Modelling Method Investigation of Drive and Motor for an Industrial Overhead Crane

Nattapong Suksabai, Jatuporn Waikoonvet, and Ittichote Chuckpaiwong*

Department of Mechanical Engineering, Mahidol University, 999 Phuthamonthon 4 Rd., Salaya, Nakhon Pathom, 73170 Thailand

* Corresponding Author: ittichote.chu@mahidol.ac.th

Abstract
Overhead cranes are commonly used to carry heavy objects from one place to another in a workspace. In common, 3-phase electric drive and induction motor are selected to drive a crane in three dimensions. Many mathematical models of a three-dimensional overhead crane were previously derived by energy equation to describe a relationship of applied force and crane movement. The problem was that the applied force could not be used for controlling most overhead crane systems whose motors were commonly controlled by velocity commands. Although, this problem was solved by creating an empirical model which contains the three functions: switch, rate limiter and linear second order, the further investigation and validation was still required. In this paper, the model of drives and motors of an overhead crane was investigated and validated by experiments using an industrial-grade 1-ton overhead crane. A unit step input of velocity command and actual velocity were used as data to create an empirical model. The model performance was experimentally evaluated by comparing with actual velocity and position of each time step. The discussion was also provided at the end.

Keywords: overhead crane, modelling, control process

1. Introduction
To transport a heavy object in a closed workspace, an overhead crane is a suitable choice. It operates on the rail system that is installed on top of the whole workspace, consists of the three components called a bridge, a trolley, and a hoist. Basically, an object is vertically lifted by a hoist which is mounted under the bridge and the trolley. The trolley can be moved along the bridge length which usually is defined as left and right direction. Eventually, the bridge moves in forward and backward direction. This simple but effective design makes overhead crane popular to manipulate the object in closed workspaces.

As global productions in many industrial cranes are increasing, overhead crane needs to be more automated. Using an operator to control crane may not suffice for today demands. A conventional overhead crane is controlled by an operator via push button to move an object in space. While an automated overhead crane promises to move an object to a target faster than a skilled operator, an automated crane relies on automatic control theory, which needs to be studied to archive a desirable control motion.
Mathematical model of an overhead crane is important for developing the control system. Previously, it was usually derived using Newton’s Law [1], and Lagrange’s equation [2]. Tuan et al. derived a mathematical model of an overhead crane and proposed the control technique for payload positioning. The control algorithm was implemented on lab-scale mini overhead crane where DC motors were used to actuate the crane movement. The result of payload positioning showed the successful control method based on the mathematical model of overhead crane [3]. Another related control algorithm based on a mathematical model was also published as well [4]. Lee Ho-Hoon implemented his control technique with AC servo motor, linear model of AC servo motor and nonlinear model overhead crane were together derived for the crane positioning and payload suppression of the control scheme. It was implemented on the crane prototype of 5.5x3.5 meter. A good result was also obtained for the prototype [5]. However, for an industrial crane, the mathematical model which describes the relation of force and acceleration may be useless. Unlike DC motor that is controlled by adjusting electrical voltage which implicitly rates to the force or even AC servo motor that can produce the linear force using its controller [5-6], an AC induction motor is controlled by an adjustable speed drive, so-called drive or inverter (alternatively called as VSD or VFD). The drive controls the AC motor using an adjustable electrical frequency that relates to angular velocity output. Since the model of the drive (inverter) and motor should base on the actual control parameter, the input should be a velocity command and the output should be an actual velocity or even distance. Sorensen and Singhose proposed the control technique for positioning of an industrial overhead crane and payload suppression using an ON-OFF relay. Regardless of the motor and drive model, the control technique results in the positioning error within 13 mm and payload oscillation reducing it to approximately 20% [7]. Later, the positioning control and payload suppression were improved by developing of drive and motor model, Sorensen and Singhose proposed an empirical model of drive and motor where input was velocity command and output was actual velocity. It consists of three functions: switch, rate limiter and linear second order. The result showed that position error was less than 10 mm and payload oscillation was reduced to 5% of the maximum [8]. However, the validation of this model still requires further investigation in various aspects before using it in the automatic control design.

In this paper, section 2 will provide a detail of drive and motor modelling method proposed by Sorensen and Singhose [8], and the extended model for the validation process. Section 3 shows an experimental setup for the studying of drive and motor model. Experimental data, resulting system identification and performance of the model prediction will be expressed and discussed in section 4. Finally, section 5 is the conclusion of this paper.

