Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 06, June - 2017

Investigating Efficiency of a Five-Mass Electromechanical System having Damping Friction, Elastic Coupling and Clearance

Mr. Aboah Boateng Emmanuel,
Student (BSc.),
Electrical and Electronic Engineering Department,
University of Mines and Technology,
Tarkwa, Ghana.

Mr. Normanyo Erwin,
Senior Lecturer,
Electrical and Electronic Engineering Department,
University of Mines and Technology,
Tarkwa, Ghana.

***Abstract*— Electromechanical systems used in industrial setups have some drawbacks in their operation which have been a major challenge of researchers over the years in their design. Notable among these drawbacks are damping friction, elastic coupling and clearance. Recent works in the literature however are limited to one-mass, two-mass and on a few occasions, three-mass system models in the quest to investigate the effects of these drawbacks. This work seeks to extend and improve upon the quality of the existing models by formulating a model of a five-mass system having these drawbacks for the purpose of efficiency investigation. In this research, a mathematical model and subsequently, MATLAB Simulink model of a generic five-mass system was developed for simulations. Simulation results revealed that in the analysis of the efficiency of a five-mass system, the effect of damping friction is paramount as compared to that of elastic coupling and clearance.**

Keywords*— *Five-mass system, electric drive, clearance, stiffness

I. INTRODUCTION

In several industrial setups such as steel rolling mills, flexible robot arms, large space structures, machine tools, helicopter control system, slurry pumping system, measurement machines and ball mill drives are mostly considered as two-mass or multi-mass systems.

Electromechanical systems used in these industrial setups consist of electrical and mechanical parts. Mechanical elements used in precision positioning systems and power transfer such as gears and clutches pose limitations like damping friction, elastic coupling and clearances which affect the efficient and effective operation of electromechanical systems [1].

Systems with infinite stiffness and without clearance are qualified as one-mass systems and are quite well analysed. Complex systems with more than one mass coupling between the driving source and connected loads are known as multi-mass systems. Mostly, the simplification as a one-mass system is not appropriate and leads to unsatisfactory control performances [2]. Moreover, in order to minimise noise and improve the efficiency of electromechanical systems, it is essential to accurately predict the dynamic behaviour of these systems, hence the need for a multi-mass system modelling.

Oscillations and instabilities in drive systems as a result of clearance, finite stiffness and friction affect the efficient transfer of power from prime mover to the connected load [3]. Energy costs have significantly increased and environmental awareness has arisen recently. This is one of the main reasons why energy effectiveness has become an important matter in designing industrial drives.

The main goal of this research therefore, is to investigate the efficient utilisation of electric power of a five-mass system having damping friction, elastic coupling and clearance.

II. RELATED WORKS

A mass system is basically a drive chain that consists of a driving machine (prime mover), coupling elements (couplings, gears etc.) and a driven machine (power consumer) [4]. The nature of the couplings between the prime mover and the mechanical elements or load classifies them as either single or multi-mass systems. One-mass systems serve as basis for modelling electromechanical systems but are not popular due to their limitations and deviations from reality [5], [4]. Two-mass systems are very popular and well analysed due to their simplicity and easy modelling with little deviation from reality. Three-mass system models have few literature related to them, though they prove to be better and closer to reality as compared to a two-mass system [6].

Works on five-mass systems however, are non-existent in the literature. Systems such as helicopter control mechanism and ball mill drives are some examples of five-mass systems. Therefore, lack of relevant literature on five-mass system models calls for further research to extend and improve upon the quality of the existing models of two-mass and three-mass systems.

III. METHODS USED

Five-mass systems are complex electromechanical systems having elastic couplings and connections between five masses with the first mass usually the prime mover transferring mechanical energy to a load (final mass) through various mechanical elements. The mechanical couplings between these masses may affect the efficient transfer of energy to the final mass due to elastic coupling, clearance, damping friction etc., which are inevitable in the design of industrial drives [1].

