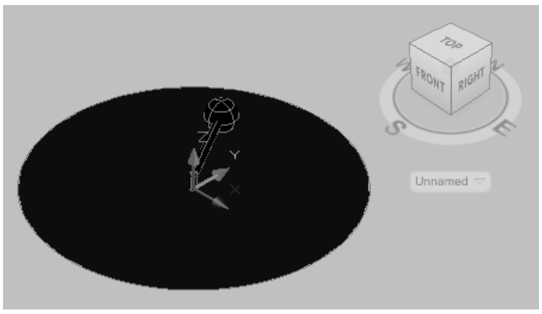

Figure 3. Simplified model with its UCS.

In reality, flat pontoon movement input is random and irregular. This research made constraint to simplify it to become one-way sinusoidal wave. The wave's assumed that comes from y-axis direction.

Pendulum movement can be categorized as damped free vibration because its restore force's obtained from gravity influence and there's no external excitation force. Generally, torsional damped free vibration pendulum equation's applied to this case. The next figure's free body diagram of pendulum-flat plate.

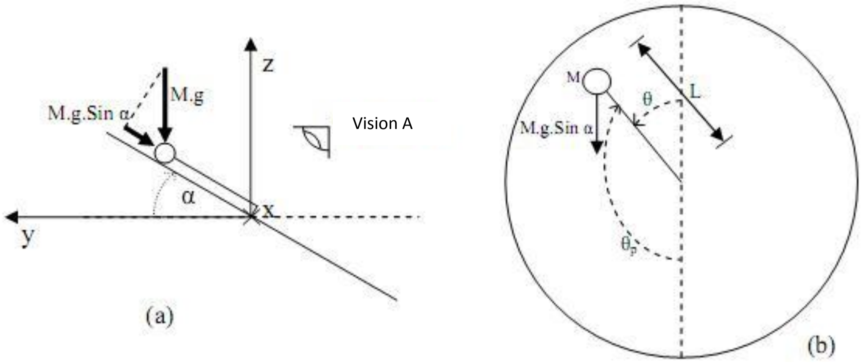

Figure 4. Pendulum-flat plate free body diagram's applied in this research. Figure a is side view of free body diagram. Figure b is A view.

Calculation of pendulum moment of inertia (J_p) is as follow.

$$J_p = M \cdot L^2 \tag{1}$$

M and L are pendulum mass and its length. Then, center pivoted rotation movement equation's applied to pendulum.

$$\sum T = J_p \cdot \ddot{\theta}_p \tag{2}$$

$$-M.g.Sin\,\alpha.Sin\,\theta_p.L - C_t.\dot{\theta}_p = M.L^2.\ddot{\theta}_p \tag{3}$$

$$0 = M.L^2.\ddot{\theta}_p + C_t.\dot{\theta}_p + M.g.Sin\,\alpha.Sin\,\theta_p.L \tag{4}$$

α angle is the slope angle of flat plate. This equation would be solved by using Simulink. Then, the relation of θ and θ_p can be shown at followed figure.

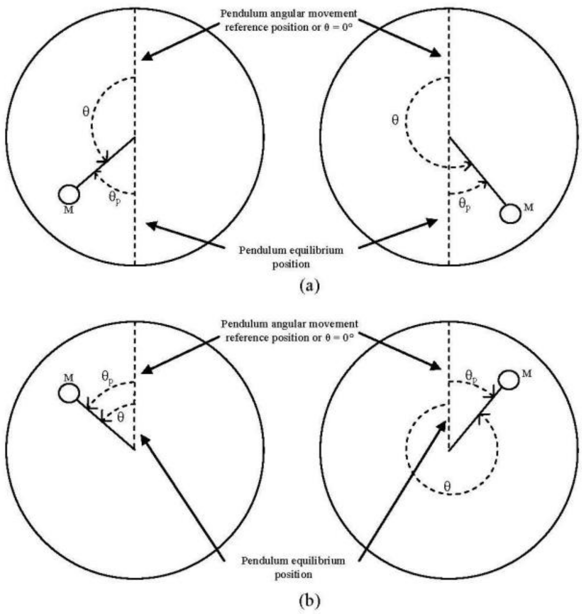

Figure 5. The relation of θ and θ_p angle is set up as the figure.

