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Modelling and Designing a Mechatronics System for High Speed Packaging Operations Using Mechatronics Methodology

Mr. Vivek Pillarisetty P.E., Purdue University Northwest

Vivek Pillarisetty is an Indian Graduate Student studying Mechatronics in Purdue University, Calumet in the state Indiana. He has done his under graduation in KLUniversity, Vijayawada, India. He is an outstanding student and favorite for all of his professors. He is an active participant in both co curricular and extra curricular activities. He is an avid reader and an interpreter. He learns the subject in depth and tries to work hands on whatever he learns. He is currently doing his research in packaging technology under Professor Akram Hossain in Purdue University, Calumet. After seeing his insight, the Professor offered him a Teaching Assistant position in the laboratory for guiding the students in the subject of Mechatronics.

Dr. Akram Hossain, Purdue University Northwest

Akram Hossain, Purdue University Calumet Akram Hossain is a professor in the department of Engineering Technology and Director of the Center for Packaging Machinery Industry at Purdue University Calumet, Hammond, IN. He worked eight years in industry at various capacities. He is working with Purdue University Calumet for the past 27 years. He consults for industry on process control, packaging machinery system design, control and related disciplines. He is a senior member of IEEE and he served in IEEE/Industry Application Society for 15 years at various capacities. He served as chair of Manufacturing Systems Development Applications Department (MSDAD) of IEEE/IAS. Currently, he is serving a two-year term as the chair of the Instrumentation of ASEE (American Society of Engineering Education). He authored over 29 refereed journal and conference publications. In 2009 he as PI received NSF-CCLI grant entitled A Mechatronics Curriculum and Packaging Automation Laboratory Facility. In 2010 he as Co-PI received NSF-ATE grant entitled Meeting Workforce Needs for Mechatronics Technicians. From 2003 through 2006, he was involved with Argonne National Laboratory, Argonne, IL in developing direct computer control for hydrogen powered automotives. He is also involved in several direct computer control and wireless process control related research projects. His current interests are in the area of packaging machinery system design & control, industrial transducers, industrial process control systems, modeling and simulation of Mechatronics devices and systems in virtual environment, programmable logic controllers, programmable logic devices, renewable energy related projects, wireless controls, statistical process control, computer aided design and fabrication of printed circuit board.

Modelling and Designing a Mechatronics System for High Speed Packaging Operations

Abstract:

Accomplishing a lean manufacturing standards and increasing rate of production are very important for today's industry. An automated system, like one that achieves packaging rates of up to 300 parts per minute, appears to be the answer. Industrial automation is an engineering marvel. Mechatronics is synergistic yet a multidisciplinary field of science which adopts and shares platform between interdisciplinary engineering technologies. The process of operation of a control systems (Mechatronics System) incorporates different modules in it, which does different tasks like an assembly line. Considering all this, high-speed systems depend on the synchronized interplay between parts. When a motor and a load are coupled together, the ratio of load inertia to motor inertia determines how well the motor can control the load during acceleration and deceleration. When it comes to high speed motion control, torque alone is not enough. Inertia mismatch between the load and the motor also plays an important role.

Applications like 300 part-per-minute packaging or 3D printing require ultrahigh operational speed accurate positioning, and tight synchronization among dozens of axes. Mechatronics (Electromechanical) systems can provide this degree of performance, but they depend on proper interplay between the mechanical properties and the electrical properties of the system. This inertia mismatch makes it difficult to synchronize the process, which is one of the most common problem that many industries face these days. To study and analyze this mismatch modeling is the most inexpensive and a great time saver in the process of designing a Mechatronics system.

There are many ways the modeling of a system can be achieved. The LabVIEW is one of most powerful software tool and we applied this to model the mechatronics (electromechanical) systems. As a matter of fact we have unleashed the power of this tool by applying it for modeling purposes. By using this tool, we could generate very accurate results that matches the desired outcome. Since our analysis using models are performed in advance, it saves time, money and provides dynamic features that was never experienced before. This model also delivers the results in graphical format which is an easier way to understand a complex mechatronics system performance. Also, our model is very suitable for future transition to real world design and implementation of mechatronics system. Use of this model would provide us with advanced understanding of torque, inertia mismatch, and motion profile of the process. Motor sizing is also done based on the surge curve and output responses that is generated through this modeling process. With the results in hand, it is an added advantage to either build a custom motor or compare with the existing motor specification already available from various manufacturers. Motion analysis of Mechatronics system using modeling is a very dynamic, inexpensive, and

provides Mechatronics system manufacturer vital information at the design and development stage.

Introduction:

As the automation in industries has become more promising and technology for motion control of electric drives became available, the use of programmable logic controllers (PLCs) with power electronics in electric machines applications has been introduced in the manufacturing process. A programmable logic controller (PLC) is an industrialized computer control system that constantly monitors the state of input devices and makes decisions based upon a custom program to control the state of output devices. Almost any production line, machine function, or process can be greatly enhanced using this type of control system.

