MODELING, SIMULATION AND ANALYSIS OF A NONLINEAR HALF MODEL SHIP MAIN ENGINE SYSTEM USING BOND GRAPH MODELING APPROACH

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Abstract— Ship vibration tends to become a great concern with the increase of ship size and speed in the ship industry. Ship main engine vibration causes particularly ship operating performance, fuel consumption and loses of capital costs. This paper deals with bond graph modeling to obtain of a ship main engine system, and to decrease of vibration oscillations on ship main engine system. The mathematic model of system was composed by Bond Graph modeling method. The effect of dynamics forces which are consisted of main engine stresses and the hydrodynamic forces which come from water effect were also taken into consideration. So as to investigate behavior of the vibration, nonlinear equations of system dynamics in state-space form were obtained among analytical and graphical techniques. During the analysis the factor has assumed as the coupled torsional and axial vibration. The developed approach has enhanced by controllers, and responses of the models with controllers were compared and discussed. We conclude that Bond Graph modeling with PID controller may be a preferred alternative approach instead of conventional methods to prevent of the ship main engine vibrations.

Index Terms— Bond Graph Modeling, Nonlinear State Space Equations, Ship Main Engine, Vibrations.

I. INTRODUCTION

Vibratory forces generated in ship propulsion systems by some internal sources such as main engine, shaft, propeller and gearbox as well as by some external sources such as wave, current and imbalanced ship loads are often unavoidable. These forces have influence on axial, radial and torsional vibrations. However, their effect on propulsion system can be minimized or reduced by different isolation methods one of which is the use of springs and damping elements for isolation between main engine and its foundations.

Shu et al. (2006) expressed coupled torsional and axial vibrations of the engine crankshaft with Rayleigh differential method. The engine crankshaft was modeled as a mass spring system to obtain natural frequency of torsional and axial vibrations. Calculated results were compared with measured results and it is recognized that torsional vibration has an enormous effect on axial vibration that causes noise and vibration in engine. Dylejko et al. (2007) used resonance changer to minimize the axial vibration transmission and to avoid excitation of hull axial resonances in marine vessels. In order to optimize the resonance changer, upper and lower constraints were determined. It was deduced that the parameter change of actuating system and resonance changer has no significant effect on vibration control response. Hara et al. (1995) established a main engine propeller shaft system by building block approach, and analyzed the torsional, axial and lateral vibrations. The three dimensional solid model of the crankshaft was analyzed by using the Finite Element Method (FEM), besides the equivalent beam model was constructed. Then, results of the model were compared with measured results. Rao (2005) modeled the power transmission system with spring and damping element as four-degrees of freedom system. The equations of model were solved theoretically and then calculated values of torsional vibration were compared to practically measured values. Some of the calculated and measured values of frequencies are very close, while there are differences in some cases, which is recognized as suitable for ISO vibration standards. S.M. Megahed and A. Kh. Abd El-Razik (2010) presented the dynamic modeling and simulation of variable inertia vibration absorbers (VIVA) for the vibration control of two DOF primary systems. In order to obtain dynamic model in an analytical form Lagrange formulation was used. The effect of mass and stiffness of VIVA was investigated. The results of between linear and nonlinear models were shown that the realistic use of this linearized model was confirmed.

Bond Graph modeling is an approach for modeling and simulation of physical systems. Breedveld, P., C., et al. (1991) was given that Bond Graph modeling of which the origin concept was established by Paynter (1961). Karnopp and Rosenberg (1983) continued to develop the approach by in their textbooks.

Especially, the method is used for complex systems that include different energy domains. Therefore, it has a huge application area. Sosnovsky E. and Forget

B. (2013) used the method for spatial kinetics analysis of nuclear reactors. Ömürlü V. E. et al. (2009) demonstrated in space vehicles that dynamic analysis of a Stewart platform as a FBW flight control unit for space vehicles was derived by Bond-Graph modeling. S.C. Sati et al. (2011) was modeled, simulated and analyzed of aircraft arresting system using Bond Graph approach. Zhao Q. and Gao F. (2012), investigated the methods in hydraulic systems that was modeled a hydraulic six-degree-of-freedom motion simulator using Bond graph modeling. Yıldız, İ et al. (2013) studied modeling and experimental validation of a Stewart platform manipulator by Bond-Graph method and expressed that coordination between simulation and experimental system was satisfactory.
B. Ould Bouamama et al. (2006) investigated the method in industrial systems that supervised steam generator. The complex industrial components such as a boiler, a condenser, etc. of a steam generator were used to form Bond graph model and validated through experimental observations. For further proceedings the fault tolerant control and reconfiguration strategies applied to supervision platform which have been deduced directly from Bond Graph model.