It's necessary to separate the identification of pendulum movement as above figure because the pendulum equilibrium position is always changing. This equilibrium position depends on the slope angle of flat plate. It must have the reference position to identify pendulum position relative to flat pontoon. Flat pontoon only has one degree of freedom, and been able to rotate against x-axis. The reference position is line position to identify 0 degree of θ angle, and having the same direction with positive y-axis when α angle's 0 degree. The positive value of it is angular pendulum movement counter clock wise at A view. The figure a is pendulum configuration when α angle has positive value. The figure b is pendulum configuration when α angle has negative value. The pendulum equilibrium position is at 180 degree against pendulum reference position. It can be described as 180 degree of δ angle. The pendulum equilibrium position is at o degree against pendulum reference position. It can be described as 0 degree of δ angle. In the mathematical model, the relation between θ angle, θ_p angle, and δ angle can be expressed as followed equation.

$$\theta(t) = \theta_p(t) + \delta(t) \tag{5}$$

Whereas, sinusoidal wave generation of α angle is obtained from amplitude (α_{max}) and frequency (ω_α). It can be expressed as followed equation.

$$\alpha(t) = \alpha_{maks} \cdot Sin(\omega_\alpha \cdot t) \tag{6}$$

The numerical solution's used by approaching non linear model with a small deviation angle. It's a validation reference of pendulum response model made before. It's from torsional damped free vibration equation. Generally, numerical solution's using related four vibration type, undamped free vibration, underdamped free vibration, critical damped free vibration, and overdamped free vibration.

Undamped free vibration occurs when ζ=0. Pendulum response's based on followed equation.

$$\theta(t) = \theta_O \cdot Cos\,\omega_n t + \frac{\dot{\theta}_O}{\omega_n} Sin\,\omega_n t \tag{7}$$

If $\dot{\theta}_O = 0$, then the equation changes as followed one.

$$\theta(t) = \theta_O \cdot Cos\,\omega_n t \tag{8}$$

Underdamped free vibration occurs when ζ<1. Pendulum response's based on followed equation.

$$\theta(t) = e^{-\zeta.\omega_n.t}\left(\theta_0.Cos\,\omega_n\sqrt{1-\zeta^2}\,t + \frac{\dot{\theta}_0 + \zeta.\omega_n.\theta_0}{\omega_n\sqrt{1-\zeta^2}} Sin\,\omega_n\sqrt{1-\zeta^2}\,t\right) \tag{9}$$

If $\dot{\theta}_O = 0$, then the equation changes as followed one.

$$\theta(t) = e^{-\zeta.\omega_n.t}\left(\theta_0.Cos\,\omega_n\sqrt{1-\zeta^2}\,t + \frac{\zeta.\omega_n.\theta_0}{\omega_n\sqrt{1-\zeta^2}} Sin\,\omega_n\sqrt{1-\zeta^2}\,t\right) \tag{10}$$

Critical damped free vibration occurs when ζ=1. Pendulum response's based on followed equation.

$$\theta(t) = e^{-\omega_n.t}\left[\theta_0 + \left(\dot{\theta}_0 + \omega_n.\theta_0\right)t\right] \tag{11}$$

If $\dot{\theta}_O = 0$, then the equation changes as followed one.

$$\theta(t) = e^{-\omega_n.t}\left[\theta_0 + \omega_n.\theta_0.t\right] \tag{12}$$

Overdamped free vibration occurs when $\zeta>1$. Pendulum response's based on followed equation.

$$\theta(t)=\frac{e^{-\zeta.\omega_n.t}}{2\sqrt{\zeta^2-1}}\left\{\left[\frac{\dot{\theta}_0}{\omega_n}+\theta_0\left(\zeta+\sqrt{\zeta^2-1}\right)\right]e^{\omega_n\cdot\sqrt{\zeta^2-1}t}+\left[-\frac{\dot{\theta}_0}{\omega_n}+\theta_0\left(-\zeta+\sqrt{\zeta^2-1}\right)\right]e^{-\omega_n\cdot\sqrt{\zeta^2-1}t}\right\} \quad (13)$$