However, the biggest benefit in using a PLC is the ability to change and replicate the operation or process while collecting and communicating vital information. It is also a modular system. It can be mixed and matched the types of Input and Output devices to best suit of any laboratory application and industrial control application. The purpose of this paper is, although most of the manufacturing and food industries are using the PLCs in their manufacturing process still there are cases where quality issues arise in the assembly or the product aesthetics (misplaced label). Among the few causes for this problem Inertia mismatch is one of the most common. As the industrial graded PLCs panels are mare often equipped or integrated with conveyors, robot arms and wired controllers that operate at higher rates. Applications like 300 part-per-minute packaging or 3D printing require ultrahigh speed operation, accurate positioning, and tight synchronization among dozens of axes. Mechatronics (Electromechanical) systems can give this level of execution. However, they rely on proper transaction between the mechanical properties and the electrical properties of the system. This unsynchronized process leads in inertia mismatch.

Inertia Mismatch:

When it comes to motion control, torque alone is not enough. Proper interplay between the mechanical properties and the electrical properties of the system. If an axis has poor mechanical characteristics caused by a high inertia mismatch between load and motor and/or significant compliance (torsional flex) in the coupling, shafts, and belts, mechanical resonances will prevent the electrical controls from performing as required. At best, you might wind up with overshoot and extended settling times; at worst, the axis may fall into runaway oscillation. It doesn’t matter how much torque you have - if your load inertia is too high for your motor and coupling, your system simply will not perform as required. The operation and the occurrence of the inertia miss match is generally found in the electromechanical systems. An electromechanical system is a mechanical system that is coupled with an electrical system such as a servo motor that is running a conveyor system which carries load.

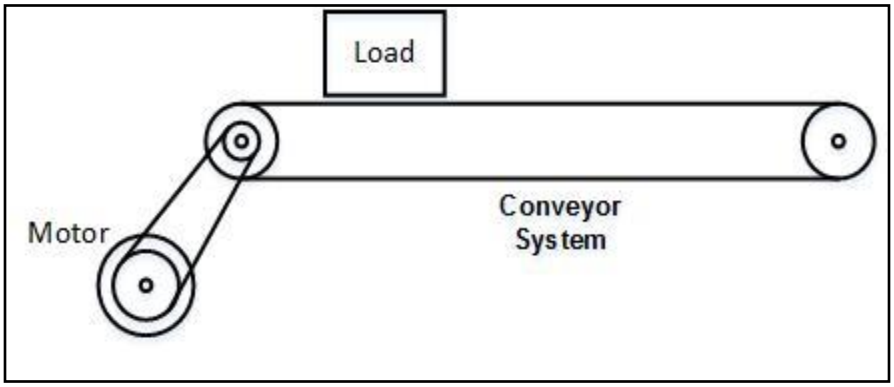


Figure 1. Electromechanical system with a motor and a conveyor

Electromechanical system is taken for the hypothesis because, in general most of the systems used in industries are of the same kind or to a rotational system. In this system, analysis can easily be performed to identify the effect of inertia mismatch. An electromechanical system is made of a motor reducer involving an external load and operates with the transition of torque from the motor side to the load side as the power outcome does not emphasize. The variables that play an important role in handling the torque shifts are the acceleration constants and inertia of the gears, reducers, motor. For modeling mechanical systems with electrical circuits, it is also necessary to define the relationship among variables within each group. Considering the use of an electromechanical system coupled with a translational system. So there is a need to analyze both the translational parameters and also the electromechanical parameters and the effect of their relation.

Translational System:

For the purpose of modeling mechanical systems with electrical circuits it is also necessary to define the relationship among variables within each group. According to Newton's Laws of motion, when a force is applied on a mass, M it accelerates and a displacement, x takes place to the mass. Based on the Alembert's principle a differential equation can be written for spring, mass and damper as:

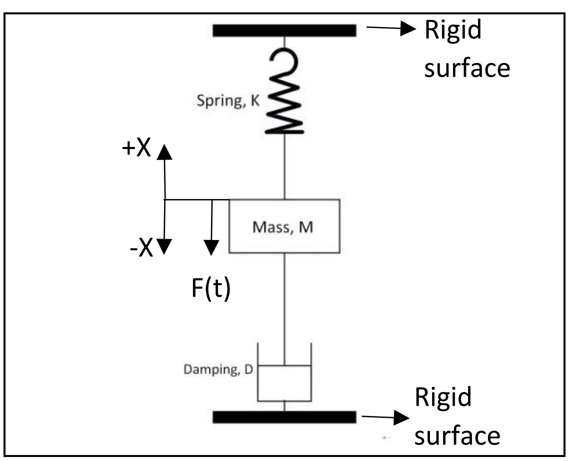


Figure 2. Mass-Damping-Spring setup

$$\frac{X(s)}{F(s)} = \frac{1}{Ms^2 + Ds + K} \qquad (1)$$

Where,

M = Mass of the Load
D = Damping coefficient
K = Spring Constant
F = Force applied

The equation 1 is the Laplace of the linear system with mass, spring and damping are fixed among two rigid surfaces.