A. Schematic Diagram of a Five-mass System

A schematic diagram of a five-mass system having elastic coupling, clearance and damping friction is shown in Fig. 1.

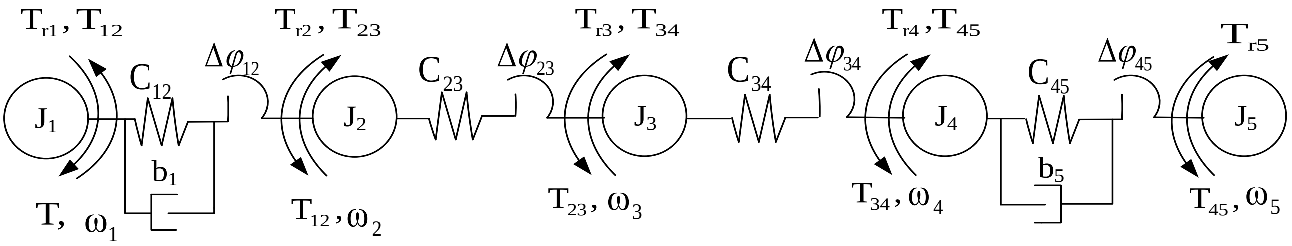

Fig. 1 A Schematic Diagram of a Five-Mass System having Damping Friction, Elastic Coupling and Clearance

The five-mass electromechanical system considered in Fig. 3.1 has moment of inertia, J_1 and J_5 representing inertia of the electric prime mover driving the system and the final load respectively. Moment of inertia J_2, J_3, and J_4 represent the masses of different mechanical elements such as gears, shafts, clutches etc. that aid in the actuator mechanism. The couplings between the masses are considered to be elastic, represented by C_{12}, C_{23}, C_{34} and C_{45} which characterise the stiffness between masses 1 and 2, 2 and 3, 3 and 4, and 4 and 5 respectively. The speed of rotation, ω_1 and ω_5 of electric prime mover and the load respectively are different. This is partly due to the elastic couplings and kinematic clearances $\Delta\varphi_{12}$, $\Delta\varphi_{23}$, $\Delta\varphi_{34}$ and $\Delta\varphi_{45}$ between masses 1 and 2, 2 and 3, 3 and 4, and 4 and 5 respectively. The damping coefficients of the prime mover and the load are denoted by b_1 and b_5 respectively.

B. *Mathematical Model of the Five-mass System*

Based on Newton's law of rotational motion, the mathematical model of the Five-mass system was derived considering the various directions of motion of the masses in Fig. 1. The mathematical model was transformed into the Laplace domain for simulations.

Based on Fig. 1, the transfer functions of masses 1, 2, 3, 4 and 5 were derived as follows:

$$G_1(s) = \frac{\omega_1}{T - T_{r1} - T_{12} + b_1\omega_2} = \frac{1}{J_1 s + b_1} \tag{1}$$

$$G_2(s) = \frac{\omega_2}{T_{12} - T_{r2} - T_{23}} = \frac{1}{J_2 s} \tag{2}$$

$$G_3(s) = \frac{\omega_3}{T_{23} - T_{r3} - T_{34}} = \frac{1}{J_3 s} \tag{3}$$

$$G_4(s) = \frac{\omega_4}{T_{34} - T_{r4} - T_{45}} = \frac{1}{J_4 s} \tag{4}$$

$$G_5(s) = \frac{\omega_5}{T_{45} - T_{r5} + b_5\omega_5} = \frac{1}{J_5 s + b_5} \tag{5}$$

Transfer functions representing rotational stiffness between masses 1 and 2, 2 and 3, 3 and 4, and 4 and 5 were also derived as follows:

$$\frac{C_{12}}{s} = \frac{T_{12}}{(\omega_1 - \omega_2)} = Y_{12} \tag{6}$$

$$\frac{C_{23}}{s} = \frac{T_{23}}{(\omega_2 - \omega_3)} = Y_{23} \tag{7}$$

$$\frac{C_{34}}{s} = \frac{T_{34}}{(\omega_3 - \omega_4)} = Y_{34} \tag{8}$$

$$\frac{C_{45}}{s} = \frac{T_{45}}{(\omega_4 - \omega_5)} = Y_{45} \tag{9}$$

The corresponding transfer functions were used to develop a block diagram of the five-mass electromechanical system for efficiency investigations as shown in Fig. 2.