The equation can be separated, then become followed equation.

$$\theta(t)=\theta_1(t)+\theta_2(t) \quad (14)$$

Each equation can be described as followed equation.

$$\theta_1(t)=\frac{e^{-\zeta.\omega_n.t}.e^{\omega_n\cdot\sqrt{\zeta^2-1}t}}{2\sqrt{\zeta^2-1}}\cdot\left[\frac{\dot{\theta}_0}{\omega_n}+\theta_0\left(\zeta+\sqrt{\zeta^2-1}\right)\right] \quad (15)$$

and

$$\theta_2(t)=\frac{e^{-\zeta.\omega_n.t}.e^{-\omega_n\cdot\sqrt{\zeta^2-1}t}}{2\sqrt{\zeta^2-1}}\cdot\left[-\frac{\dot{\theta}_0}{\omega_n}+\theta_0\left(-\zeta+\sqrt{\zeta^2-1}\right)\right] \quad (16)$$

If $\dot{\theta}_O=0$, The equation changes as followed one.

$$\theta_1(t)=\frac{e^{-\zeta.\omega_n.t}.e^{\omega_n\cdot\sqrt{\zeta^2-1}t}}{2\sqrt{\zeta^2-1}}\cdot\left[\theta_0\left(\zeta+\sqrt{\zeta^2-1}\right)\right] \quad (17)$$

and

$$\theta_2(t)=\frac{e^{-\zeta.\omega_n.t}.e^{-\omega_n\cdot\sqrt{\zeta^2-1}t}}{2\sqrt{\zeta^2-1}}\cdot\left[\theta_0\left(-\zeta+\sqrt{\zeta^2-1}\right)\right] \quad (18)$$

So, θ(t) equation can be described as followed one.

$$\theta(t)=\frac{e^{-\zeta.\omega_n.t}.e^{\omega_n\cdot\sqrt{\zeta^2-1}t}}{2\sqrt{\zeta^2-1}}\cdot\left[\theta_0\left(\zeta+\sqrt{\zeta^2-1}\right)\right]+\frac{e^{-\zeta.\omega_n.t}.e^{-\omega_n\cdot\sqrt{\zeta^2-1}t}}{2\sqrt{\zeta^2-1}}\cdot\left[\theta_0\left(-\zeta+\sqrt{\zeta^2-1}\right)\right] \quad (19)$$

Non linear numeric solution simulation validation's observing pendulum response error against approached solution or linearization result at very small deviation angle. Deviation angle has so small value that its sinus value can approach to its value itself. The response simulation's considered as valid if error's less than 0,1. It's necessary to recheck, redesign, and rebuild simulation model if error's more than 0,1. The error is ratio of the both two solution period difference and linearization result period. It can be expressed as followed equation.

$$\varepsilon=\frac{\left|T_{linear}-T_{nonlinear}\right|}{T_{linear}} \quad (20)$$

ε is error. T_{linear} is pendulum response from linearization solution. $T_{nonlinear}$ is pendulum response from non linear numeric solution. The validation's applied to undamped free vibration or underdamped free vibration because of compared period.

4. Modeling and Simulation

Main model's made by using MATLAB Simulink for obtaining the pendulum response graphics. It's consisted of input block, system block, and output block. Inputs of this model are pendulum mass, pendulum length, pendulum torsional damping value, α angle wave frequency and amplitude. Outputs of this model are pendulum responses, θ, $\dot{\theta}$, and $\ddot{\theta}$.

Input blocks are constant block type. They are M block, L block, Ct block, g block, Frek Alpha block, and Alpha Maks block. M block denotes pendulum mass input. L block denotes pendulum length input. Ct block denotes pendulum torsional damping value input. Frek Alpha block denotes α angle wave frequency input. Alpha Maks block denotes α angle wave amplitude input.

System blocks are process block that represent numerical solution of pendulum response. They are Alpha (t) block, *Flat Pontoon* block, *Pendulum Motion* block, Theta, Theta Dot, and Theta Double Dot block. Alpha (t) block denotes sinusoidal α angle generation. *Flat Pontoon* block denotes the slope of flat plate as sinusoidal α angle consequence. *Pendulum Motion* block denotes angular pendulum movement process. Theta, Theta Dot, and Theta Double Dot block denotes output of pendulum response, angular motion, angular velocity, and angular acceleration.