II. BOND GRAPH MODELING

Bond Graph modeling is an approach for modeling and simulation of physical systems. Bond Graph modeling is also a graphical approach for modeling to transfer of energy between different systems components which are connected by bonds. Complex physical systems that have several energy domains in its complicated structure are converted into a single model by the method. Therefore, the energy transformation in the model can be realized quite easily, and this provides convenience to researchers to model their complex system. Hence the further proceedings will process upon the model.
The method has a significant property that the system can be obtained directly geometrical and observational way in any complex physical system. Besides, Bond Graph modeling has some advantages of which are compliance, graphical structure and conciseness. The compliance is about the physical system model and the Bond Graph model that preserves the structural information. The model can represent more information; namely, effort and flow, in the graphical structure than block diagram. Since the physical system topology, the method is conciseness.
Two types of information are necessary and sufficient to describe the energetic transfers inside the system transfer in Bond Graph modeling: effort and flow. These variables are shown in Table 1 in some different energy domains.
Hroncová D. et al. (2012) represented that the elementary components are classified by their energetic behavior (energy dissipation, energy storage, etc.), by their function inside the system (flow sensor, etc.) as it is shown in Table 2.
R, I and C elements are named as 1-port elements, TF and GY as 2-ports elements, and 1 and 0 junctions as 3-ports elements. R, I and C analogous elements are given with terms and representation of different energy domains together in Table 3. Gawthrop P. J. and Bevan G. P. (2007)

Table I. Effort and flow variables in different physical domains

Energy Domains		Effort, e	Flow, f
Mechanical	Translational	Force	Velocity
	Rotational	Momentum	Angular velocity
Electrical	Electrical	Voltage	Current
	Electromagnetic	Magnetomotive Force	Magnetic Flux Rate
Hydraulic		Pressure	Volume Flow Rate
Thermal		Heat	Entropy Change Rate
Chemical		Chemical Potential	Molar Flow

Table II. Elementary components of Bond Graph, Hroncová D. et al. (2012)

Components	Nomenclature	Description
Active Elements	SE	Effort generation
	SF	Flow generation
Passive Elements	R	Energy dissipation node
	I	Effort dissipation node
	C	Flow dissipation node
Conversion Elements	TF	Energy transformation implying
	GY	Energy transformation implying

Table III. R, I and C analogous elements in different energy domains.

Components	Translation	Rotation	Electrical	Hydraulic
R	Damper N*s/m	Rot. Damper N*m*s/rad	Resistance Ω	Restrictor Pa*s/m^3
I	Mass kg	Inertia kg*m^2	Inductance H	Flow inertia kg/m^4
C	Spring N/m	Torsion spring N*m/rad	Capacitor F	Accumulator Pa/m^3

The simple representation of 1 and 0 junctions in Bond-Graph modeling are given in Figure 1. The effort and flow equations of the junctions are demonstrated in (1) and (2). While all efforts are equal in 0 junctions, all flows are equal in 1 junction.