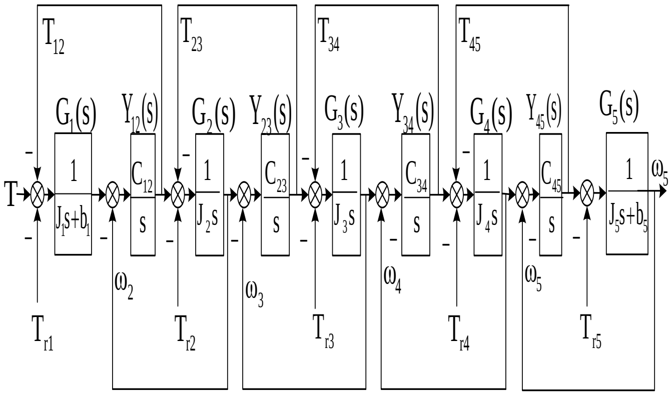

Fig. 2 Block Diagram of the Ball Mill Drive as a Five-Mass Electromechanical System having Damping Friction, Elastic Coupling and Clearance

C. *Simulations*

Fig. 3 represents a MATLAB Simulink model of the five-mass system having damping friction, elastic coupling and clearance. The model was designed in such a way to produce a corresponding output power and efficiency of the system as the input parameters changes. The clearance in the model of Fig. 3 is expressed by the dead zone block of Simulink.

A number of scenarios were considered in the simulations of the five-mass system model. The scenarios considered are as follows:

1. Varying damping coefficients at constant stiffness and clearance parameters.
2. Varying stiffness values at constant damping and clearance parameters.
3. Varying clearance parameters at constant stiffness and damping friction.

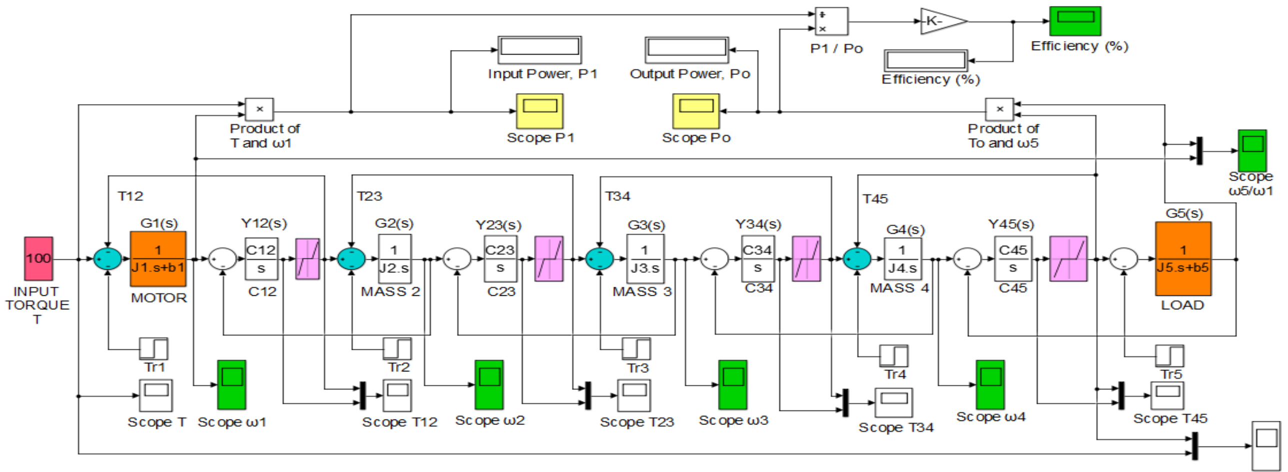

Fig. 3 Simulink Model of the Five-mass System having Damping Friction, Elastic Coupling and Clearance