Output blocks are using scope block (for output graphics visualization), and display block (for real-time value visualization). They are Theta, Theta Dot, and Theta Double Dot. Theta is angular pendulum distance value output. Theta Dot is angular pendulum velocity value output. Theta Double Dot is angular pendulum acceleration value output.

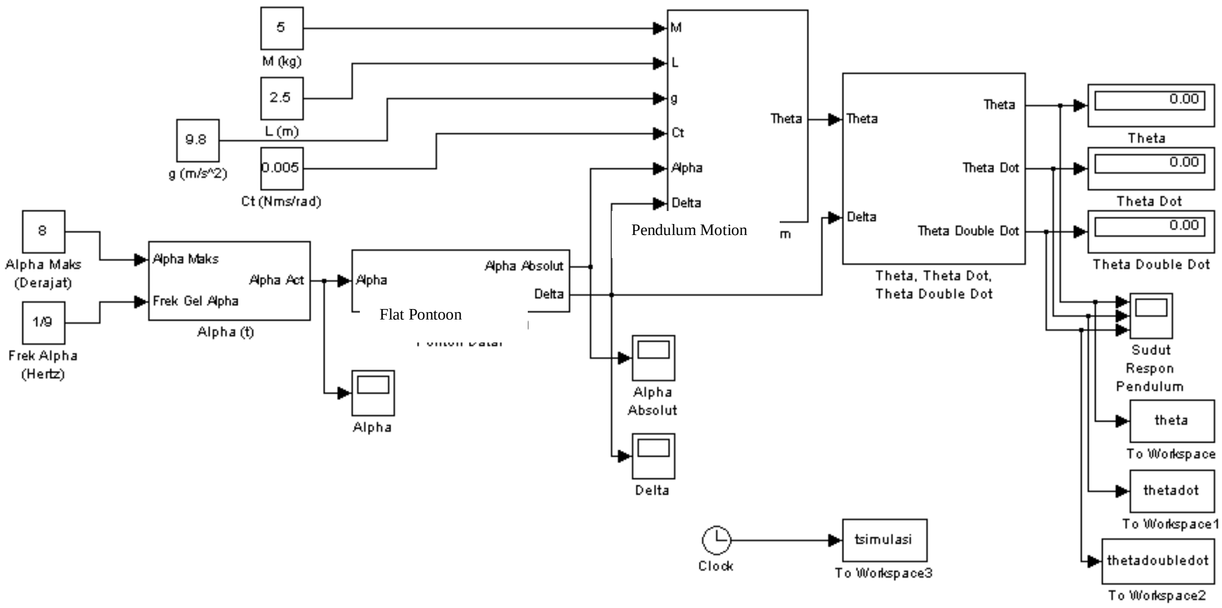

Figure 6. Simulink Model that simulates dynamic system of pendulum-flat plate. This model needs validation by comparing with linearization model.

Other model’s made for linearization numeric solution. Input blocks are pendulum mass, pendulum length, pendulum torsional damping value, coefficient of gravity, α angle, and initial pendulum deviation angle. Input of linearization model is same as non linear one that can be compared each other. Alpha angle is constant at linearization condition. Alpha angle can be described as constant block at simulation model.

