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Design and Control of a System for Lifting Loads, Using State Feedback and PID Controllers

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Abstract

Hoists are systems used for handling loads in the industry, commonly used in overhead cranes in many operations such as transporting materials. The complexity of these will depend on the loads that will be mobilized. In this document is presented the design of a hoist and the load-position controller, comparing the response of the system to state feedback controller and PID controller. For this, a two-pulley system drive by a DC motor was designed, which is modeled separately and through some transformations obtain a transfer function. Base on this transfer function, a state feedback controller was designed and compared to a PID controller. The two controls are both designed and simulated under the same parameters, the results illustrate a similar behavior with de two controllers, but one of them is the one that best adapts to this type of systems, avoiding unwanted behavior on the load.

Keywords – Hoist, control, state feedback, PID, overhead cranes

INTRODUCTION

From the transport of raw material to the loading of merchandise, aerial cranes or hoists play a very important role in the industry. Every day these processes must be more agile and more precise, so a lot of research has become about the control of these systems in order to avoid accidents and speed up the operation. Much of this work focuses on reducing or eliminating the oscillation of the load while it is suspended [1] [2] [3].

One of these works [4] proposes a control to track the car to the desired position while raising or lowering the load, in order to obtain the desired cable length and thus eliminate the load's swinging as quickly as possible. In another investigation to solve this problem [5] it is proffered a control in which the feedback gains are determined by the use of robust optimization on the length of the string. This control is based on a previous linearization of the system.

Most of these works propose a control which is fed back with a vision system, given the difficult maintenance and the high cost of these systems [6] they have designed a system that includes an anti-oscillation controller, an oscillation speed observer and an oscillation angle detection method in which is used an inclinometer that replaces these systems.

In another study [7] the use of a combined feedback and input configuration controller was proposed to compensate for the positioning error in the upper support and to deny the oscillation induced by the movement of the payload. This controller sends on-off command which facilitates the operation of any crane.

Although a large part of the studies aim to reduce the oscillations in the load, some works such as [8] propose to re-feed the position of the load to avoid collisions with obstacles in a 3D trajectory, so, unlike the previous works, it focuses on the displacement made by the load and not on the displacement made by the car across its work space.

The project developed in this document presents the design and control of a hoist anchored to a structure driven by a DC motor. The behavior of the system will be compared to a control by state feedback and a PID control, where the response speed and the error in stable state will also be compared.

METHODS AND MATERIALS

The system shown in this work is based on the design, control and simulation of a cargo transport mechanism, mainly used in overhead cranes. Figure 1 shows the solution proposed for the system, where when a reference is entered the control carries the load to the desired point.

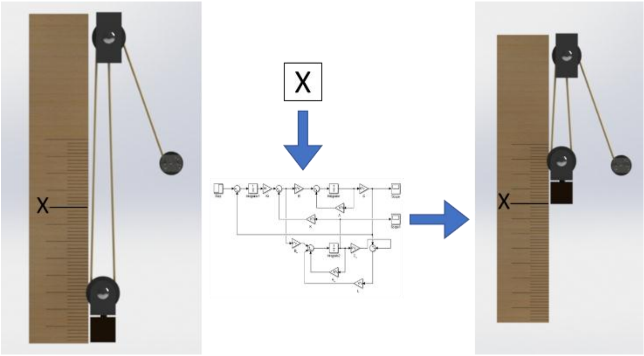

Figure 1. Diagram Outline.

The system was designed based on a hoist of simple configuration of two pulleys, which is shown in figure 2. One of the pulleys is anchored to a structure of dimensions 100x100x200 mm, this pulley is known as a fixed pulley. The other, called the mobile pulley, is suspended on a rope attached to the fixed pulley armature at one end and coupled to the motor on the other, as shown in figure 4. The pulleys have a diameter of 2 cm. The structure offers a space of 120mm displacement to the load.

Figure 2. Mechanical Design.

