A Mathematical Model of Geared DC Motor Based of Overhead Crane Control System Prototype

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Abstract

Overhead crane system is largely used in the heavy industries as the main part of material handling mechanism. The overhead crane operated by the electric motor and its controller shall fulfill two major requirements which are fast response as well as accurate positioning during moving the goods from one location to another location. However, to simulate the real overhead crane system is tedious and time-consuming due to the large structure and safety reasons. Thus, this project will try to simulate the performance of the prototype version of the overhead crane system that has been predicted to perform like the original one but in a small scale. In order to simulate that, a mathematical model of the geared DC motor-based of overhead crane control system prototype shall be formulated. The mathematical model is developed and tested by using Matlab/Simulink software. The mathematical model is being tested in two conditions, without controller and with controller. To acquire the gain value of the controller, first method of the Ziegler-Nichols method is applied. The developed model will be verified for various positions and loads. The performance of the model will be measure in terms of the time response which are rise time, peak time, percentage overshoot, and settling time as well as the steady-state error for the position accuracy. The results will confirm that a good mathematical model will give the best projection to imitate the performance of the real size of the overhead crane.

Keywords: Geared DC motor, overhead crane system, first method of Ziegler-Nichols, time respond, position accuracy

Introduction

Usually in industries or warehouses, there will be one section that raw material is kept. To transfer the raw material, an overhead crane is commonly used. An overhead crane consists of two parallel runways which support a horizontal beam (often called the bridge or simply the crane) on which a
hoist run. The supporting runways can be attached to the building walls or columns at a raised level, or be supported themselves by a series of columns (Crane and Machinery, 2021). Overhead crane comes together with series of pulleys and cables. This will help to perform of the lifting process. Most of the overhead crane motorized by hydraulics or electrical batteries. Basically, overhead crane is used to transport load from one place to another in industrial. Overhead crane is a necessary in factory as they making the processes became more systematic.

Besides, as crane is used to move loads, it helped in controlling the number of accidents in workplace. As the loads is moved more efficiently, more time can be saved and increased the productivity of production. Overhead crane or also known as bridge crane has many types depending on the functioning.

According to research by (Mahmud et al., 2010), there are many ways to control the overhead crane systems. For example, in closed loop there are proportional integral derivative (PID) and fuzzy logic. For supporting the different cable length, PID controllers able to modulate according to the length. As for proportional derivative (PD) type controllers is also used to manage the sway angles in overhead control system since it able to dealing with oscillation problems. Fuzzy logic controller (FLC) is also commonly used in overhead crane due to the ability to deal with a nonlinearities. Therefore, the complex system can be easily solve for optimal point control problems. There are few performance that required in overhead crane control system.

Firstly is accuracy where the overhead crane able to put the material to the designed area. Next, the fast response of the overhead crane control system as if there is any fatal, the crane able to stop when need. Lastly, (Liyana et al., 2020) found that the swing control approach to avoid any incident happen if external disturbance and under actuated overhead crane having payload hoisting crosssimultaneously. As we knew, a real overhead crane is really big and it takes most of the space.

Besides, most of manufacturer and industries are using Alternant Current (AC) motor for overhead crane control system. It will be a bit impossible for us to model the real overhead crane. In order to overcome this problem, a lab-scale prototype of overhead crane control system as model is needed that functioning like real one. This prototype here is using a geared DC motor. Currently, there is no mathematical model that suitable for this prototype. Therefore, the objectives of this isto implement and evaluate the geared DC motor mathematical modelling using Matlab and Simulink.