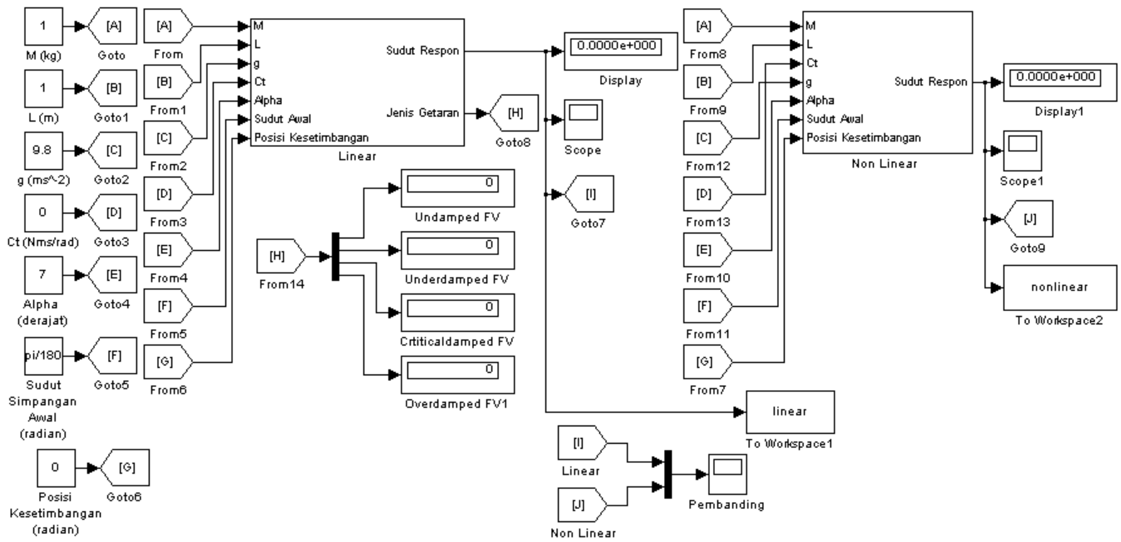

Figure 7. Simulink Model that simulates linearization result of pendulum-flat plate. This model simulates pendulum response with very small initial deviation angle.

5. Results and Discussions

Validation model simulates pendulum-flat plate at two conditions, undamped and underdamped condition. Pendulum response observed is theta angle, θ, angular pendulum movement. Graphics results of all model simulation have x-axis that describes time with second unit. Their y-axis describes theta angle in degree unit. The graphics will be separated by color diference. The red graphic is non linear pendulum response result. The blue one is linearization result.

First validation model simulates at undamped condition. Model inputs are pendulum mass, 1 kg, pendulum length, 1 m, torsional pendulum damping value, 0 N.m.s/rad, coefficient of gravity, 9,8 m/s^2, α angle, 7 degree, initial deviation angle, 1 degree, and pendulum equilibrium position, 0 degree. The model simulation has graphic result as followed.

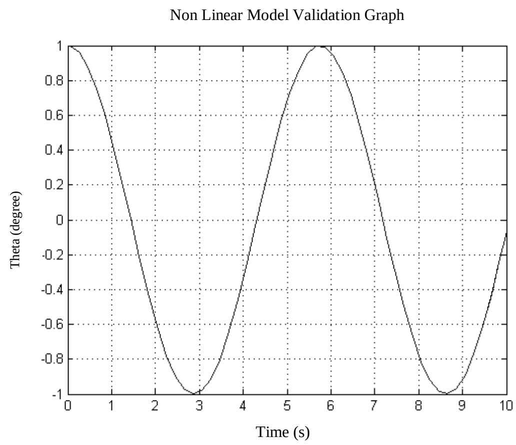

Figure 8. Simulink Model that simulates linearization result of pendulum-flat plate in undamped condition. This model inputs are M=1 kg, L=1 m, Ct=0 N.m.s/rad, g=9,8 m/s^2, Alpha=7 degree, initial deviation angle=1 degree, and equilibrium position=0 degree.

Figure 8. can describe almost identical pendulum response of non linear and linear condition. They have same period time, and its error approaching zero that non linear model can

consider to be valid. Next graphics will refer the other results to convince in non linear model validation.

Non Linear Model Validation Graph

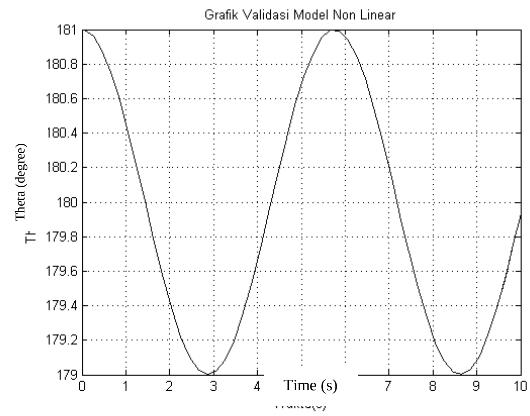

Figure 9. Simulink Model that simulates linearization result of pendulum-flat plate in undamped condition. This model inputs are M=1 kg, L=1 m, Ct=0 N.m.s/rad, g=9,8 m/s^2, Alpha=7 degree, initial deviation angle=1 degree, and equilibrium position=180 degree.