2. Modelling of Drive and Motor

2.1 Proposed Model Development

By observing a crane movement during the experiment, Sorensen and Singhose [8] proposed an empirical model of the drive and motor for an industrial overhead crane. Initially, three velocity step commands were used as an input to the drive and motor then three output as actual velocity was collected to analyse the movement behaviour. Three velocity step commences are velocity step from rest to maximum (0 to 100%), from rest to medium (0 to 50%), and maximum to a maximum in another direction (100 to -100%). The corresponding three actual velocities were plotted separately; vertical and horizontal axis are actual velocity and time, respectively. In a case of rising velocity (0 to 100% and 0 to 50%), actual velocity raised from zero to 100% and 50% with infinite slope at the beginning and end and also minimum overshoot. The responding S-curve profile looked like a heavily damped second-order function. The difference of both settling times reminded that the system has some acceleration limit. In the case of transitional velocity when the motor is driven forward 100% and immediately commanded to 100% in the reverse direction, the system acted the same way before. That is, the S-curve profile decreased smoothly from 100 to 0% then increased smoothly from 0 to 100% in the reverse direction. As all mentioned an empirical model of drive and motor was proposed
as a combination of a second-order transfer function, a rate limiter, and a transitional velocity switch. When S-curve profile was represented by a second-order transfer function, a rate limiter described the difference of settling time of the two velocities commence, and transitional velocity switch was used to emulate an actual velocity profile at transitional velocity zone for smoothing stop and smoothing start. Figure 1 shows the three elements of the empirical model.

**Figure 1.** The representative of drive and motor model

Where $V_c$, $V_r$, and $V_a$ are a velocity command, limited velocity command and actual velocity, respectively. The three blocks, $TF$, $RL$, and $SW$, are a second-order transfer function, a rate limiter, and a transitional velocity switch, respectively. $TF$ is a standard form of a second-order transfer function, which is expressed in Equation (1).

$$ TF = \frac{V_a}{V_r} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} $$

$\omega_n$ and $\zeta$ are natural frequency and damping ratio of the system, which have to be identified. $V_a$ is output and $V_r$ is an input, which is filtered by the rate limiter before. Block $RL$ is a rate limiter that limits the rate of change of velocity commence ($V'_c$). If the rate of change of input signal is greater than the rising limit, ($R$) and falling limit ($F$), block $RL$ passes a signal not exceed $R$ and $F$ setting value. Otherwise, if the rate of change of signal input is less than raising limit ($R$) and falling limit ($F$) range, block $RL$ passes an original input signal. Equations (2) and (3) express discrete function of the rate limiter. Subscribe $i$ and $i-1$ are the time step at the current and one previous step, respectively.

$$ V_r(i) = \Delta t \cdot R + V'_c(i-1) \quad \text{rate} > R $$
$$ V_r(i) = \Delta t \cdot F + V'_c(i-1) \quad ; \quad \text{rate} < F $$

$$ V'_c(i) = V'_c(i) \quad F < \text{rate} < R $$

Where

$$ \text{rate} = \frac{V'_c(i) - V'_c(i-1)}{\Delta t} $$

The transitional velocity switch is expressed in Equation (4), which is used to delay velocity command. When reversing velocity command is occurred and absolute actual velocity is greater than $V_{\text{switch}}$, zero will be sent to rate limiter instead of the velocity command. When absolute actual velocity is lower than $V_{\text{switch}}$, the velocity command will be passed transparently.

$$ V'_c = \begin{cases} 
V_c, & \text{sign}(V_c) = \text{sign}(V_a) \\
|V_a| \leq V_{\text{switch}}, & \text{otherwise} \\
0, & \text{otherwise}
\end{cases} $$

As the proposed model, equation (1) – (4) are the representation of a drive and a motor of an industrial overhead crane.
2.2 Extended Model
According to the proposed modelling method, the three-step inputs as velocity command ($V_c$) should be sent to a motor drive, 0 to 100%, 0 to 50%, and 100% to -100% and actual velocity ($V_a$) must be measured. If the input and output were known, system parameters could be identified by some methods. However, hardware limitation exists in this study, actual velocity cannot be measured but positioned instead. Therefore, the proposed model is extended here using a satisfying assumption. That is, if there is no slip between wheel and rail, the crane position $P$ can be calculated by integration of the actual velocity, which is shown in Figure 2.