The clearance in the model of Fig. 3 is expressed by the dead zone block of Simulink which specifies the upper and lower limits of the torsional angle at the joints. Only electromagnetic transients are expected in the system before the dead zone is passed and afterwards the next mass starts to exert influence on the dynamics of the system [4].

It is convenient to investigate dynamic characteristics of the five-mass system in Simulink because it provides the possibility to consider non-linearity of any type.

Table 1 shows the preferred standard parameters used for the simulation of the five-mass system model. These parameters were varied in various scenarios to identify the influence of damping friction, elastic coupling and clearance on the efficiency of the system.

Table 1: Standard Parameters of Simulations

Parameter	**Value**	**Unit**
Step Input Torque, T	100	Nm
Stiffness Coefficient, C_{12}	50,000	Nm/rad
Stiffness Coefficient, C_{23}	60,000	Nm/rad
Stiffness Coefficient, C_{34}	3,000	Nm/rad
Stiffness Coefficient, C_{45}	3,000	Nm/rad
Clearance, $\Delta\varphi_{12}$	5	mm
Clearance, $\Delta\varphi_{23}$	8	mm
Clearance, $\Delta\varphi_{34}$	5	mm
Clearance, $\Delta\varphi_{45}$	8	mm
Damping Friction of Motor (b_1)	3	Nm/rad/s
Damping Friction of Load (b_5)	10	Nm/rad/s

IV. RESULTS AND DISCUSSIONS

The result of the simulations of the various scenarios are presented and discussed in this section. The central point of discussions of the results is the influence of damping friction, elastic coupling and clearance on electric power utilisation and stability of the five-mass system.

A. *Simulation Results*

The results of input and output power as well as efficiencies of simulations of the generic five-mass system model are presented in Fig. 4 to Fig. 7.

With the exception of Fig. 7, the first three graphs of Fig. 4, 5 and 6 are related to power consumption whereas their last graphs (fourth) are related to efficiency of the system.