Second validation simulation has same inputs as first one, except its equilibrium position, 180 degree. It means opposite equilibrium position compared to first simulation. Generally, figure 9. has same shape of curve as figure 8. Non linear and linear graphics results have same period time, and its error approaching zero that non linear model can be considered valid. Figure 8. and 9 have no decrement amplitude because of undamped condition.

Third validation model simulates at undamped condition. Model inputs are pendulum mass, 1 kg, pendulum length, 1 m, torsional pendulum damping value, 0 N.m.s/rad, coefficient of gravity, 9,8 m/s^2, α angle, 7 degree, initial deviation angle, 0,5 rad or 28,6 degree, and pendulum equilibrium position, 0 degree. The model simulation has graphic result as followed.

Non Linear Model Validation Graph

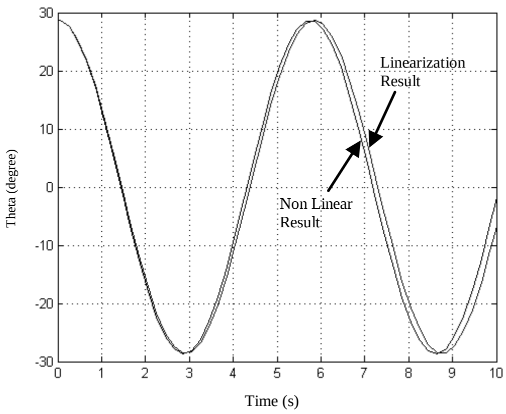

Figure 10. Simulink Model that simulates linearization result of pendulum-flat plate in undamped condition. This model inputs are M=1 kg, L=1 m, Ct=0 N.m.s/rad, g=9,8 m/s^2, Alpha=7 degree, initial deviation angle=0,5 rad=28,6 degree, and equilibrium position=0 degree.

Figure 10. describes non linear and linearization result pendulum responses graphics. Two graphics are not so close that we can observe them clearly. Linearization result has 5,75 seconds of

pendulum period while non linear one has 5,854 second of pendulum period. Pendulum period error is about 0,0181 in order that non linear simulation model can be considered valid. This conditions meet at one cycle. More cycle greater period error value.

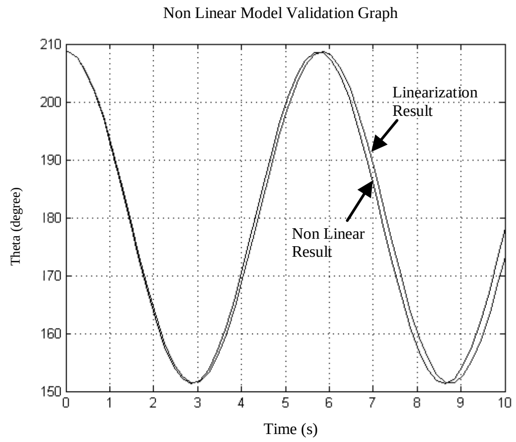

Figure 11. Simulink Model that simulates linearization result of pendulum-flat plate in undamped condition. This model inputs are M=1 kg, L=1 m, Ct=0 N.m.s/rad, g=9,8 m/s^2, Alpha=7 degree, initial deviation angle=0,5 rad=28,6 degree, and equilibrium position=180 degree.

Fourth validation simulation has same inputs as third one, except its equilibrium position, 180 degree. It means opposite equilibrium position compared to third simulation. Generally, figure 11. has same shape of curve as figure 10. Non linear and linear graphics results have different period time, 5,75 seconds for linearization result, and 5,854 seconds for non linear one. Their error is about 0,0181 that non linear model can be considered valid. Figure 10. and 11. have no decrement amplitude because of undamped condition.