Electromechanical System:
A motor is an electromechanical component that yields a displacement output for a voltage input, that is, a mechanical output generated by an electrical input. It consists of an armature circuit that drives the rotor which gives an angular displacement.

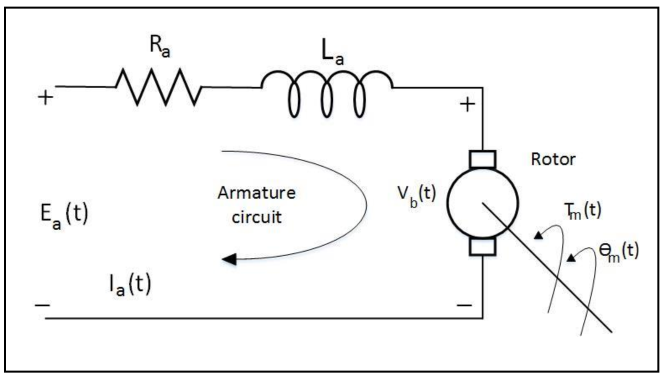


Figure 3. Electromechanical system

To derive the relation between the angular displacement (Θ_m) to the voltage input E_a we need to consider from the rotor side

$$V_b(t) = K_b \frac{d\,\theta_m(t)}{dt} \tag{2}$$

$$R_a I_a(s) + L_a s\, I_a(s) + V_b(s) = E_a(s) \tag{3}$$

The torque developed by the motor is proportional to the armature current; thus,

$$T_m(s) = K_t I_a(s)$$

Where, T_m is the torque developed by the motor, and K_t is a constant of proportionality, called the motor torque constant, which depends on the motor and magnetic field characteristics.

Substitute equation (2) in equation (3) and rearranging this equation yields

$$\frac{(R_a + L_a s)T_m(s)}{K_t} + K_b s\,\theta_m(s) = E_a(s) \tag{4}$$

Now we must find $T_m(s)$ in terms of $\Theta_m(s)$ if we are to separate the input and output variables and obtain the transfer function $\Theta_m(s) / E_a(s)$. Following Figure shows typical equivalent mechanical loading on a motor. J_m is the equivalent inertia at the armature and includes both the armature inertia and, as we will see later, the load inertia reflected to the armature. D_m is the equivalent viscous damping at the armature and includes armature viscous damping and, as we will see later, the load viscous damping reflected to the armature.

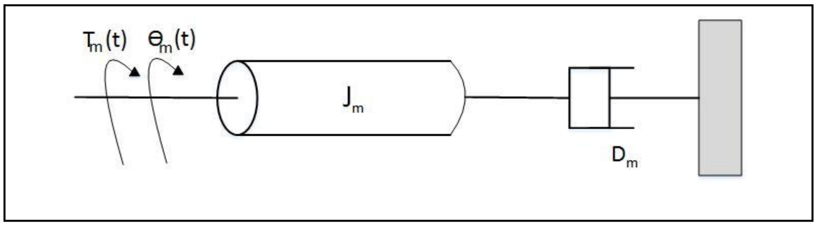


Figure 4. Mechanical load on a motor

$$T_m(s) = (J_m s^2 + D_m s)\theta_m(s) \quad (5)$$

Substituting the equation (5). into the (4) and assume that the armature inductance, La is small compared to the arm resistance, Ra, which is usual for a DC motor, then the equation will be,

$$\left[\frac{R_a}{K_t}(J_m s + D_m) + K_b\right] s\theta_m(s) = E_a(s) \quad (6)$$

Therefore, the transfer function for the electromechanical system will be

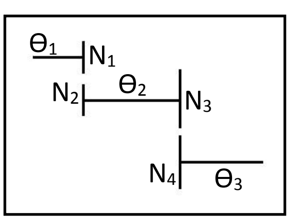
$$\frac{\theta_m(s)}{E_a(s)} = \frac{K_t / (R_a J_a)}{s\left[s + \frac{1}{J_m}\left(D_m + \frac{K_t k_b}{R_a}\right)\right]} \quad (7)$$

Where,

E_a = Applied Voltage to the Armature
K_t = Torque Constant
V_b = Back emf induced in the armature
θ_m =Angular position of the motor shaft
R_a = Armature resistance
i_a = Armature Current
K_b = Motor Constant (volt-sec/radian)
K_g = Gear ratio
L_a = Armature inductance
J_M = Motor inertia

Generic Gearbox:

To eliminate gears with the large radii, a gear train is used to implement large gear ratios by cascading smaller gear ratios.



$$\frac{\Theta_3}{\Theta_1} = \frac{N_4}{N_3} * \frac{N_2}{N_1} \quad (8)$$

Electromechanical System Coupled with Translational System:

Reason for opting is we mostly see this kind of motion transfers, either to a Rotational or Translational. Here in this model chosen we are transforming the torque outcomes from an electromechanical system which is a motor to a liner spud gear driven belt with a gear ration of N_M/ N_L.