In this configuration, the fixed pulley changes the applied force direction. While the mobile pulley provides a mechanical gain to the system. Figure 3 shows the behavior of the forces on the pulley.

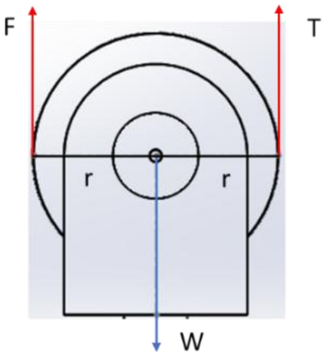

Figure 3. Forces on the mobile pulley.

Observing the forces acting on the pulley we have a force (F) that will be applied to the system, a tension (T) to which the rope is subjected at the point that is anchored to the fixed pulley, and a weight (W) which will be the weight of the pulley with the load suspended.

Taking into account the Law of Moments, it is analyzed at point T as shown in equations (1) and (2) [9]. From which it is obtained that the force applied in the system will be half the weight of the load, as shown in equation (4). By means of equation (3) it is observed that the force is not affected by the radius of the pulley.

$$\sum M_t = 0 \tag{1}$$

$$2r * F - r * W = 0 \tag{2}$$

$$2r * F = r * W \tag{3}$$

$$F = \frac{W}{2} \tag{4}$$

For the modeling of the system, the hoist and the DC motor are modeled separately. The model of the hoist is made with the mobile pulley, since the fixed pulley only changes the direction of the force that is considered ideal. Taking the combined weight of the pulley with the suspended mass, plus the friction of the rope with the pulley, and the elasticity of the rope, the analysis of a spring mass system is carried out from which the equation (5) is obtained. This equation is also where it is obtained the transfer function (6) whose input is the difference between the applied force and the weight and its output will be the linear displacement of the load.

$$M\ddot{X} + B\dot{X} + KX = -W + F \tag{5}$$

$$\frac{X(s)}{F - W} = \frac{1/M}{s^2 + \frac{B}{M}s + \frac{K}{M}} \tag{6}$$

Where:

M is the mass of the load, equal to 47.31 g.

W is the weight of the load, 0.4641 N.

B is the friction presented between the rope and the pulley, equal to 0.25181 N.

K is the elasticity of the rope, equal to 6082 N/m.

In the industry more complex configurations of these machines are handled, its choosing will depend on the loads to be handled and their application. According to the configuration used, the force applied is equal to half the weight of the load. Given the low weight of the load used and the mechanical gain given to the system by this configuration, the selected motor has a nominal torque that offers a force four times greater than that necessary to raise the load.

Figure 4. Hoist with coupled motor.

With the model of the hoist done, it is proceeded to model the motor. Which is anchored to the structure and the string is attached to a reel as shown in figure 4. The modeling of the motor starts from equation (7) obtained in the motor armature mesh, figure 5. The inductance value is very small for this moor, so it is unpriced in the calculations.

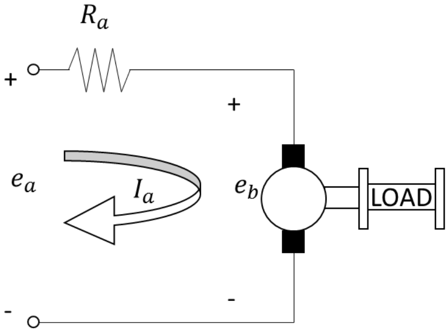

Figure 5. Electric DC Motor Model.

