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MODELLING OF PHYSICAL SYSTEM FOR DESIGN AND CONTROL OF MECHATRONIC SYSTEM: A CASE STUDY

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Declaration

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Abstract

Today's automotive control system engineering requires precision and accuracy. The cost of a controller designed with conservative margins may increase significantly, causing the design, when produced and marketed, to be less competitive. On the other hand, Mechatronic design requires that a mechanical system and its control system be designed as an integrated system. This contribution covers the background and tools for modelling and simulation of physical systems and their controllers, with parameters that are directly related to the real-world system. Achieving a system design involves careful analysis of the controller and plant operating together. This paper discusses how MATLAB and Simulink can be leveraged to ensure the PID control of a mechatronic system design. The merits of the network approach as a technique for modelling physical systems as an alternative to the signal flow (block diagram) approach are also discussed. Finally, the advantages of integrating these methods within Simulink as the environment for Model-Based Design for mechatronic systems are presented. The main focus of this project will be discussing the process of creating models of the physical system variances. As a simple illustration, consider the problem of modelling a DC motor with speed control. MATLAB/SIMULINK is used because of the short learning curve that most students require to start using its wide distribution and its general-purpose nature. This will demonstrate the advantages of using MATLAB for analyzing power system steady state behavior and its capabilities for simulating transients in power systems and power electronics, including control system dynamic behavior. The enabling technology for the network approach is a modelling language for formulating the component's characteristics equations relating the through and across variables in the various domains. The Simscape language, based on MATLAB [16], provides the necessary constructs for modeling the multi domain aspects of mechatronic systems. In the DC motor example, the motor equations can be directly modeled using the Simscape language.

Key word: Matlab and simulink, simscape language.

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1. Introduction

Mechatronics design deals with the integrated design of a mechanical system and its embedded control system. This definition implies that it is important, as far as possible, that the system be designed as a whole. This requires a systems approach to the design problem . Because in mechatronics the scope is limited to controlled mechanical systems, it will be possible to come up with more or less standard solutions. An important aspect of mechatronic systems is that the synergy realized by a clever combination of a mechanical system and its embedded control system leads to superior solutions and performances that could not be obtained by solutions in one domain. Because the embedded control system is often realized in software, the final system will be flexible with respect to the ability to be adjusted for varying tasks. Mechatronics is a commonly used term for describing the combination of electromechanical physical systems with computer controls. Designers of embedded controls for mechatronic systems face difficult challenges. The completion of a successful mechatronic system design requires the integration of multiple engineering domains and collaboration between the engineering teams. The principles of Model-Based Design as a proven technique for creating embedded control systems and apply equally as well when designing mechatronic systems. Using Model-Based Design, the various design teams can evaluate design alternatives without relying solely on expensive prototypes. A Model-Based Design environment allows engineers to mathematically model the behaviour of the physical system, design the software and model its behaviour, and then simulate the entire system model to accurately predict and optimize performance. In this work, Linear Quadratic Regulator (LQR) controller is used in order to control the DC motor speed as we required. This techniques is used for tracking set point commands and reducing sensitivity to load disturbances. MATLAB is used to design and tune the LQR controller and be simulated to mathematical model of the DC motor. The Linear Quadratic Regulator (LQR) controller is a new method of controlling the motor. Linear Quadratic Regulator (LQR) is theory of optimal control concerned with operating a dynamic system at minimum cost.

1.1 Problem statement : As a simple illustration, consider the problem of modeling a DC motor with Speed Control.

1.2 Modelling and Simulation

The modeling and simulation of this thesis helped to generate expected outcomes of the project design. The program used was called SIMULINK, a sub program of the mathematical and simulation software MATLAB. This software is used to provide simulation design and results for evaluation of the transient response of a DC motor. The SIMSCAPE LANGUAGE, based on MATLAB, provides the necessary constructs for modeling the multidomain aspects of mechatronic systems. In the DC motor example, the motor equations can be directly modeled using the Simscape Language. And the measure of controller is how well it controls the desired output when Load are present. The physical plant model is encapsulated into a simulink subsystem complete with sensors and actuator so that it can be connected to a PID controller.

- The main goal of this projectthe physical plant model is encapsulated into a Simulink subsystem complete with sensors and actuator so that it can be connected to a PID controller. And compare the response of a DC motor using MATLAB/SIMULINK.
- Modeling of physical system as example of modeling of D.C. motor with speed and current control

2. Modelling Of Physical System

Model-Based Design is widely used to develop software algorithms for deployment onto an embedded controller. In order to perform closed-loop tests on the control algorithm, the first thing that is needed is a representation of the plant. There are no shortages of techniques for modeling physical systems. Some commonly used methods include signal flow diagrams[5], bond graphs[6] and even manually coding the system equations in C or Fortran. Since a mechatronic design relies on collaboration between engineering teams, it is imperative that the model can be easily shared and understood by the various stakeholders. While the methods above are perfectly valid for accurately modelling the physics, none of these are particularly well-suited for meeting the collaboration and integration needs of a multi-domain mechatronic system design. As a simple illustration, consider the problem of modelling a DC motor with Speed Control.