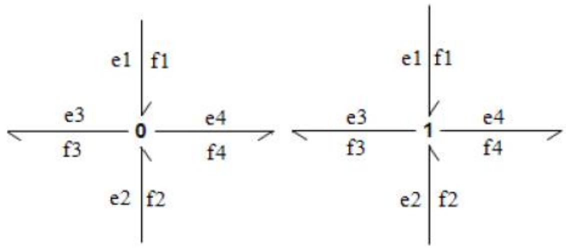

Fig 1. 0 and 1 Junctions

0 Junction: $e_1=e_2=e_3=e_4$ and $f_1+f_2=f_3+f_4$ (1)

1 Junction: $f_1=f_2=f_3=f_4$ and $e_1+e_2=e_3+e_4$ (2)

III. TORSIONAL VIBRATIONS MODELING OF PROPULSION PLANT

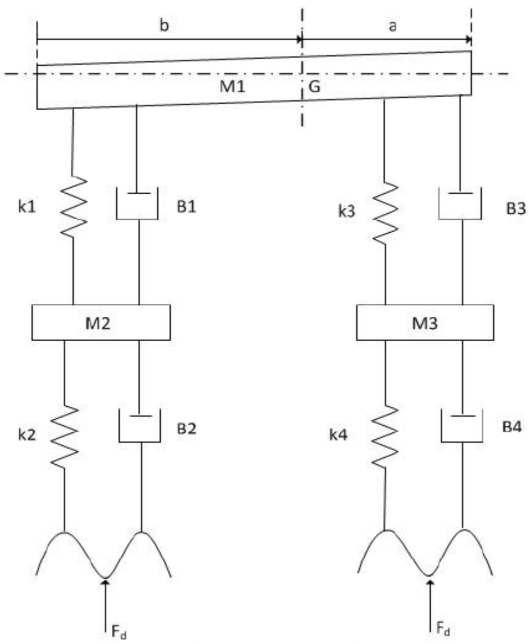

Fig 2. The half main engine block system

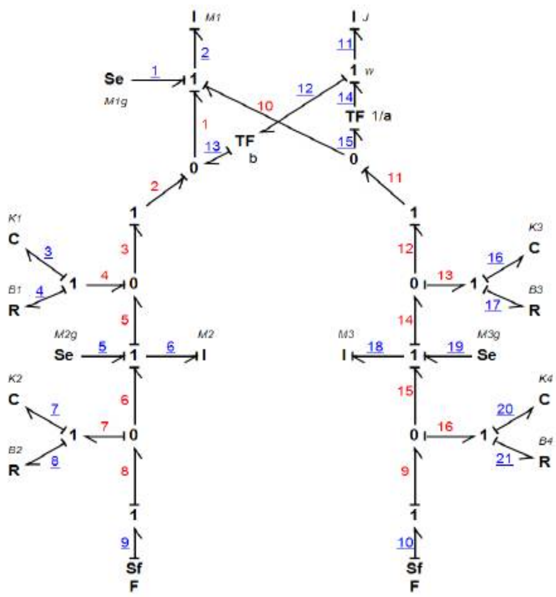

Fig 3. The Bond Graph of the system

Using Bond Graph modeling the mathematical model of a system can also be obtained by analytical way. Figure 3 shows Bond Graph of the system, and blue underlined numbers dedicate the system variables, while red numbers represent transmission points. Transmission points were considered as underlined when system dynamic equations were obtained.

The system dynamic equations may be generated by answering the following two questions:

a) What do all the elements give to the system?
b) What does the system give back to the storage elements? (D.Karnopp and R.C. Rosenberg, (1983)).

Effort is generally given as $e=\dot{p}$, and p represents momentum. Flow is shown as $f=\dot{q}$, and q denotes displacement. R and C elements give to the system effort, while I element gives flow. The equations (3-5) show how to answer question a, and to derive state-space equations.

$$e = R * f \qquad (3)$$

$$e = q/C \qquad (4)$$

$$f = p/I \qquad (5)$$

The answer of the question b gives us state-space equations. The state variables in Bond Graph modeling are storage elements. In our model we have eight state variables, namely;

$$\dot{x} = [\dot{p}_2 \ \dot{q}_3 \ \dot{p}_6 \ \dot{q}_7 \ \dot{p}_{11} \ \dot{q}_{16} \ \dot{p}_{18} \ \dot{q}_{20}] \qquad (6)$$

P_{11} represents the angular velocity of the main body of the ship main engine. (*1), (*2) and above expressions were used to derive state-space equations. The following expression shows the nonlinear state-space is equation of the Bond Graph modeling of ship main engine.