From the equation of the armature circuit (7) the transformation (8) is performed to obtain the motor torque and the transformation (9) of the motor speed [10]. With the new armature equation (10) and the mechanical equation of the motor (11), the transfer function (12) of input voltage and output torque is obtained.

$$e_a = I_a R_a + e_b \tag{7}$$

$$T_m = I_a K_t \tag{8}$$

$$e_b = K_p W_m \tag{9}$$

$$e_a = \frac{T_m}{K_t} R_a + K_p W_m \tag{10}$$

$$T_m = J_a S W_m + b_a W_m \tag{11}$$

$$\frac{T_m}{e_a} = \frac{K_t (J_a S + b_a)}{R_a J_a S + R_a b_a + K} \tag{12}$$

The parameters used in the design correspond to the motor Maxon RE 25 Ø25 mm, Graphite Brushes, 20 Watt, as shown in table 1 [11].

Table 1

Constant Motors maxon re 25, ref 339152

Symbol	Parameter	Value / Units
	Nominal torque (max. continuous torque)	30.4×10^{-3} Nm
Ra	Resistance	1.53 Ω
Ja	Inertia Moment	1.47×10^{-6} Kgm^2
Ba	Air Viscosity	1.38×10^{-6} Kgm^2/s
Kt	Torque Constant	20.8×10^{-3} Nm/A
Kp	F.e.m Constant	0.0208 V/(rad/s)

$$F = \frac{T_m}{d} \tag{13}$$

Given that what is applied in the hoist to displace the load is a force and not a torque, the substitution shown in equation (13) is performed, where 'd' equals the distance of the motor drum (0.03m). With this last substitution and through Matlab, the transfer function of the system (14) is obtained, with which the control is carried out.

$$Ft = \frac{2.102e^{-5}s - 0.004224}{2.249e^{-6}s^3 + 4.451e^{-5}s^2 + 0.2911s + 55.89} \tag{14}$$

To start with the design of the control, parameters are chosen according to the behavior of the system. The simulation of the open-loop system is carried out by means of the transfer functions obtained from the models, as shown in figure 6.

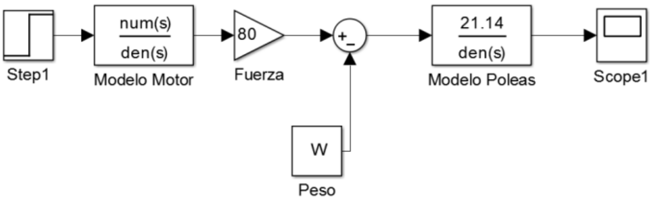

Figure 6. Block diagram of the open loop system.

Where the first block is the motor transfer function with voltage input and torque output. Followed by a gain equal to the division of the torque and its application radius, from which results the force that subtracted with the weight acts as an input for the hoist transfer function, which has as output the linear displacement of the load.

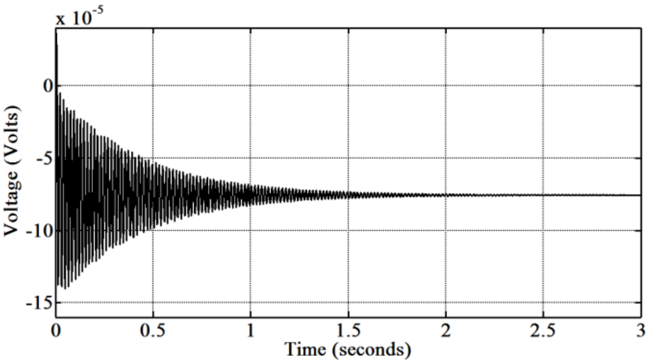

Figure 7. Open loop system, response to entrance step.

According to what is shown in figure 7, it is observed that the system has a fast behavior, since at 2 seconds after the step is applied it reaches a stability point. It was stated that the time of establishment of the system would be 1.5 seconds, and that to avoid the load suffering very strong movements, it was determined that the control would have a critically damped behavior ($\xi = 1$)

With the establishment time parameters and the ξ established, the state feedback control was performed. For this purpose, the matrices of states were obtained through Matlab, with which the control and observer constants be determined.