2.1 Problem Statement

A simple model of a DC motor driving an inertial load shows the angular rate of the load, w(t)as the output and applied voltage,Vapp(t) as the input. The ultimate goal of this example is to control the angular rate by varying the applied voltage. This figure shows a simple model of the DC motor. A Simple Model of a DC Motor Driving an Inertial Load , In this model, the dynamics of the motor itself are idealized; for instance, the magnetic field is assumed to be constant. The resistance of the circuit is denoted by R and the self-inductance of the armature by L. If you are unfamiliar with the basics of DC motor modeling, consult any basic text on physical modeling. With this simple model and basic laws of physics, it is possible to develop differential equations that describe the behavior of this electromechanical system. In this example, the relationships between electric potential and mechanical force are Faraday's law of induction and Ampère's law for the force on a conductor moving through a magnetic field.

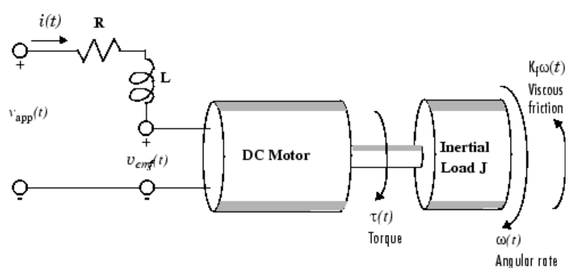


Figure 1 *Physical Model of DC Motor*

2.2 Mathematical Derivation

To design the control algorithm, first find the transfer function to develop the block diagrams of the open and close loop systems. These transfer function are obtained using the differential equation that descried the system dynamic. Kirchhoff's voltage is use to map the armature circuitry dynamic of the motor.

$$\frac{di}{dt} = -\frac{R}{L} * i(t) - \frac{K_b}{L} * w(t) + \frac{1}{L} * V_{app}(t) \tag{1}$$

Using Newton's second law

$$J\frac{dw}{dt} = \sum Ti \tag{2}$$

*No table of figures entries found.*The electromagnetic torque developed by the permanent-magnet DC motor is found as,the torque T seen at the shaft of the motor is proportional to the current *i* induced by the applied voltag

T(t)=Km* i(t) (3)

where *K*m, the armature constant or torque constant, is related to physical properties of the motor, such as magnetic field strength, the number of turns of wire around the conductor coil, and so on. The viscous friction torque

Tviscuos = B*w(t) = Kf * w(t) (4)

The back (induced) electromotive force,Vemf , is a voltage proportional to the angular rate w seen at the shaft,

Vemf(t)=Kb * w(t)

where *K*b, the emf constant, also depends on certain physical properties of the motor. The mechanical part of the motor equations is derived using Newton's law, which states that the inertial load *J* times the derivative of angular rate equals the sum of all the torques about the motor shaft. The result is this equation,

$$J\frac{dw}{dt} = \sum T_i = -K_f * w(t) + K_m * i(t) \quad (5)$$

Where Kf *w(t) is a linear approximation for viscous friction. Finally, the electrical part of the motor equations can be described by

$$V_{app}(t) - V_{emf}(t) = L\frac{di}{dt} + R * i(t) \quad (6)$$

solving for the applied voltage and substituting for the back emf,

$$V_{app}(t) = L\frac{di}{dt} = R * i(t) + K_b * w(t) \quad (7)$$

$$\text{or } Vt = Ra*Ia + La\frac{dIa}{dt} + Ea \quad (8)$$

This sequence of equations leads to a set of two first order differential equations that describe the behavior of the motor, the first for the induced current,

$$\frac{di}{dt} = -\frac{R}{L}* i(t) - \frac{K_b}{L}* w(t) + \frac{1}{L}* Vapp(t) \quad (9)$$

and the second for the resulting angular rate

$$\frac{dw}{dt} = -\frac{1}{J}K_f * w(t) + \frac{1}{J}K_m * i(t) \quad (10)$$

To find the transfer function, the derived three first-order differential equation and taking Laplace transform

$$S\ I(s) = -\frac{R}{L}I(s) - \frac{K}{L}w(s) + \frac{1}{L}V_{app}(s) \quad (11)$$

$$S\ w(s) = -\frac{1}{J}K_f(s) + \frac{1}{J}K_m(s) \quad (12)$$

From the transfer function, the block diagram of the permanent-magnet DC motor is illustrated by figure 2.1

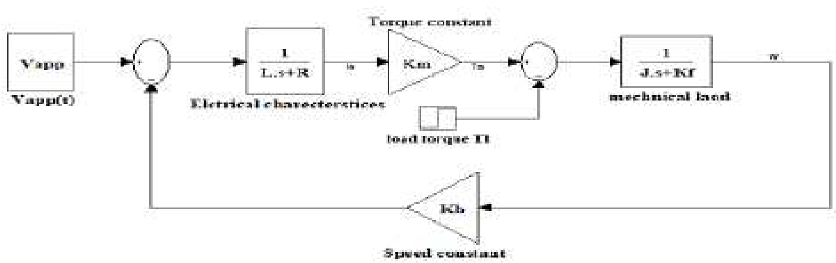


Figure 2.1 *Block diagram of the open-loop DC motor*

A simplified model of the DC motor is shown above. The torque Td models load disturbances. The speed variations induced by such disturbances can be minimized From equation (to find matrix)

$$\frac{di}{dt} = -\frac{R}{L} * i(t) - \frac{K_b}{L} * w(t) + \frac{1}{L} * Vapp(t) \quad (13)$$

$$\frac{dw}{dt} = -\frac{1}{J} K_f * w(t) + \frac{1}{J} K_m * i(t) \quad (14)$$

2.3 Armature-Controlled Dc Motor

In armature-controlled DC motors, the applied voltage Va controls the angular velocity w of the shaft.In this experiment two techniques for reducing the sensitivity of w to load variations (changes in the torque opposed by the motor load) is used. A simplified model of the DC motor has been discussed in previous chapters. The torque Td models load disturbances. The speed variations induced by such disturbances are minimize.