$$\begin{bmatrix}\dot{p}_2\\ \dot{q}_3\\ \dot{p}_6\\ \dot{q}_7\\ \dot{p}_{11}\\ \dot{q}_{16}\\ \dot{p}_{18}\\ \dot{q}_{20}\end{bmatrix} = \begin{bmatrix} -\frac{B_1+B_2}{M_1} & K_1 & \frac{B_1}{M_2} & 0 & \frac{b*B_1-a*B_3}{J} & K_3 & \frac{B_3}{M_3} & 0 \\ -\frac{1}{M_1} & 0 & \frac{1}{M_2} & 0 & \frac{b}{J} & 0 & 0 & 0 \\ -\frac{B_1}{M_1} & -K_1 & \frac{B_1 \ B_2}{M_2} & K_2 & \frac{b*B_1}{J} & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{M_2} & 0 & 0 & 0 & 0 & 0 \\ \frac{b*B_1 \ a*B_3}{M_1} & -b*K_1 & -\frac{b*B_1}{M_2} & 0 & -\frac{b^2*B_1+a^2*B_3}{J} & a*K_3 & \frac{a*B_3}{M_3} & 0 \\ -\frac{1}{M_1} & 0 & 0 & 0 & -\frac{a}{J} & 0 & \frac{1}{M_3} & 0 \\ \frac{B_3}{M_1} & 0 & 0 & 0 & \frac{a*B_3}{J} & -K_3 & -\frac{B_3+B_4}{M_3} & K_4 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{M_3} & 0 \end{bmatrix} \begin{bmatrix}p_2\\ q_3\\ p_6\\ q_7\\ p_{11}\\ q_{16}\\ p_{18}\\ q_{20}\end{bmatrix} + \begin{bmatrix} m1g \\ 0 \\ \frac{B2F-m2g}{F} \\ 0 \\ 0 \\ \frac{B4F-m3g}{F} \end{bmatrix} \qquad (7)$$

$$\begin{bmatrix}\dot{p}_2\\ \dot{q}_3\\ \dot{p}_6\\ \dot{q}_7\\ \dot{p}_{11}\\ \dot{q}_{16}\\ \dot{p}_{18}\\ \dot{q}_{20}\end{bmatrix} = \begin{bmatrix} -2,2 & 15000 & 3,334 & 0 & 0,167 & 15000 & 3,334 & 0 \\ -0,002 & 0 & 0,034 & 0 & 0,0057 & 0 & 0 & 0 \\ -0,2 & -130000 & -30 & 250000 & 0,567 & 0 & 0 & 0 \\ 0 & 0 & 0,034 & 0 & 0 & 0 & 0 & 0 \\ 0,1 & 28800 & 6,667 & 0 & 1,448 & 18000 & 4 & 0 \\ -2,002 & 0 & 0 & 0 & -0,204 & 0 & 0,035 & 0 \\ 0,2 & 0 & 0 & 0 & 0,4 & -15000 & -16,667 & 250000 \\ 0 & 0 & 0 & 0 & 0 & 0 & -0,033 & 0 \end{bmatrix} \begin{bmatrix}p_2\\ q_3\\ p_6\\ q_7\\ p_{11}\\ q_{16}\\ p_{18}\\ q_{20}\end{bmatrix} + \begin{bmatrix} -4905 \\ 0 \\ 7857 \\ \vdots \\ 0 \\ 0 \\ 7857 \\ \vdots \end{bmatrix} \qquad (8)$$

When we look at the root of the system, we can see that the system is stable. According to this result, we can apply controller and take effective result for linear and nonlinear condition.

IV. SIMULATIONS

Simulation results shown as below in Fig 4,5,6,7.