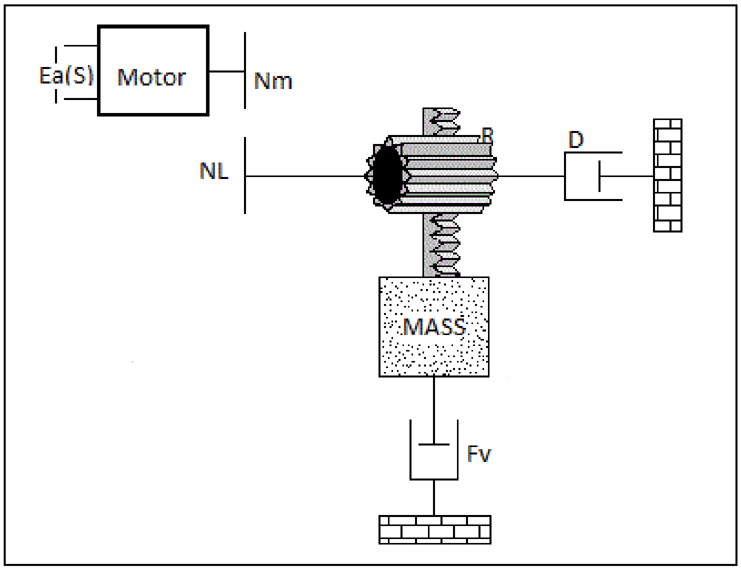


Figure 5. Electromechanical to translational system

Equation (1) and (7) are the transfer function of the linear system and an electromechanical system respectively. By considering the gear ratio and transferring the torque from the motor side to the load side which is mass in this case we will generate the equation

$$\frac{X(s)}{E_a(s)} = R\left(\frac{N_1}{N_2}\right)\left[\frac{\frac{Tstall}{e_a(s)}\cdot\frac{1}{Jeq}}{S^2+\frac{1}{Jeq}\left(D_{eq}+\frac{Tstall}{W_{no\ load}}\right)s+\frac{K.R}{Jeq}}\right] \tag{9}$$

If we are going to consider the usage of motor coefficients then the constants of the motor K_t, K_b, and R_a then we by substituting the respective constants in the above equation we get

$$\frac{X(s)}{E_a(s)} = R\left(\frac{N_1}{N_2}\right)\left[\frac{\frac{\mathrm{Kt}}{\mathrm{Ra}}\cdot\frac{1}{Jeq}}{S^2+\frac{1}{Jeq}\left(D_{eq}+\frac{\mathrm{Kt.Kb}}{\mathrm{R_a}}\right)s+\frac{K.R}{Jeq}}\right] \tag{10}$$

Where,

R = radius of the spud gear used

D_{eq} = equivalent damping

N_1, N_2 = No of teeth on the gears

J_{eq} = equivalent inertia

Modeling of a Mechatronics System:

A control system is generated by considering the output responses of a system to a desired input signal. Every control system can be mathematically represented in the form of a transfer function that is in the ratio of the output response to the input. A mechatronics system is also a control system, with the combination of mechanical and electrical components which follow the laws of conservation of energy. To analyze the operation and characteristics of any mechatronics system modeling is an inexpensive and great time saver in design process. As the process of modelling is done before the actual hardware is purchased, this will help one to understand and analyze the operation ahead of time.

There are many ways modeling of a mechatronics system is done, like using software tools like MATLAB, Simulink, Allen Bradley motion analyzer etc. The LabVIEW is one of most powerful software tool and we applied this to model the mechatronics (electromechanical) systems. As it has wide variety of mathematical models which can be used to develop a desired control system for an application we are looking to develop to run or generate a specific application. The most of the design considerations that are keenly followed in doing this project is to use this model for the further usage in applying the real-time coefficients that we can find from the pre-determined components we use. For example, if we are using already existing equipment that provides the platform to test it and modify it as required and as a cost-efficient way of production, which would not only increase in production value of the firm but also in acquaintance of the machinery used by the technicians would help in less confusion in handling the product.