2.3 (a) The angular velocity response of D.C. Motor : A state-space model of the DC motor with two inputs (Va,Td) and one output (w) is constructed. The plot of the angular velocity response to a step change in voltage Va is shown in Fig 2.3a.

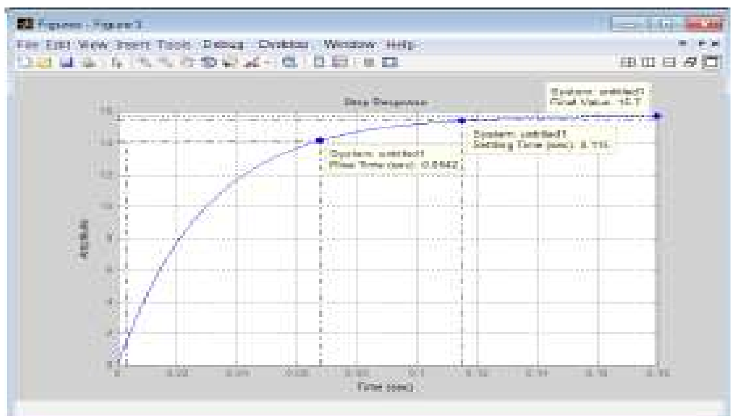


Figure 2.3a *The plot of angular velocity response to a step change in voltage*

2.3 (b) Response of D.C.Motor using Feed forward control: In feed forward control of D.C. motor. The feed forward gain Kff should be set to the reciprocal of the DC gain from Va to w. To evaluate the feedforward design in the face of load disturbances, the response to a step command w_ref=1 with a disturbance Td = -0.0002 Nm between t=5 and t=10 seconds is simulated:

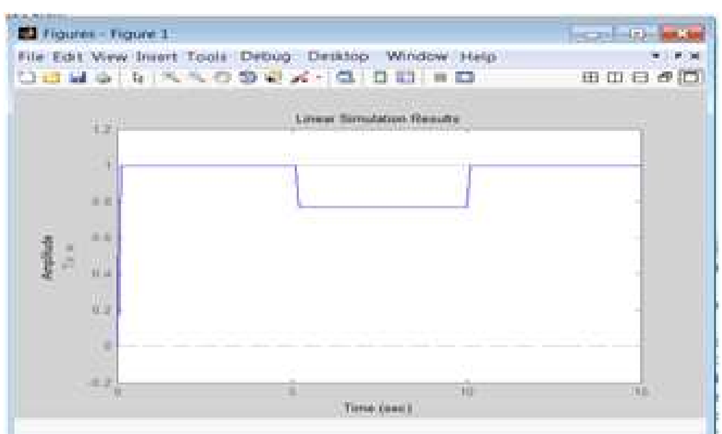


Figure 2.3b *Feedforward control response of D.C.motor*

It can be observed very clearly from the above figure that feedforward control handles load disturbances poorly.

2.3 (c) Response of D.C.Motor using Feedback control : To enforce zero steady-state error, use integral control of the form

C(s) = K/s

where K is to was determined.

To determine the gain K, you can use the root locus technique applied to the open-loop 1/s * transfer(Va->w).

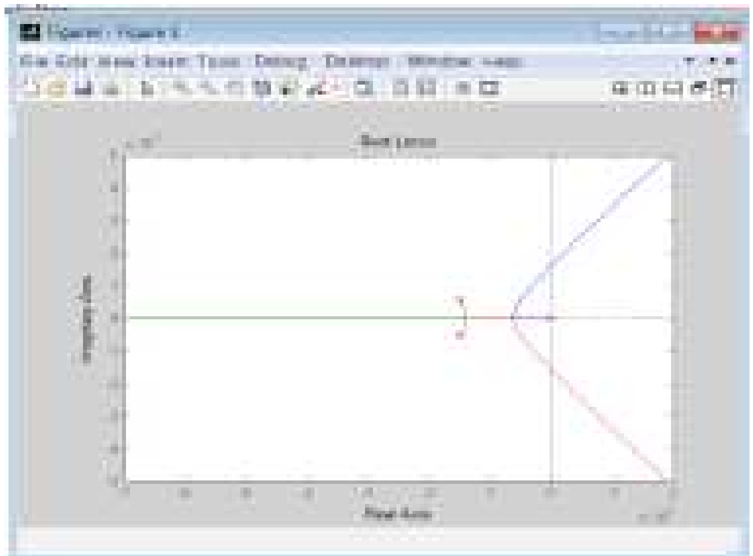


Figure 2.3c *Root locus plot for feedback control response of D.C. Motor*

2.3 (d) Comparison between feedforward and feedback control of D.C.Motor with root locus : It can be observed from fig 4.13 that the root locus design is better at rejecting load disturbances.