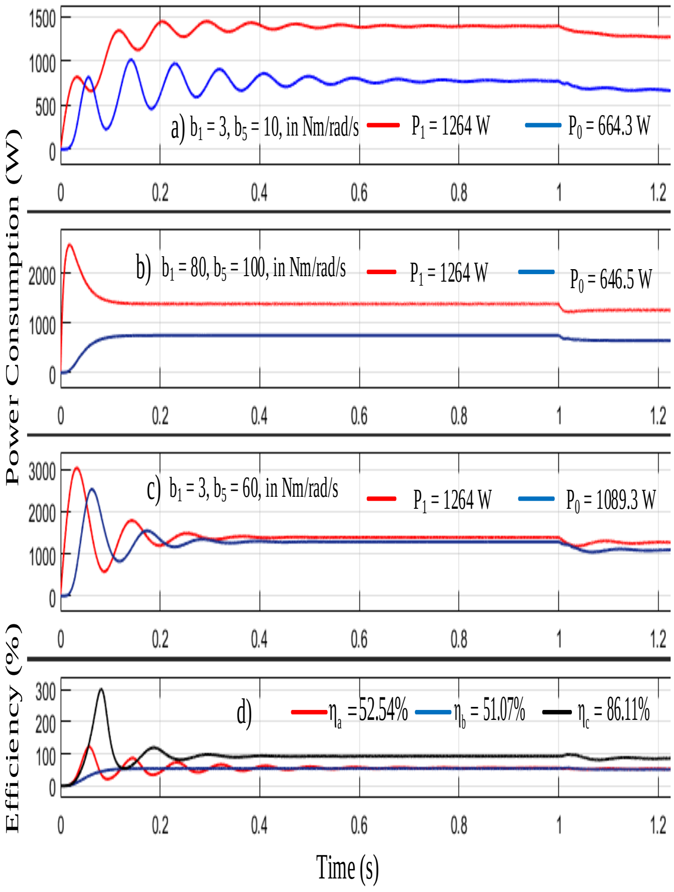

Fig. 4 Varying Damping Coefficients at Constant Stiffness and Clearance

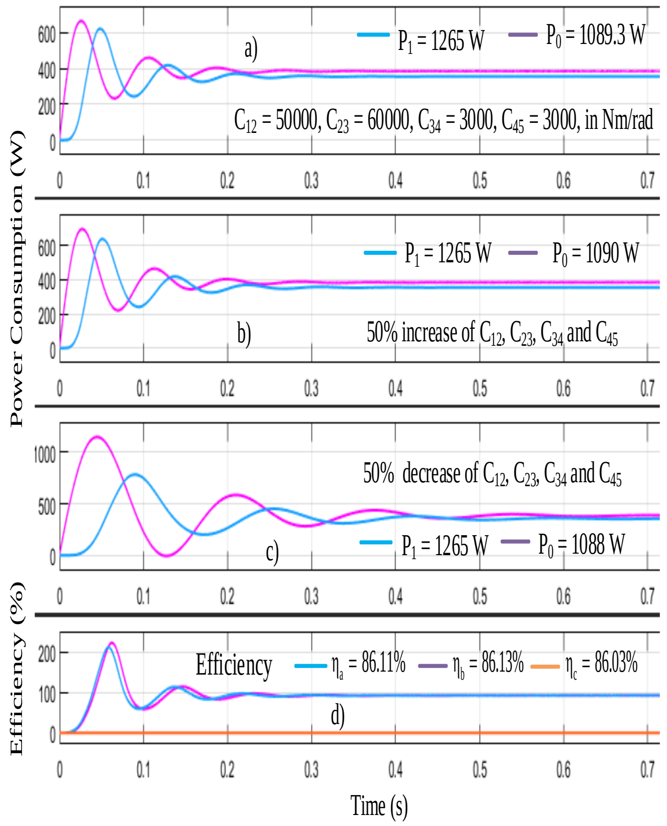

Fig. 5 Varying Stiffness Values at Constant Damping and Clearance Parameter

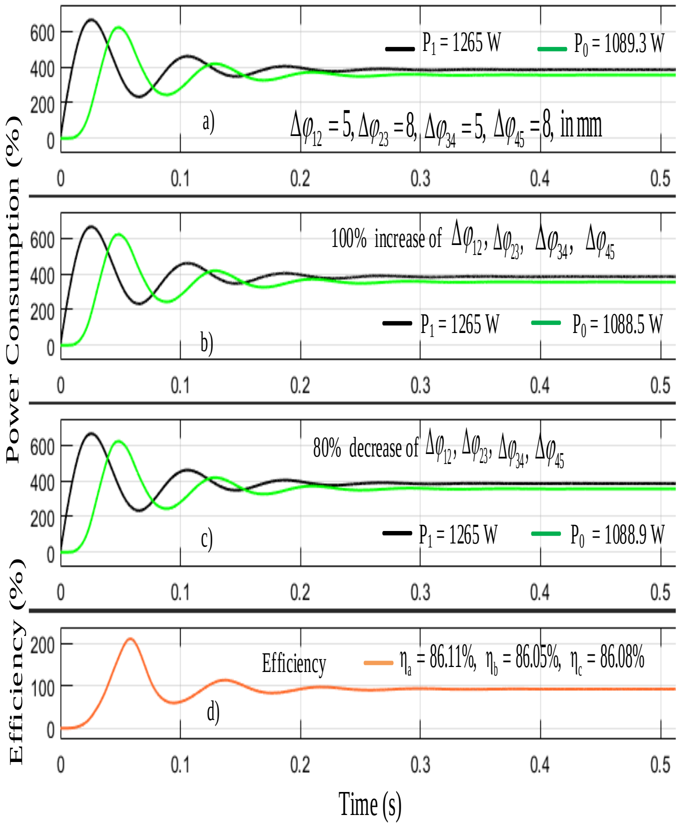

Fig. 6 Varying Clearance Values at Constant Stiffness and Damping Coefficients

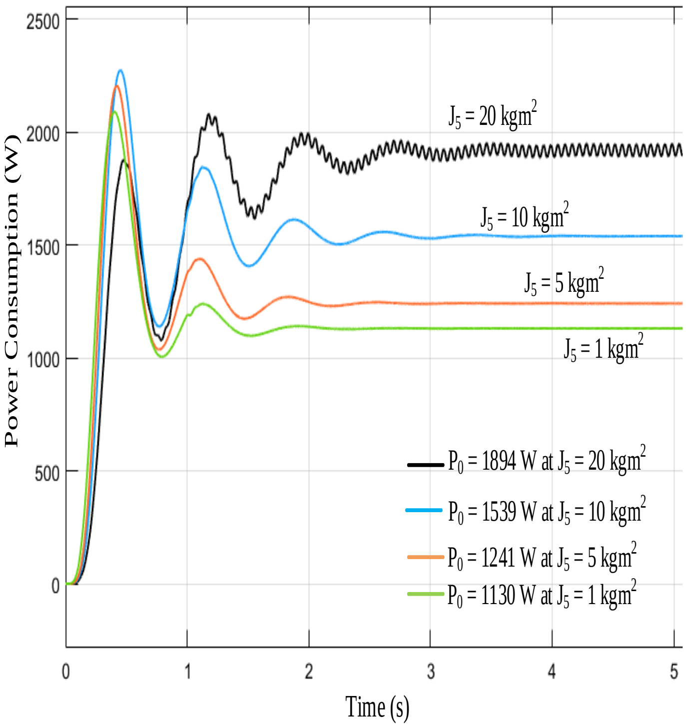

Fig. 7 Varying Mass 5 (Load) at Constant Stiffness, Damping Friction and Clearance Coefficients

B) Discussions of Simulation Results

The simulation results of Fig. 4 showed that damping friction had the greatest influence on the efficiency of the generic five-mass system model. For an input power of 1264 W, relatively high damping coefficients of b_1 = 80 Nm/rad/s and b_5 = 100 Nm/rad/s resulted in a very low output power of 646.5 W with a corresponding poor efficiency of 51.07%. This was due to the fact that the system was overdamped and hence a higher percentage of the input energy was converted to heat, resulting in higher losses. At relatively low damping coefficients of b_1 = 3 Nm/rad/s and b_5 = 10 Nm/rad/s for the same input power, a low output power of 664.3 W was recorded for an efficiency of 52.54%. This was as a result of the system being underdamped, hence there was a high level of instability and oscillations in the system which affected the efficient operation of the system. However, at moderate damping coefficients of b_1 = 3 Nm/rad/s and b_5 = 60 Nm/rad/s, there was an increase in output power to 1089.3 W giving an efficiency of 86.11%. This was due to the tolerable damping friction during the transient period for only 0.3 s.

From Fig. 5, stiffness values of the elastic couplings had less effect on efficiency of the five-mass system but they rather affected the stability of the system. From Fig. 4.2, at 50% decrease in the preferred stiffness values, the output power decreased slightly to 1088 W giving an efficiency of 86.03%. However, there was poor stability of the system due to higher frequency of oscillations during the transient period. Moreover, 50% increase in the preferred stiffness values resulted in a little increase in the output power to 1090 W offering an efficiency of 86.13% and a higher stability, which was attributed to lower amplitudes of oscillations for a less settling time of 0.3 s. Finally, results of the preferred stiffness values of C_{12} = 50000 Nm/rad, C_{23} = 60000 Nm/rad, C_{34} =

3000 Nm/rad and C_{45} = 3000 Nm/rad produced an output value of 1089.3 W resulting in an efficiency of 86.11% with high system stability.