Since our analysis using models are performed in advance, it saves time, money and provides dynamic features that was never experienced before. This model also delivers the results in graphical format which is an easier way to understand a complex mechatronics system performance. One key benefit of the graphical system design approach is that researchers can use the same technology in the final phase of experimental development, the deployment phase. This phase is mostly related to industry, and, with graphical system design, researchers can easily transfer the technology to market because the same tools and platforms are used in both the research/development phase in the academic environment (labs and research centers at university campuses) and the deployment phase (industry). Another key benefit of graphical system design with LabVIEW is that it offers easy and seamless integration with legacy and traditional benchtop, stand-alone instruments commonly found in research labs. In this way, even the students in school who already had LabVIEW in their course structure are able to easily fit into the industrial environment and also this reduces the transition gap between the educational backgrounds to the industrial reality.

One of the main reason for opting for LabVIEW is that the ease of determining the type of input signal taken. As the cycle of operation that a machine follows is called as motion profile.

Integration of modeling concepts into the curriculum.

Mechatronics Engineering Technology uses a combination of Mechanical and Electrical Technology courses, as it is a modular and flexible to be compatible with different concepts from other departments. However, concept of inertia mismatch is one of the highly occurred problems industries. As the curriculum of Mechatronics program already deals with the concepts of motion profile, servo programming, modeling a control system and analysis. Inertia mismatch needs to be analyzed and taken required measures to reduce it. This paper explains how the necessary concepts, missing from the traditional electrical and mechanical curriculums, are integrated into the Mechatronics program by enhancing a sequence of four courses. The student learning outcomes related to the Mechatronics concepts that have been added to the existing courses are as follows:

1. Model and analyze performance of mechanical components
2. Model and perform response analysis of mechatronics systems using software tools
3. Perform LabVIEW analysis of the electromechanical system transfer function
4. Generation of motion profiles using LabVIEW
5. Size a servomotor for a given conveyor belt application
6. Perform time-response analysis of a Mechatronics setup by varying motor, load, gearbox parameters.
7. Model and analyze performance of a control system

Motion Profile:

In assembly process in any industry high-speed and high-precision positioning stages are widely used for the inspection and operations in a process. The demand for higher precision in motion controlled system is huge. To increase the rate of operation higher velocities and accelerations are required which indeed leads to vibrations or jerks. This acceleration and deceleration in the operation of a motor is called motion profile. In position control applications, there are many ways to move from one point to another, trapezoidal motion profile is one of it. To reduce the change rate of the acceleration (jerk), the acceleration profile of a conventional square wave is modified to have a trapezoidal wave form type for the acceleration and deceleration periods. In the given Figure 6 below the acceleration time and deceleration time are intentionally kept different because the profile can be created based on the application.

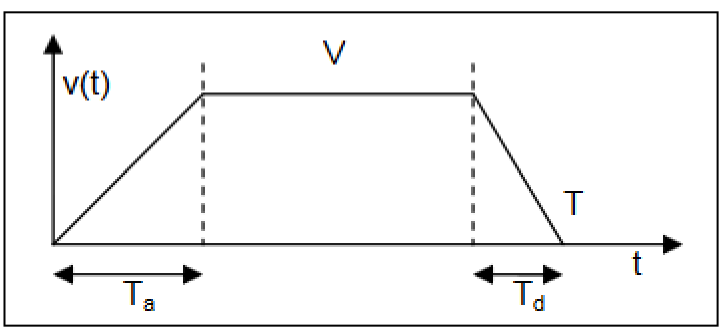


Figure 6. Trapezoidal motion profile

A trapezoidal signal has a linear acceleration followed by a constant speed and a linear deceleration, this type of motion profile will lead in having a reduced jerk in the load motion profile with the synchronization between motor and load

The main disadvantage of the trapezoidal move profile is that the higher rate of acceleration makes abrupt changes. In mechanical engineering this is quantified by “jerk” as the time derivative of acceleration (by the way “snap” is the derivative of “jerk”, “crackle” is the derivative of “snap” and “pop” is the derivative of “crackle” ...). In the case of trapezoidal moves, jerk is infinite (at least in theory, typically accelerations do not change infinitely fast).

Purpose of analyzing the motion profile is that, the impact on motor power and torque is significant. If the motor power and torque are under-sized, increased errors occur in process (or stalling in case of stepper motors) will result from torque saturation. This is the main cause for inertia mismatch.

In LabVIEW we can generate the type of input signal needed and the input signal taken for this research is trapezoidal as this signal if pushed for higher rate of acceleration it generates jerks and also is as responsive to the variable change.

Generation of Trapezoidal Signal

A trapezoidal signal has a constant rise in acceleration and a slew time or zero acceleration with constant speed and followed by a deceleration to stop. This is a complete cycle of motion profile and in industries this is looped to run a recursive operation. This trapezoidal signal needs to be generated per the requirement of slope of the acceleration and slew time and total time for a complete cycle including the stop time.

Generating of this trapezoidal signal is done by using arbitrary signal generation module. As discussed earlier regarding different types of panels and as all the arithmetic operations are done in the block diagram, signal generation module is chosen in the block diagram and respective values to the slope of the acceleration and total time of the signal is given. The values given here does not intend any imitation or standards is a random signal of time equal to one cycle.