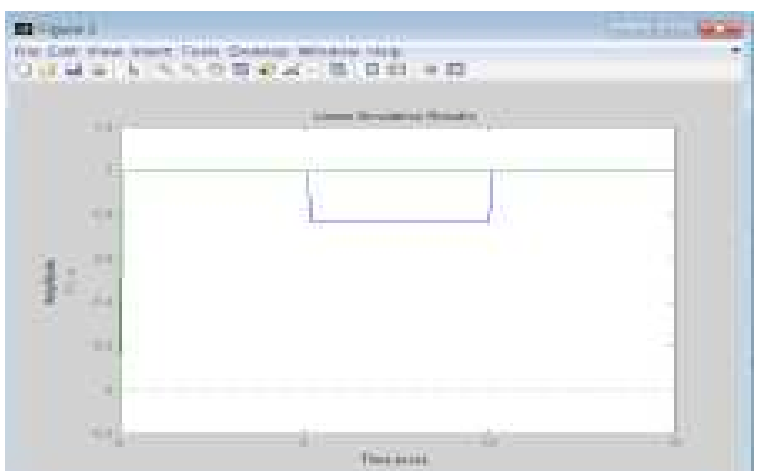


Figure 2.3d *Comparison between feedforward and feedback control with root locus*

In the above figure the blue line represents the response of feedforward control and green line represents response of feedback control with root locus.

3. Signal Flow Approach

Simulink by The MathWorks is widely used to design control algorithms using the signal flow approach. Once implemented in Simulink®[7], Model-Based Design methods are commonly used to verify the controller design and automatically generate the code for deployment onto the microcontroller for rapid prototyping and production. As a result, Model-Based Design methods are commonly used to verify the controller design and automatically generate the code for deployment onto the microcontroller for rapid prototyping and production. A common representation of a DC motor is shown in Figure 2.

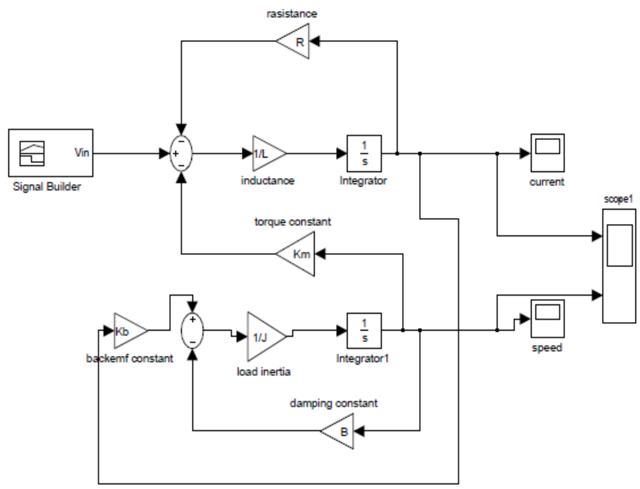


Figure 3 *DC Motor Signal Flow Model*

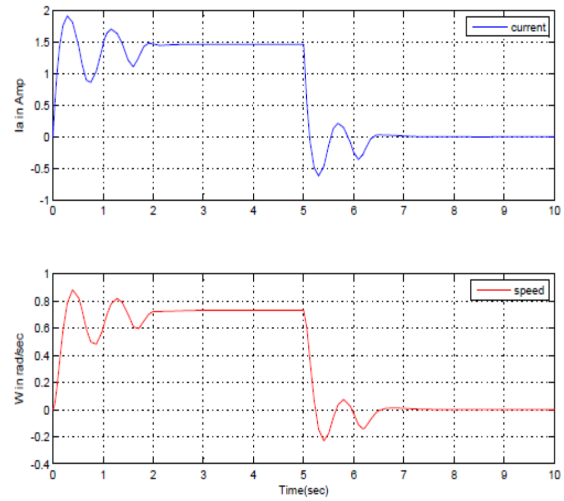


Figure 3 *Signal flow approach Simulation Results (speed and current)*

4. Network Approach

A more universal method for modeling multi-domain physical systems is often referred to as the network modeling approach[8]. Its origins come from the method of network analysis for electrical systems, and can been extended to also model systems consisting of mechanical, hydraulic, thermal and magnetic components. The main advantage of a network model over a signal flow model is the noncausal or sometimes called acausal[9] nature of the connection ports. In signal flow diagrams, the connections are causal. That is, every block is a