To obtain the control constants, a new matrix shown in equation (15) is formed, which contains the state matrices A, B and C, and a row vector K composed of the constants and a constant Ki. This matrix called A * subtracts an identity matrix, which has previously been multiplied by s [12]. The determinant is obtained from the matrix product of this subtraction, which is equal to the desired polynomial (16). From this equality equations (17) (18) (19) (20) are obtained, from which the constants K1, K2 and K3 are cleared to form the vector K and the constant Ki.

$$A^{*} = \begin{bmatrix} A + B * K & B * K_i \\ -C & 0 \end{bmatrix} \qquad (15)$$

$$de\,t(SI - A^{*}) = Pd \qquad (16)$$

$$197.9102 - K_1 = 58.6667 \qquad (17)$$

$$129440 - K_2 = 1002.7 \qquad (18)$$

$$-1878.2 * K_i = 5056.8 \qquad (19)$$

$$2.4851x10^{7} - K_3 + 4401300 * K_i = 4171.9 \qquad (20)$$

From the equations previously presented, we obtain:

$$K = [139.2435 \quad 128430 \quad 2.4847x10^{7}]$$
$$K_i = -2.6924$$

In a similar way to the previous one the constants of the observer will be obtained. For this, a matrix operation composed of the identity matrix multiplied by s, the state matrices A and C, and the column vector L (21) is performed. To the result of this operation, O *, the determinant will be obtained, which will be equal to the desired polynomial of the observer (22).

$$O^{*} = SI - (A - L * C) \qquad (21)$$

$$\det(O^{*}) = Pdo \qquad (22)$$

From the equality (22), equations (23) (24) (25) are obtained, with which the constants L1, L2, and L3 that form the vector column L are cleared.

$$197.9102 + 9.3464 * L_2 - 1878.2 * L_3 = 320 \qquad (23)$$

$$129440 + 9.3464 * L_1 - 28.4251 * L_2 - 371710 * L_3 = 14933 \qquad (24)$$

$$2.4851X10^{7} - 1878.2 * L_1 - 371710 * L_2 - 4.7537x10^{8} * L_3 = 189630 \qquad (25)$$

Clearing the equations it is obtained:

$$L = \begin{bmatrix} -178.1796 \\ 72.9431 \\ 0.2980 \end{bmatrix}$$

ANALYSIS OF RESULTS

With the calculated constants, the simulation of the system was performed with its control by state feedback, shown in figure 8.

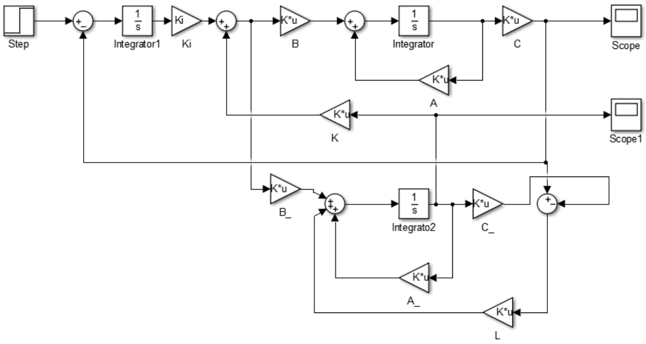

Figure 8. System control by state feedback.

In Figure 9 it is observed that the system is controlled according to the previously established parameters. Stabilizing in 1.5 seconds and with a critically damped behavior, it is assured that the load will not suffer strong movements when moved up or down.

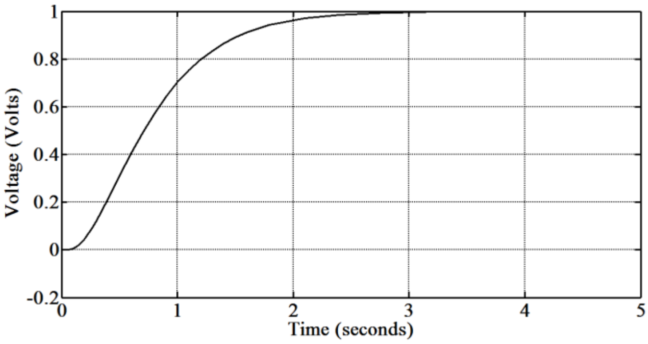

Figure 9. Response of the controlled system to entrance step.