From Fig. 6, the results of varying clearance values showed that clearance had no meaningful effect on efficiency of the generic five-mass system. At standard clearance values of and the output power stood at 1089.3 W giving an efficiency of 86.11%. However, for 100% increase and 80% decrease in the standard clearance values, the output power was 1088.5 W and 1088.9 W respectively which resulted in efficiencies of 86.05% and 86.08% respectively. With no significant influence of clearance on the system's efficiency, it buttressed the point that clearance in mass systems cause the load shaft speed to lag behind the motor shaft speed during transient periods but once steady state is achieved, they settle at the normal operating speeds resulting in normal output power [4].

Higher load inertia resulted in higher power consumption with less stability and vice versa as shown in Fig. 7. At load inertia of 20 kgm^2, the power consumption was relatively high at 1894 W with less stability. This was because at higher moment of inertia, more kinetic energy is required to cause rotation of the load and vice. Hence, load inertia of 10 kgm^2, 5 kgm^2, and 1 kgm^2 resulted in decreasing rate of power consumption of 1539 W, 1214 W and 1130 W respectively. It was posited by [3] that increasing values of load inertia result in increasing transient periods of speed and torque. This explains why the settling times and overshoots of power consumption waveforms of Fig. 7 increased with increasing load inertia since power is a product of speed and torque.

V. CONCLUSIONS

Based on the findings of the generic five-mass system model, it can be concluded that:

1. Very low and very high damping coefficients result in poor efficiency whilst moderate damping coefficients give efficiencies more than 85%.

2. Changes in standard stiffness values to the tune of hardly affect the efficiencies which stand high at values of at least 86%. It rather affects the stabilty of the five-mass system. Thus, the lower the stiffness value, the less stable the system.

3. Changes in standard clearance values from 80% to 100% of the preferred values result in no meaningful change in efficiency that stands at above 86%.

4. The more the load inertia, the higher goes the power consumption and more unstable the five-mass mechanical system becomes.

REFERENCES

[1] F.Y.M. Mohd, Q. Abdul, and B.A. Aminudin, B. A, "Comparative Study on Control Method for Two-mass Systems", *International Journal on Advanced Science Engineering and Information Technology*, Vol. 2, pp. 63 – 67, 2012.

[2] S. Juraitis, R. Rinkeviciene, and A. Kilikevicius, "Two-mass Variable Speed Drive*", Electronics and Electrical Engineering Journal*, Vol. 30, No. 4, pp. 25 – 28, 2010.

[3] K. Drozdz, "Adaptive Control of the Drive System with Elastic Coupling using Fuzzy Kalman Filter with Dynamic Adaptation of Selected coefficients", *Maintenance and Reliability*, Vol. 17, No. 4, pp. 561 – 568, 2015.

[4] S. Juraitis, "Research of Transient Process in Electromechanical Two-mass System", *Unpublished Summary of Doctoral Dissertation*, Vilnius Gediminas Technical University, Lithu ania, 24pp, 2013.

[5] S. Ghazanfar, "Modelling and Simulation of a Two-mass Resonant System with Speed Controller", *International Journal of Information and Electronics Engineering*, Vol. 3, No. 5, pp. 449 – 452, 2013.

[6] M. Kobusch, S. Eichstadt, L. Klaus, and T. Bruns, (2014), "Investigations for the Model-based Dynamic Calibration of Force Transducers by using Shock Forces", *3rd TC22 International Conference, Cape Town*, South Africa, pp. 127 – 135, 2014.