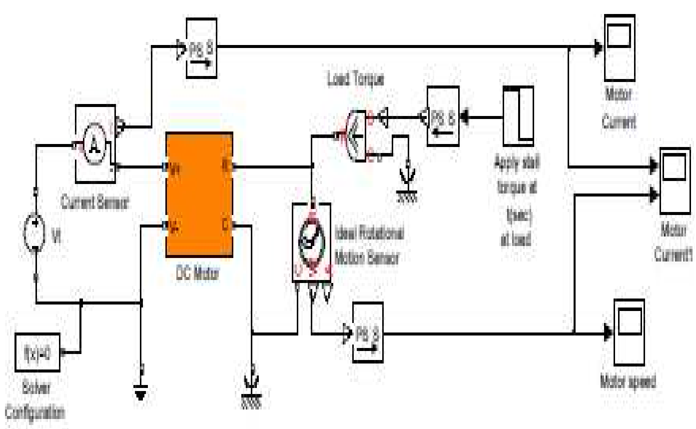


Figure 4 DC *Motor Network Model*

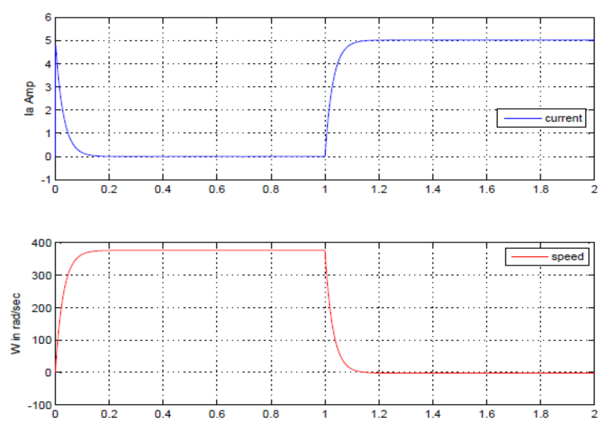


Figure 4 *this is dc motor using Simscape of network model and simulation results.*

transfer function with a signal on the input causing the output to behave according to the defined transfer function. A quick look at the model in Figure 4 illustrates how data flows through the model. Any interaction between blocks must be explicitly modeled by creating feedback loops. As the interactions become more complex and commonplace as with a mechatronic system, the signal flow method quickly becomes untenable for all but the most expert users. For example, if additional effects like damping, friction or hard stop limits are desired, the system equations (1) and (2) would need to be reformulated and the model recreated, resulting in an even more complicated model that is more difficult to interpret. To illustrate, let's look at the same DC motor model using the network approach modeled using foundation blocks from the SimscapeTM[10] multi-domain physical modeling environment within Simulink:

5. Network Approach (DC Motor Model With Hardstop As Load)

The electrical side of the model solves for the quantities current and voltage while the mechanical side solves for torque and angular velocity resulting in identical simulation results to the signal flow model. In the network terminology, these quantities are commonly referred to as "through" and "across" variables. Notice how current and torque "scopes" are placed in the network to measure the through variables and the RPM scope to measure the across variable of motor shaft speed. These measured quantities can also be easily fed back to the control algorithm modeled in Simulink for closed-loop system analysis (more on this later).

A major advantage of the network approach is the ability to quickly modify the system model without the need to derive the system equations. Here, the individual "blocks" contain the fundamental component equations defining the relationship between the through and across variables. The system equations (1) and (2) are then automatically formulated by interconnecting the components into the desired topology. For example the rotational damper component contains the equation:

$$T = B.\omega \qquad (41)$$

Defining the relationship between the through variable (torque) and the across variable (angular velocity) as a linear relationship with the damping coefficient (B) as a constant of proportionality. This method of embedding the first principle equations into the component models allows additional physical effects to be easily added to the system model without needing to worry about reformulating the overall system equations. For example, let's say we want to add limits to the angle of rotation. Using the network approach, you can simply connect a rotational hardstop to the motor shaft as shown in Figure 4

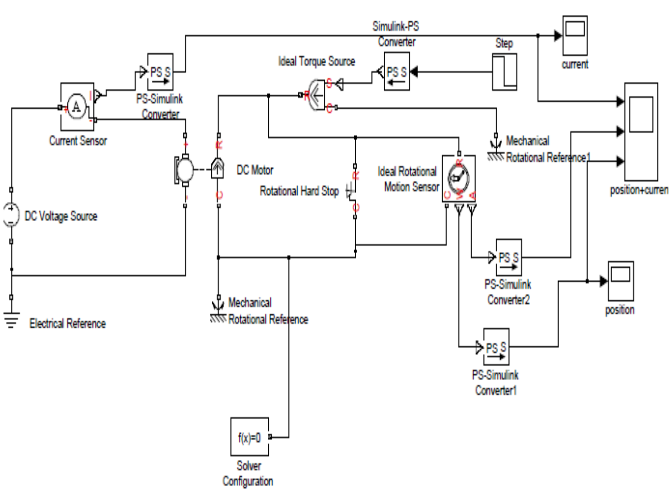


Figure 5. DC *Motor Model with Hardstop as Load*

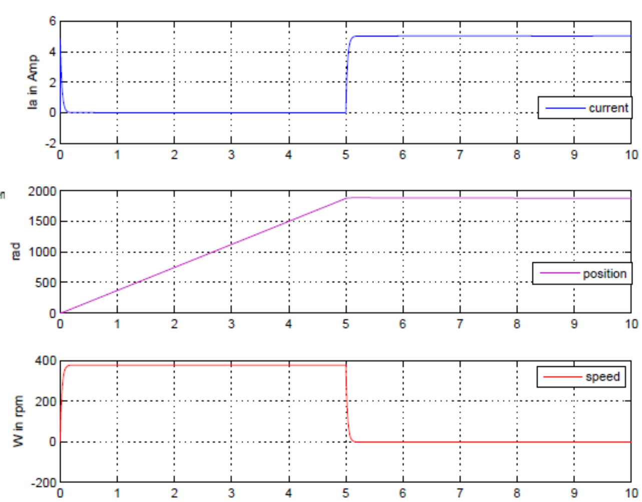


Figure 5. *Simulation results of speed, Current and position without hard stop*

6. Mechatronic System Integration

Using the network approach a complex system model can be quickly constructed by interconnecting the individual component models. The resulting model representation is intuitive and easily interpreted due to the physical connection ports. The overall system equations are automatically formulated from the individual component equations along with how they are interconnected. As an example, consider the system modeled in Figure 6 . Here the DC motor is integrated into a linear actuation system with speed control. The speed and current control subsystems are PI controllers made from standard Simulink blocks while the rest of the model is constructed with physical blocks. The DC motor is driven by electrical PWM and H-Bridge block from the SimElectronics.