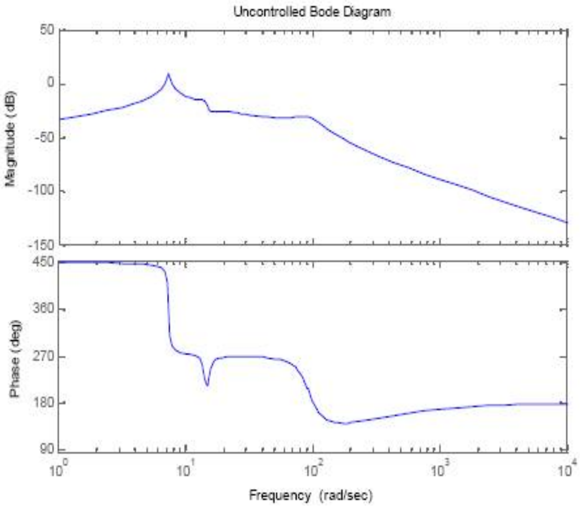

Fig 4. The bode diagram of uncontrolled system

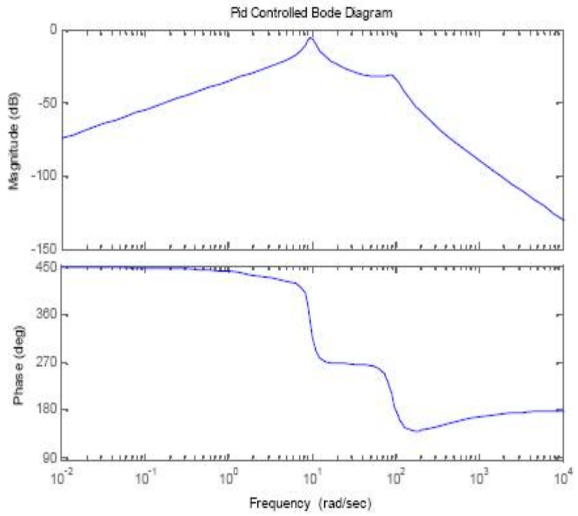

Fig 5. The bode diagram of PID controlled system

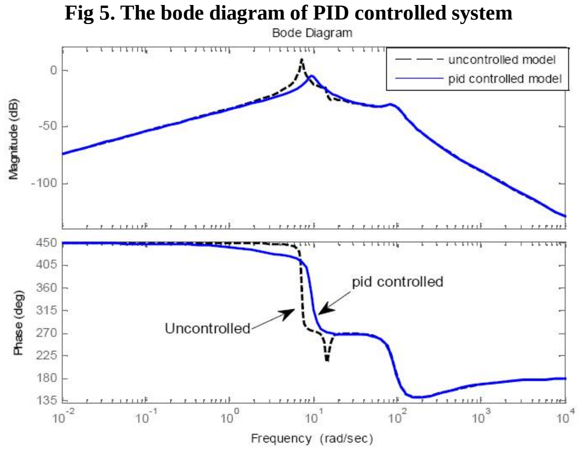

Fig 6. The bode diagram of linear uncontrolled and PID controlled system.

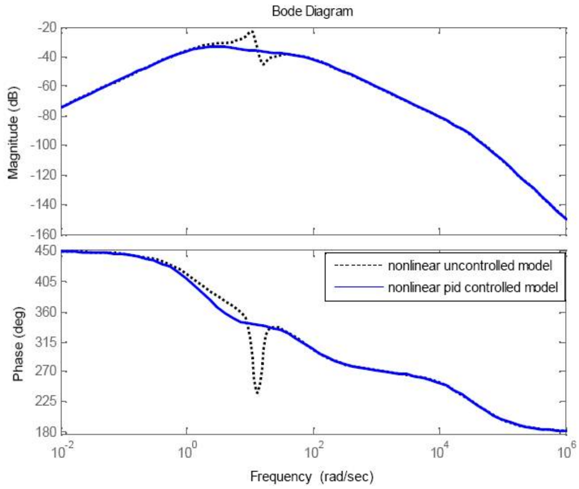

Fig 7. The bode diagram of nonlinear uncontrolled and PID controlled system

CONCLUSION

In this study, vibrations occurring in the main engine system equipments are examined. The mathematic model of ship main engine system is formed by Bond Graph method. The effect of dynamics forces resulting in main engine and hydrodynamic forces related to water effect were taken into account. Nonlinear equations of system dynamics are expressed in state-space form. According to the responses of the model, frequency response is simulated to controlled and uncontrolled condition. The bode diagram of nonlinear PID controlled system represents positive effect in terms of frequency peak. Bond Graph modeling with PID controller may be a preferential alternative approach instead of conventional methods to prevent of the ship main engine vibrations.

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