To compare the results of the control by state feedback, the implementation of a PID control over the plant was proposed. For this, by means of the PIDTOOL of Matlab and using the same control parameters, the constants Kp, Ki and Kd were obtained. With which the simulation shown in figure 10 was performed.

$$K_p = -160.3345$$
$$K_i = -33877.9526$$
$$K_d = -0.1897$$

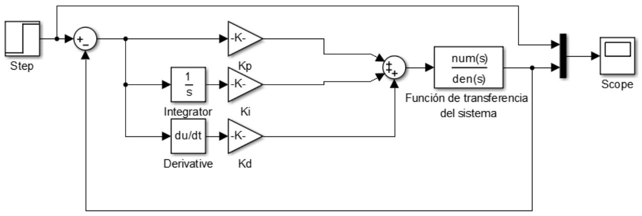

Figure 10. PID control applied to the system.

As seen in Figure 11, the system complies with the previously established control parameters. But unlike the behavior with the control by feedback of states, with the PID the system maintains an oscillation during its transitory state and its stable state.

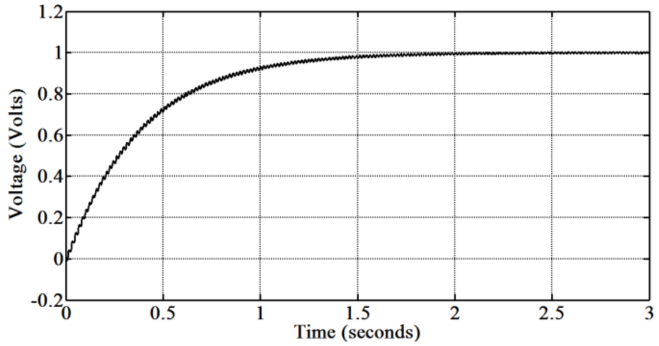

Figure 11. Response of the system to entrance step.

By tuning the constants it was observed that by means of only the integral action the system is controlled by reducing the frequency of the oscillations, as shown in figure 12.

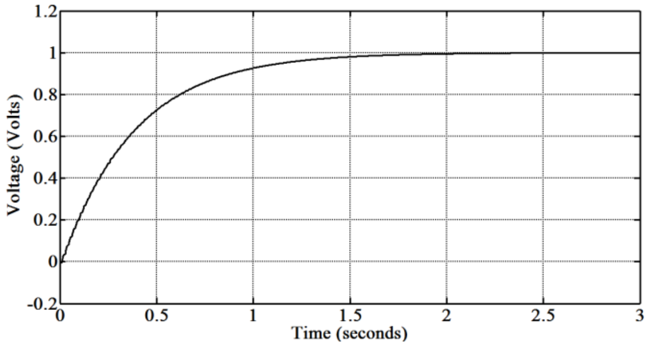

Figure 12. System response with integral control.

CONCLUSIONS

For the design and construction of a hoist there are a variety of configurations. The choice of one or the other will depend on the application of the equipment and the capacity of its capacity. These two factors are very important in order to not have a hoist that needs a lot of space for its operation or simply cannot lift the necessary loads.

Classic control methods such as PID are widely used by the industry. This type of controllers suffice to solve a large number of industrial control problems, since many systems can be represented as first and second order dynamics and correctly meet the established design parameters. But when the system exceeds the second order the PID, although it still meets the design requirements, it generates unwanted behavior at the output of the system, such as the oscillations in this particular case. This is because the controller does not have the necessary extent of freedom to manipulate all the information in the system.

For these cases, control by feedback of states presents a better response, given that this control strategy manipulates all the information in closed loop.

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