**Materials and Methods**

**General equations of dc motor mathematical modelling**

Transfer function is defined as the relationship between the input and the output of the system. Usually, it written with s variables in Laplace transform. For a geared DC motor, it convert from electrical energy to mechanical energy through rotation of the rotor. Figure 1 shows the schematic diagram of geared DC motor.
The electrical equation, mechanical equation, and electro–mechanical equation are used to generate the Transfer Function (T.F) in a geared DC motor. The Kirchhoff's Voltage Law (KVL) is used to derive the electrical equation, which is as follows:

\[ V(t) = R_a I_a + L_a \frac{di}{dt} + \text{Emf} = 0 \]  

(1)

To obtain the Back Electromagnetic Force (Emf) is induced by the angular speed of the motor shaft:

\[ \text{Emf} = K_b \theta_m(t) \]  

(2)

The mechanical equation is based on Newton's Law of Motion, which can be summarised as follows:

\[ T_m(t) = J_m \ddot{\theta} + B_m \dot{\theta}(t) \]  

(3)

As the response of the motion of rotor by the motor torque, the magnetic flux is shown as below:

\[ T_m(t) = K_t I_a(t) \]  

(4)

By substituting Equation 4 into Equation 3,

\[ K_t I_a(t) = J_m \ddot{\theta} + B_m \dot{\theta}(t) \]  

(5)

From all equations stated above, it will be converted into the Laplace transform which is the equation will be in s form;

From (1):

\[ V(s) = (R_a + L_a s) I_a(s) + K_b s \theta_m(s) \]  

(6)

From (5):

\[ I_a(s) = \frac{(s (J_m s + B_m) \theta_m(s))}{K_t} \]  

(7)
Substituting the Equation 6 and Equation 7 into the motor speed T.F yield;

$$\frac{\dot{\theta}_m(s)}{V(s)} = \frac{K_t}{[(Ra+La s)(Jm s+Bm)+Kb]s}$$ (8)

Simulink in Matlab has been used to develop the geared DC motor modelling. In an earlier article, the parameters of the geared DC motor are listed in Table 1 (Zhu et al., 2014).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ra</td>
<td>Armature resistance</td>
<td>$11.2\Omega$</td>
</tr>
<tr>
<td>La</td>
<td>Armature inductance</td>
<td>$0.1215H$</td>
</tr>
<tr>
<td>Jm</td>
<td>Moment of inertia</td>
<td>$0.022145kg m^2$</td>
</tr>
<tr>
<td>Bm</td>
<td>Viscous friction coefficient</td>
<td>$0.002953Nm s/\text{rad}$</td>
</tr>
<tr>
<td>Kt</td>
<td>Electromechanical coupling coefficient</td>
<td>$1.28N m/A$</td>
</tr>
<tr>
<td>Kb</td>
<td>$E_{mf}$ constant</td>
<td>$1.28V s/\text{rad}$</td>
</tr>
</tbody>
</table>

The parameters in Table 1 is being used in Matlab coding to find the value of proportional controller. Next, all the proportional controller had been tested with and without the controller. The step input were adjusted to 5m, 10m and 20m. Figure 2 shows the block diagram used in this project. As for the Figure 3 and 4, it shows the subsystem of geared DC motor without controller and with controller.

**Figure 2.** Block diagram of geared DC motor without controller and with P controller

**Figure 3.** Subsystem of geared DC motor without controller
Results and Discussion

Simulink of block diagram

The result from the Simulink will be shown and discussed in detail. During the simulation, there are two sets of simulations. The first set is the geared DC motor without controller and it being tested using three step input which are 5m, 10m, and 20m. By using different step input, different simulation graphs are obtained as shown in Figure 5 until Figure 7.

From Figure 5, Figure 6 and Figure 7, the system response shown for these three different position or step input, they have similar pattern. The only different is the positions or the input step being used. For Figure 5, the step input was 5m, followed by Figure 6 with 10m of step input, and in Figure 7 the step input used was 20m.
Figure 6. Geared DC motor without controller and with P controller (10m)

Figure 7. Geared DC motor without controller and with P controller (20m)

**Transient response**

By referring to the step response graph in Figure 5 until Figure 7, the transient response for each controller are being recorded as shown in Table 2 below. The performance of geared DC motor position will be analysed.
Table 2. Transient response of controller