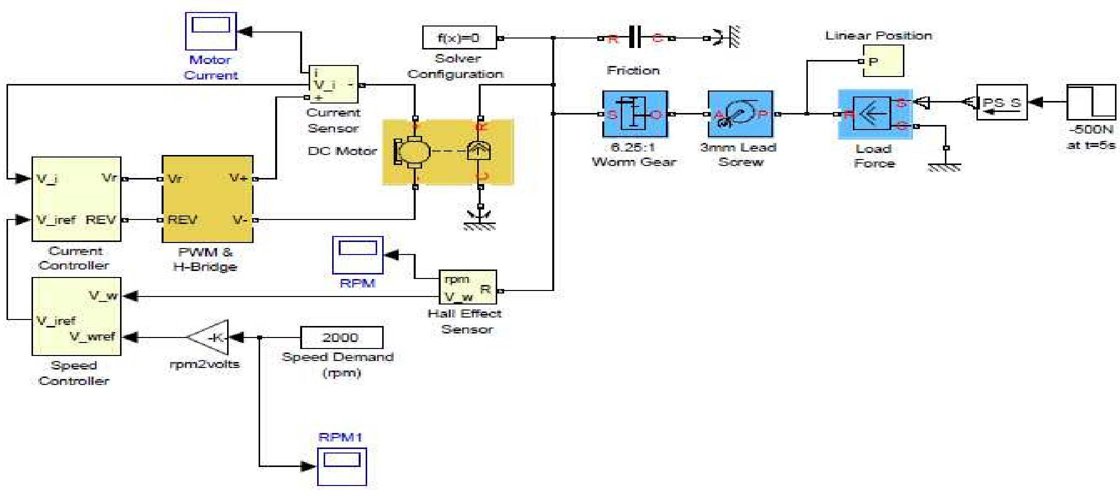


Figure 6. *Linear Actuator with Speed Control*

The mechanical load includes a worm gear with friction connected to a lead screw to convert rotational to linear motion modeled in Simscape. The two inputs to the system are the constant set point signal of 2000 RPM for the desired motor speed into the controller and a disturbance force of -500N occurring at 5 seconds on the mechanical load. The goal of the simulation is to see how well the controller responds to the disturbance in closed-loop system. The network approach allows additional effects (like friction) to be easily inserted. As shown simulation results in figure 6**.**

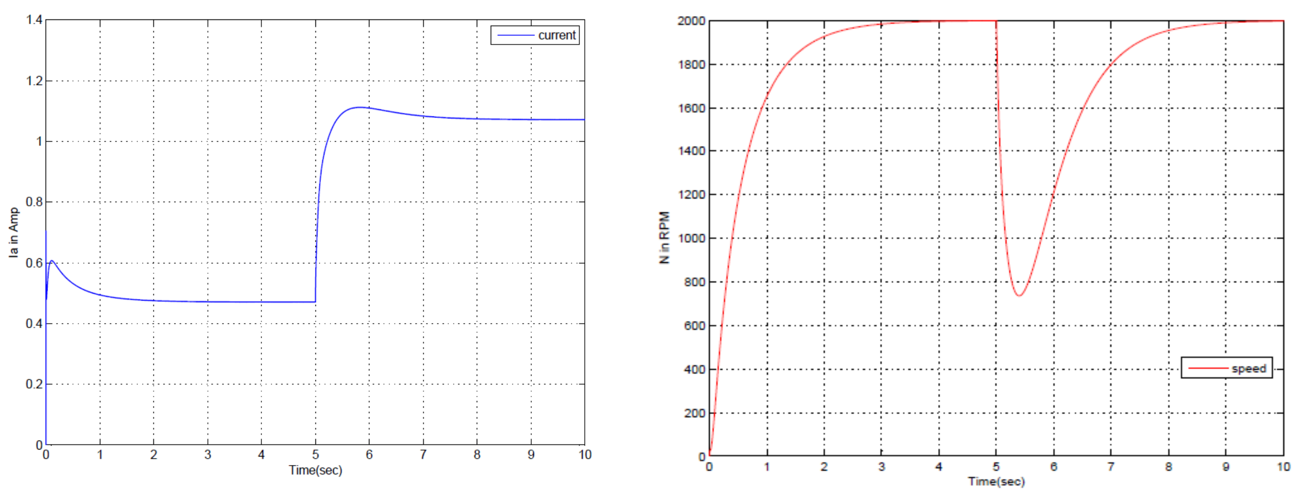


Figure 6. *Motor Current and Motor Speed - Closed-Loop Response*

7. Control of Mechatronic System (Speed Control of DC Motor)

Understanding the effects of disturbance force of -500N occurring in 5sec on mechanical load of the physical system provides valuable insight from an open loop perspective. During controller design, it is important to understand the effects of disturbance force on the closed loop performance. The measure of PID controller is how well it controls the desired output when disturbance force are present. In Figure 5.20, the physical plant model is encapsulated into a Simulink subsystem complete with sensors and actuator so that it can be connected to a PID controller. A set point is introduced for the desired speed, and the overall performance is measured by comparing the system output with the set point. The initial choice of PID gains resulted in a poor response when connected to the plant model, but closed-loop response after tuning the gains is much more acceptable.