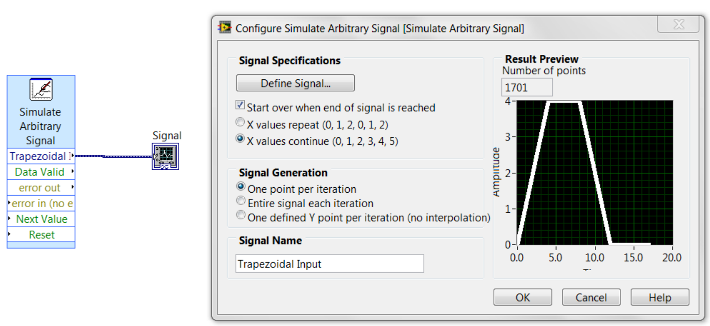


Figure 7. Generation of trapezoidal signal

This signal generated is made to run as a recursive loop so as to study the responses for the variable change for a mechatronics system.

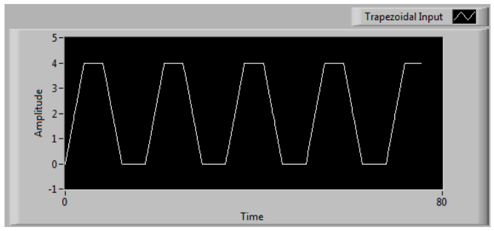


Figure 8. Trapezoidal input signal

This generated trapezoidal signal is taken as an input signal to the study that is preformed to analyze the inertia mismatch, Motor sizing and for signal processing applications.

Implementation of the Mechatronics Model in LabVIEW:

As the LabVIEW is a modular type of software and logical operations are taken in form of blocks the transfer functions (8) and (9) that are derived for an electromechanical to translational system are used to create this model in LabVIEW that replicates the mathematical operation of a real-time assembly line with load transported from point A to B.

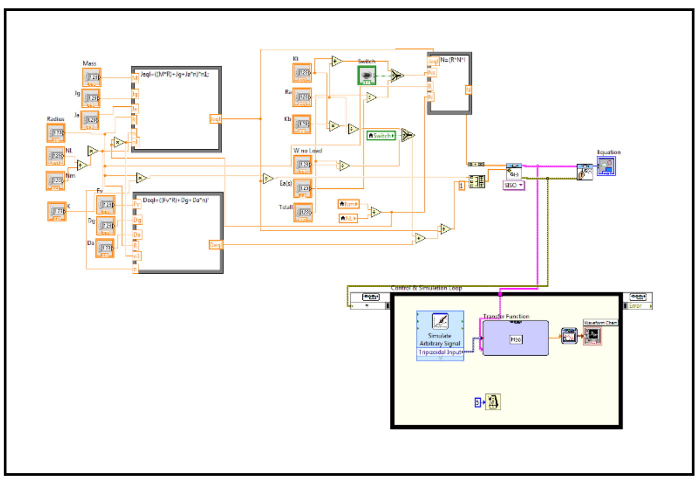


Figure 9. Block Diagram of LabVIEW model

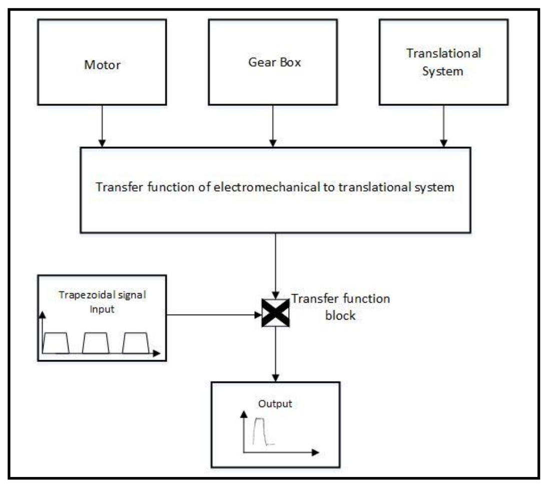


Figure 10. Block Diagram

Change in the variables can be easily done in the front panel while the operation is running and the implementation of the outcome results in graphical representation will deliver the differences in results more clear and precise.

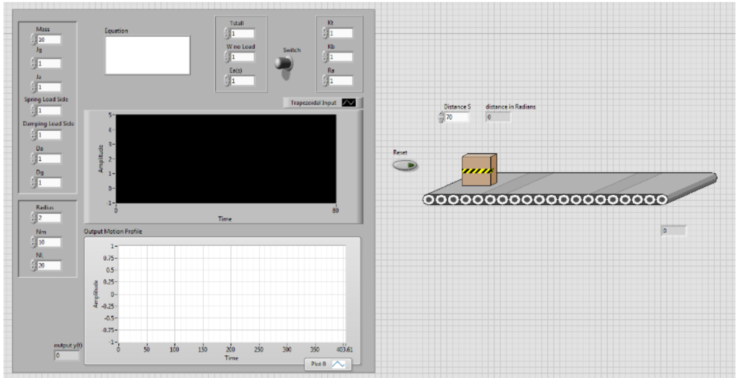


Figure 11. Front panel view of the electromechanical system

The inertia miss match occurred due to the change in the load and the significance of this method can be found by comparing the results with the actual input signal generated and by comparative analysis.