Underdamped condition is also required to validate non linear simulation model. It's used for next model simulation. Fifth validation model simulates at underdamped condition. Model inputs are pendulum mass, 1 kg, pendulum length, 1 m, torsional pendulum damping value, 0,05 N.m.s/rad, coefficient of gravity, 9,8 m/s^2, α angle, 7 degree, initial deviation angle, 1 degree, and pendulum equilibrium position, 0 degree. The model simulation has graphic result as followed.

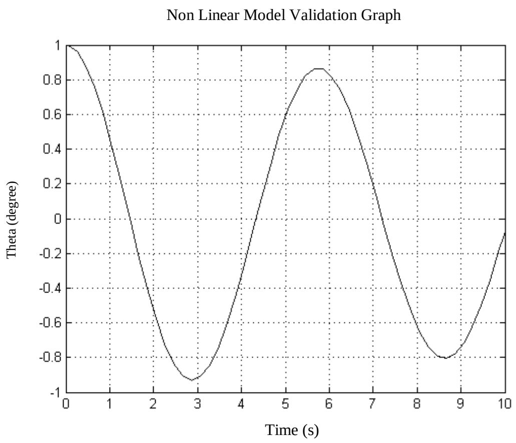

Figure 12. Simulink Model that simulates linearization result of pendulum-flat plate in underdamped condition. This model inputs are M=1 kg, L=1 m, Ct=0,05 N.m.s/rad, g=9,8 m/s^2, Alpha=7 degree, initial deviation angle=1 degree, and equilibrium position=0 degree.

Non linear and linearization solution pendulum response are so close that we can consider them identical. It means that they have same period time and decrement of amplitude. The pendulum period error can be approached to zero in order that non linear simulation model is valid in this condition.

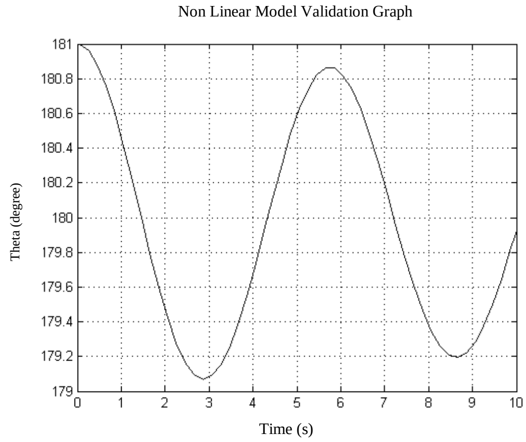

Figure 13. Simulink Model that simulates linearization result of pendulum-flat plate in underdamped condition. This model inputs are M=1 kg, L=1 m, Ct=0,05 N.m.s/rad, g=9,8 m/s^2, Alpha=7 degree, initial deviation angle=1 degree, and equilibrium position=180 degree.

Sixth validation simulation has same inputs as fifth one, except its equilibrium position, 180 degree. It means opposite equilibrium position compared to fifth simulation. Generally, figure 13. has same shape of curve as figure 12. Non linear and linear graphics results have same period time, and its error approaching zero that non linear model can be considered valid. Figure 12. and 13 have decrement amplitude because of underdamped condition.

Seventh validation model simulates at underdamped condition. Model inputs are pendulum mass, 1 kg, pendulum length, 1 m, torsional pendulum damping value, 0,05 N.m.s/rad, coefficient of gravity, 9,8 m/s^2, α angle, 7 degree, initial deviation angle, 0,5 rad or 28,6 degree, and pendulum equilibrium position, 0 degree. The model simulation has graphic result as followed.

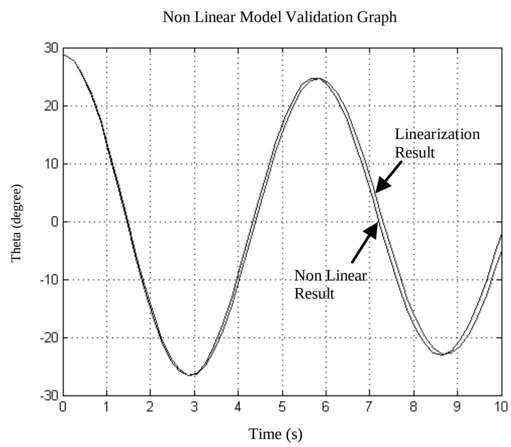

Figure 14. Simulink Model that simulates linearization result of pendulum-flat plate in underdamped condition. This model inputs are M=1 kg, L=1 m, Ct=0,05 N.m.s/rad, g=9,8 m/s^2, Alpha=7 degree, initial deviation angle=0,5 rad=28,6 degree, and equilibrium position=0 degree.