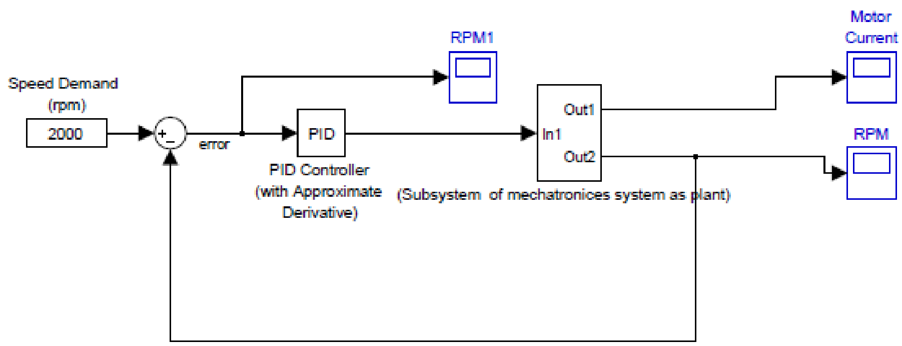


Figure 7. *Closed-loop system model with controller and physical plant subsystem*

8. Results and Discussions

8.1 Comparison between the designs of feedforward, feedback and linear quadratic regulator control response of D.C. Motor

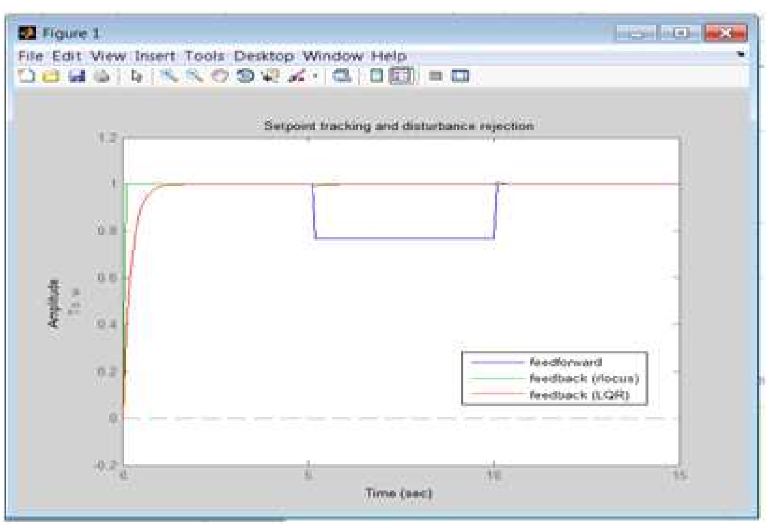
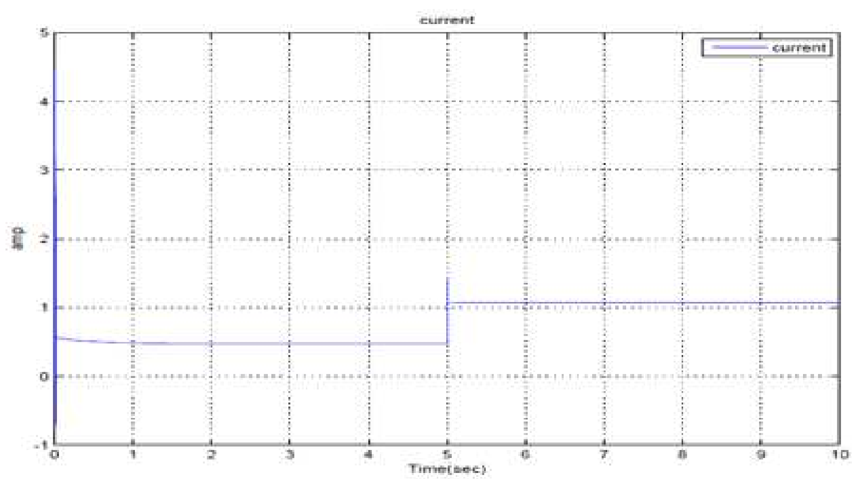


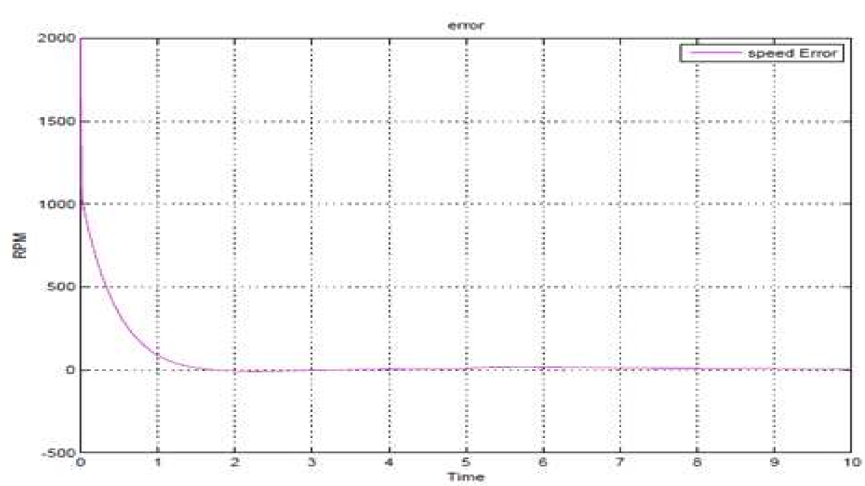
Figure 8.1 *Comparison between the designs of feedforward, feedback and linear quadratic regulator control response of D.C. Motor.*

In the above figure the blue line represents the response of feedforward control and green line represents the Bode plot response of feedback and red line represents the Bode plot response of linear quadratic regulator control of D.C. Motor.It can be observed from the above plot that the Linear Quadratic Regulator compensator performs best at rejecting load disturbances than feedback and feedforward control.