Testing of this method for accuracy and reliability is done based on comparative analysis, in the Figure 10 stated above the first graph is the input trapezoidal motion profile. And the second graph is the angular velocity outcome at the linear side which in a translator system. The occurrence of jerks is seen on both the peaks. The number of samples taken to test this model for its response to the abrupt change in the load. Where the values for the variable mass M is chosen for a smaller value a moderate and one with higher mass. This will let the model to observe the change and identify the parameters that minimize the jerks occurred due to significant change in mass for the same values to the other parameters.

Outcome for different samples of Mass:

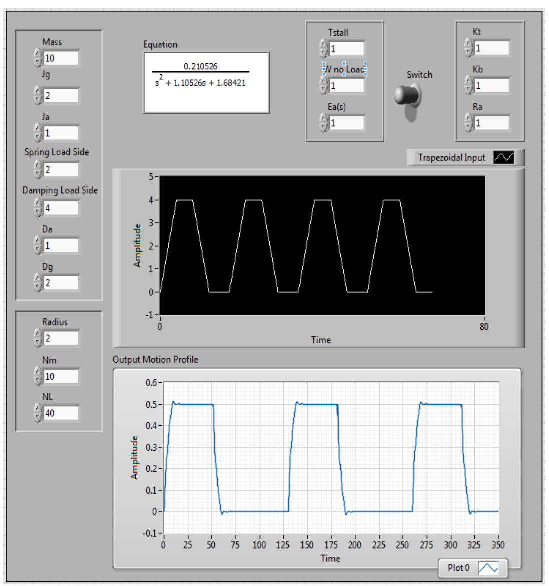


Figure 12. For sample of Mass (M) = 10lb

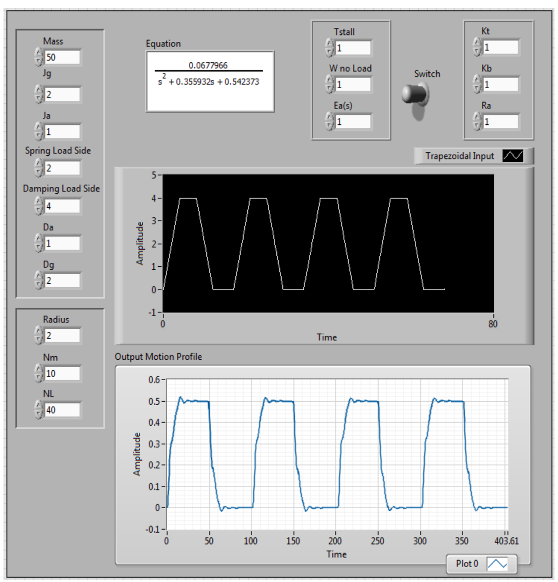
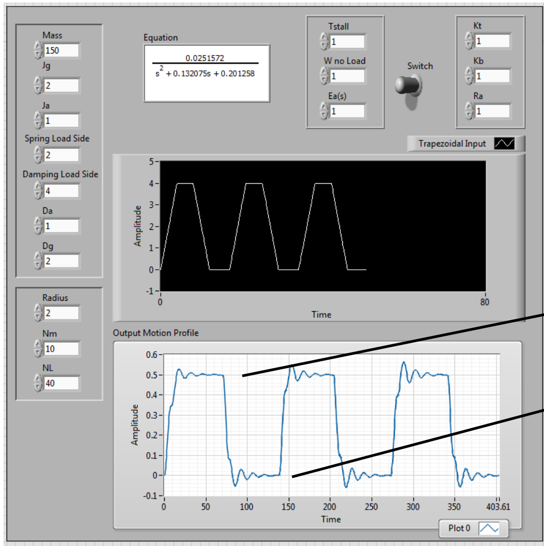