<table>
<thead>
<tr>
<th>Motor Position</th>
<th>Performances</th>
<th>Rising Time, ( T_r(s) )</th>
<th>Settling Time, ( T_s(s) )</th>
<th>Percentage of overshoot, ( %OS ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geared DC motor without controller</td>
<td>5m</td>
<td>3.535</td>
<td>1.370</td>
<td>0.505</td>
</tr>
<tr>
<td></td>
<td>10m</td>
<td>3.580</td>
<td>1.406</td>
<td>0.505</td>
</tr>
<tr>
<td></td>
<td>20m</td>
<td>3.632</td>
<td>1.452</td>
<td>0.505</td>
</tr>
<tr>
<td>Geared DC motor with Proportional controller</td>
<td>5m</td>
<td>1.305</td>
<td>0.141</td>
<td>0.459</td>
</tr>
<tr>
<td></td>
<td>10m</td>
<td>1.298</td>
<td>0.154</td>
<td>0.459</td>
</tr>
<tr>
<td></td>
<td>20m</td>
<td>1.289</td>
<td>0.158</td>
<td>0.459</td>
</tr>
</tbody>
</table>

From the step response simulation graph in Simulink, and the transient response for input step of 5m, the geared DC motor without controller needed about 3.535s to rise the time response from initial value of 10% to reach 90% of steady state response. Meanwhile, the geared DC motor with Proportional controller only need shorter time for about 1.305s to rise in time response. As for geared DC motor without controller with 10m of input step, the time taken to rise is 3.580 longer than geared DC motor with Proportional controller which is 1.298. Next, for 20m of step input for geared DC motor without controller it needed 3.632s to rise longer geared DC motor with Proportional controller which is 1.289. For geared DC motor with Proportional controller, the step input 20m has the lowest time rise because the longer the position, the shorter time it take to rise.

As for settling time, \( T_s \) which is time needed to reach and stay 2% of steady state values, the geared DC motor without controller in 5m, 10m and 20m need time corresponding to 1.370s, 1.406s and 1.452s. In geared DC motor with Proportional controller, the time needed are 0.141s, 0.154 and 1.58 for ascending positions. Different from time rise, \( T_r \) the longer the position, the slower time is consumed for settling.

The percentage overshoot meaning by the response to exceeded time in steady state value (final value). Both geared DC motor with and without controller has small overshoot and same for all position. The smallest overshoot to the system response 0.459%, which belongs to geared DC motor with controller.

Thus, after analyse all the transient response, it is proven that geared DC motor with controller has better performance compared to geared DC motor without controller. It gives the quickest time rise, \( T_r \) and the percentage of overshoot does not exceed 10%, which mean the system are stable.

From this project, there are some improvement that can be done in the future. This project can be tested in hardware application such as X-Y table position. Next, the simulation also can be improvise using other controller such as particle swarm optimisation algorithm or Neural Network Proportional Integral Derivative controller. Lastly, the performance of transient response can also be added, for instance the peak time and steady state error.

**Conclusion**

In this project, there are two condition that being compared. The first one is the geared DC motor without controller and the other one geared DC motor with controller. The simulation experiment is then setup to compare the performance with different input step which are 5m, 10m and 20m. This simulation will be the combination of proportional gain with the transfer function of geared DC motor.
From this project and simulation, geared DC motor position with proportional controller shows better performance compared to geared DC motor without controller in term of time taken to reach certain position or set point that have been set. According to the transient response parameter, these controllers can be briefly compared in terms of rise time, $T_r$, settling time, $T_s$ and percentage overshoot.

Thus in this project, the performances being compared according to the transient response and it shows that combination of geared DC motor position with proportional controller have better performances compared to geared DC motor without controller based on the rise time, settling time and overshoot. By using proportional controller, it required shortest time from initial value of 10% to reach 90% of steady state response, to reach and stay 2% of steady state response and lastly small value of overshoot that is still in range of 10% which will make the system stable

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