8.2 Control of Mechatronic System (Speed Control of DC Motor)

The MATLAB is used to obtain a closed-loop transfer function directly from the open-loop transfer function. Using KP with a gain of 80, the simulation response can be shown as in Figure 8.2. Trying a PID controller with small KI and KD, the resulting response will be plotted as in Fig.8.2. By tuning the gains of the PID controller and producing the optimum response using trial and error method (it provides simplest way to achieve a good compensator), the simulation start with the best initial gains. So it is necessary to increase KI to reduce the settling time. Changing KI to 3 makes the response looks as in Fig. 8.2. The response in the Fig.8.2 seems much faster than before, but the large KI has worsened the transient response (big overshoot). Therefore, KD must increase to reduce the overshoot. controller with KP=80, KI=3, and KD=40, all of the design requirements will be satisfied, providing the desired response. Changing KD to 40 can get the plot seen in Fig.8.2. So, it must be known that using (after several trial and error runs) a PID controller with KP=80, KI=3, and KD=40, all of the design requirements will be satisfied, providing the desired response





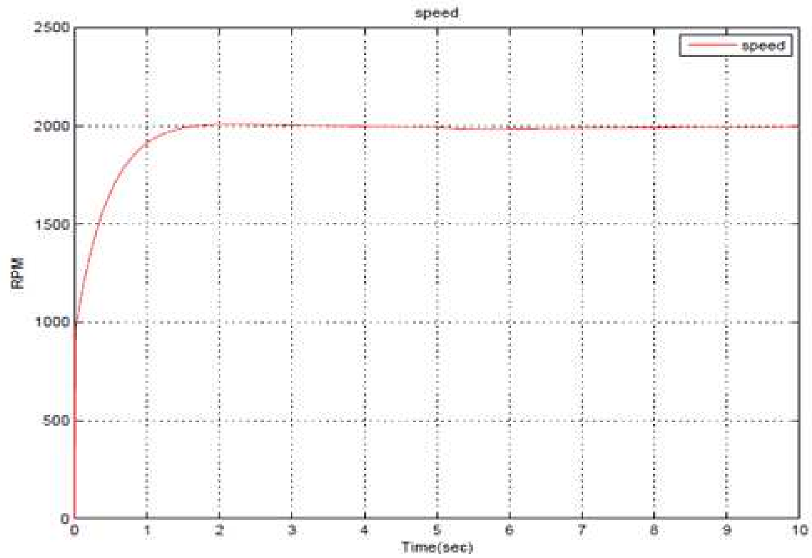


Figure 8.2 *Motor Current and Motor Speed - Closed-Loop Response with PID Controller.*

9.Conclusion

In this Project, the block diagram of a DC motor was developed and by using SIMULINK, a toolbox extension of the MATLAB program, the block diagram was simulated with expected waveforms output. Furthermore, by varying certain parameters of the DC motor block diagram, the output waveform of the simulation would change accordingly. These parameters include the field current, armature circuit resistance and armature voltage. The simulation and modelling of the DC motor also gave an inside look of the expected output when testing the actual DC motor. The results from the simulation were never likely to occur in real-life condition due to the response times and condition of the actual motor.

This experiment was meant to verify that using MATLAB to develop an Linear quadratic regulator control system offers many advantages over the typical method of hand translation from pseudocode to source code. There is an inherent advantage in using MATLAB to model the control system. It saves time and effort, allowing the engineer to design the system in a straightforward manner, rather than wasting time writing source code from scratch.

In the above experiment it is observed very clearly from the above figure that feedforward control handles load disturbances poorly which can be improved by using feedback control. Finally it was observed that Linear Quadratic Regulator compensator performs best at rejecting load disturbances than feedback and feedforward control.

In this Project, Design and Control of Mechatronic System, Considering the problem of Modelling as a DC Motor with Speed and Current Control. To test the controller using Model Based Design, must create a model of the physical system or plant. Signal flow modeling techniques have been traditionally used by control engineers to model the plant. The network approach offers many advantages over traditional signal flow or block diagram methods that are typically employed by controls engineers, especially for multidomain mechatronic systems.

The network approach to physical modeling uses non-causal connections between the physical component models. The benefit to this approach is that the system equations are automatically derived when the interconnecting components into a complete system.

Instead of relying on domain expertise to develop andmodel the system equations, the network approach with the aid of a modeling language applies first-principle equation modeling at the component level. The individual components are then combined to model the larger system. The result is a very readable system model that can be easily shared with others on the team and quickly modified to account for additional effects as needed. In constructing the system model in this way, the engineer can then apply optimization techniques to find a set of nominal parameters to meet the performance requirements.

Now Mechatronic System is modeled using Network approach and Signal flow approach, as DC motor. For different Load variations, PID controller has been design to control the Speed and to make the System stable.

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