Figure 13. For sample of Mass (M) = 50lb



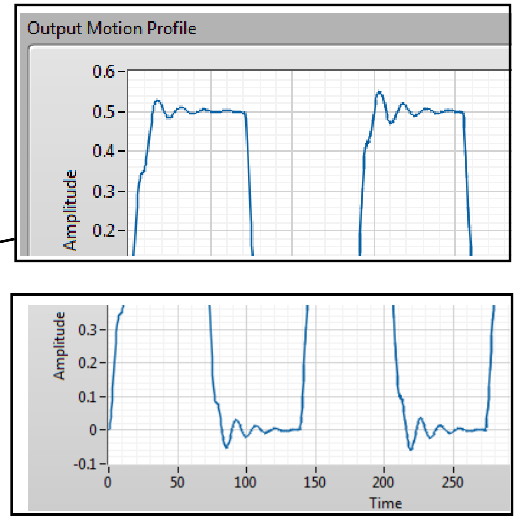
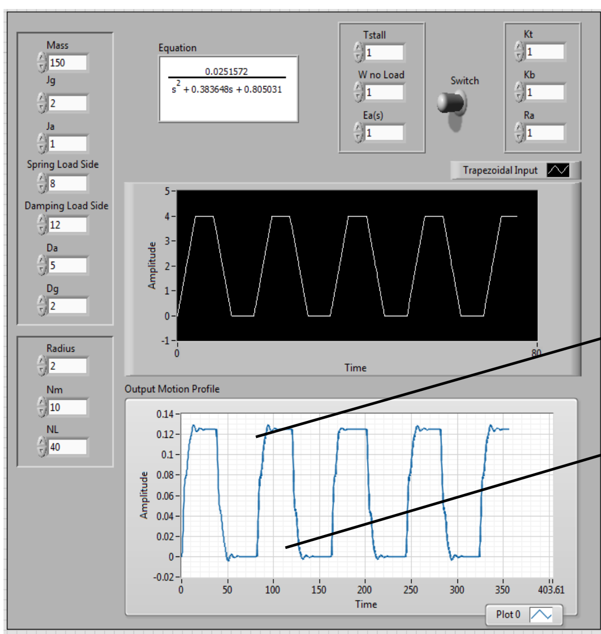


Figure 14. For sample of Mass (M) = 150lb

Figure 15. Jerks occurred at peaks

Because of the change in load the inertia ratio between the load and motor has changed and the jerks reflected the effect of the mismatch.



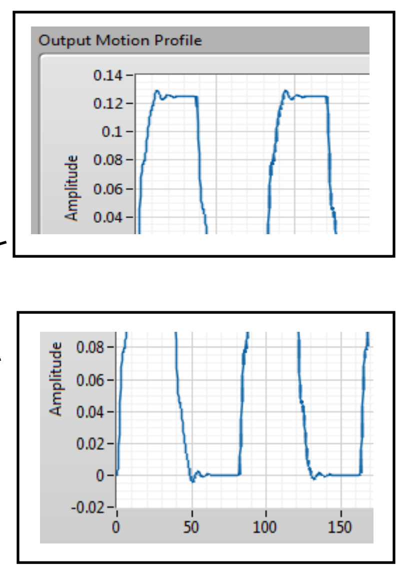


Figure 16. For sample of Mass (M) = 150lb Stabilize

Figure 17. Stabilized jerks

Discussion of results:

We have used this model to analyze a set of samples in which we have changed the mass with other to know the difference in the jerk obtained and also stabilized one which in turn provides the result that by using this model we can not only understand the operation of the machine in the mere future but also have a chance of modifying it by changing the parameters which will not disturb the production or the product we use. So, if we observe this model with a mass of 50lb we can see that this model has been designed to take either the motor constant or the specifications. The gear ratio is taken such a way that the ratio is maintained 1:2 with the radius of the spud gear as 2. In the following models, I have kept the other specification constant apart from the mass and observed the jerks that are occurred in the process. So, by observing the model with mass 150lb we can see that this model has jerk that are in unacceptable in many of the processes where there is a need for 300 parts per sec to be moved. So, by a detailed study on the inertia mismatch problems and also the thumb rule I came with a solution where without resizing the motor or the spud gear radius, but by changing the spring coefficients on the load side and damping coefficients on the load side will result in not only stabilizing the process but also to an extent where we can neglect the minor jerk that occur will be stabilized before the next process even starts.

Advantages in using this model:

- Easy to study the effect of inertia mismatch.
- Reliability in Rotating machine and drive system design.
- Generic approach in modeling of a mechatronics system. (Not manufacturer specific).
- Optimizing the product for enhanced performance.
- Reduction of production cost.
- Graphical representation which leads to better understanding of the process.
- Generation of .exe file (or) an applications which allows in easier access.

Conclusion:

Implementation of this model would help in having higher understanding on the torque outcomes, motion profile of the process which is designed to a specific system and all this is done ahead of time which reduces production costs**.** Use of mechatronics methods helps this system to mismatch the modules used as this is a modular type. In order to implement these models in the engineering education the model chosen is a direct resemblance of the electromechanical system without a gear train. In addition to this knowledge on inertia mismatch will give a board understanding on the concepts of motion profile, effect of gear ratio on the torque transferred, damping and spring coefficient variations. This will result in students graduating with these background will have immense knowledge in high speed motion controlled applications.

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