Figure 14. describes two pendulum responses graphics not so close that we can observe them clearly. Linearization result has 5,75 seconds of pendulum period while non linear one has 5,855 second of pendulum period. Pendulum period error is about 0,0183 in order that non linear simulation model can be considered valid. This conditions meet at one cycle. More cycle greater period error value.

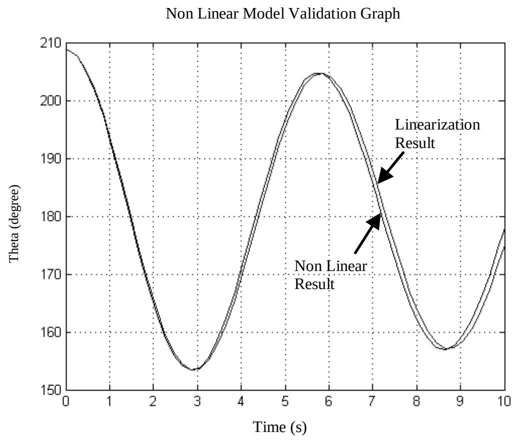

Figure 15. Simulink Model that simulates linearization result of pendulum-flat plate in underdamped condition. This model inputs are M=1 kg, L=1 m, Ct=0,05 N.m.s/rad, g=9,8 m/s^2, Alpha=7 degree, initial deviation angle=0,5 rad=28,6 degree, and equilibrium position=180 degree.

Eighth validation simulation has same inputs as seventh one, except its equilibrium position, 180 degree. It means opposite equilibrium position compared to third simulation. Generally, figure 15. has same shape of curve as figure 14. Non linear and linear graphics results have different period time, 5,75 seconds for linearization result, and 5,855 seconds for non linear one. Their error is about 0,0183 that non linear model can be considered valid. Figure 14. and 15. have decrement amplitude because of underdamped condition.

Figure 10., figure 11., figure 15. and figure 14. can describe that the more pendulum cycles, the greater pendulum period error will be. It's considered that non linear simulation model will be valid in short period once after pendulum cycle begin. It's required to begin non linear simulation with certain value of initial pendulum deviation angle after non linear simulation runs in certain short period.

6. Conclusion

Non linear simulation model of pendulum-flat plate can be considered valid by analyzing and observing validation graphics at eight conditions if pendulum period error of each result graphics approaches to zero. Initial pendulum deviation angle will influence pendulum period error. The smaller initial pendulum deviation angle, the smaller pendulum period error will be. Non linear and linear conditions have same decrement of deviation angle amplitude at the same torsional damping value.

References

[1] **Dirk Spreemann, B. Folkmer, D. Mintenbeck, Y. Manoli**, 2005, *Novel Non-resonant Vibration Transducer for Energy Harvesting*, The Fifth International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Application, University of Tokyo, Japan, pp 144-146.

[2] **Tzern T. Toh, A. Banzal, G. Hong, Paul D. Mitcheson, Andrew S. Holmes, Eric M. Yeatman**, 2007, *Energy Harvesting From Rotating Structures,* Proceeding Power MEMS 2007, Freiburg, Germany, pp. 327-330.

[3] **Yu-Jen Wang, Chung-De Chen, Cheng-Kuo Sung**, 2012, *System Design of a Weighted-Pendulum-Type Electromagnetic Generator for Harvesting Energy From a Rotating Wheel*, IEEE/ASME Transactions on Mechatronics, Digital Object Identifier 10.1109/TMECH.2012.2183640.

[4] **Masashi Kashiwagi, Saki Nishimatsu, Katsuhiro Sakai**, 2012, *Wave-energy Absorption Efficiency by a Rotating Pendulum-type Electric-power Generator Installed inside a Floating*, The 27th International Workshop on Water Waves and Floating Bodies, Copenhagen, Denmark.