![Figure 2](image)

Figure 2. The representative of drive and motor model with an extended part

However, to relate the velocity command and the crane position, the velocity command ($V_c$) should also be identified, not in percentage but in the same unit (i.e. meter per second). Therefore, to model the drive and motor of the overhead crane according to the proposed model, all the mentioned parameters must be identified, including natural frequency and damping ratio for the $TF$ block, raising and falling rate for $RT$ block, $V_{switch}$ for $SW$ block, and velocity command in m/s.

3. Experimental Setup
A 1-ton industrial overhead crane was used to verify the proposed empirical model of a drive and a motor. To make the crane moved in a horizontal direction, 380 VAC motors and drives were used. These horizontal axes are normally called bridge and trolley, whose travelling spans were 23 and 9 meters, respectively. Figure 3 shows a hardware overview of the crane system. A wireless control pendant was used for sending a digital signal to PLC. PLC received that signal and sent a velocity step command ($V_c$) to motor drives or inverters. Two-position sensors measured bridge and trolley positions ($P$) and fed back to PLC for data recording. A PLC used in this work consisted of several units: CPU, option board, and analogue input units. The CPU unit is Omron NX1P2-1040DT, built-in with digital input ports for receiving signals from the wireless control pendant. NX1W-CIF11 is a serial communication option board, mounted on the CPU unit for sending velocity command to two YASKAWA AC Drives: V1000, called bridge inverter and trolley inverter. Modbus RTU protocol was selected for serial communication between PLC and inverters. NX-AD2203 is an analogue input unit, used for data recording from two DL50 P1123, range distance sensors, via 4-20 mA analogue output.

![Figure 3](image)

Figure 3. Hardware overview of the 1-ton overhead crane
4. Results and Discussion

4.1 Experimental Result
Due to the hardware setup as mention before, crane positions were used as outputs of the system, instead of actual velocity. Square-wave velocity commands were inputs of the system. Therefore, arbitrarily periods of two square-wave velocity commands ($V_c$) were sent to the bridge inverter and the trolley inverter with no payload in this testing. Figure 4 shows the plot of crane positions and velocity commands over time for bridge and trolley.

![Figure 4. Crane positions and velocity commands over time](image)

In figure 4, the red lines and the blue lines represent crane positions and velocity commands for 100% and 50%, respectively. Velocity commands and crane positions will be used for system identification in the next section.

4.2 Identification Result
To identify the proposed model parameters, a trial and error technique was used based on a rational principle. The proposed model consists of three elements that are second-order transfer function ($TF$), rate limiter ($RL$), and transitional switch ($SW$). For the $TF$ block, it was originally defined as a heavily damped system, thus, given the system as critical damp at the first trial is reasonable. Then the natural frequency is easy to be tuned. For the $RL$ block, the rising and falling rate is approximately defined by acceleration and deceleration times in the drive (inverter) parameter setting, which need to be fine-tuned later. For the $SW$ block, the velocity switch is usually approximated to 10 to 20% of the maximum velocity. After a few trials, all above-mentioned parameters were tuned to fit the experimental data. For the bridge direction, natural frequency and damping ratio, rising rate, falling rate, $V_{switch}$, and maximum velocity are 4.8, 1, 1, -1, 12%, and 0.36 m/s, respectively. And for the trolley direction, natural frequency and damping ratio, rising rate, falling rate, $V_{switch}$, and maximum velocity are 10, 1, 1, -1, 15%, and 0.33 m/s, respectively. Figure 5 compares the data from the experiment and the proposed model of bridge and trolley, respectively.
Figure 5. Comparison of experimental data and proposed model

Red lines and blue lines represent both bridge and trolley positions from experimental data of 100% and 50% velocity command. Black lines represent outputs of the proposed model, which are bridge and trolley positions. It can be seen that the outputs of the proposed model track the experimental data nicely.

4.3 Discussion

Parameter identification result was done by trial and error technique. Figure 6 shows the performance of model prediction by plotting error over time. That said, a static and dynamic error is less than 20 and 40 mm, respectively. Although, using the trial and error method provides a good result of parameter identification, but a better result may be achieved by some powerful optimization techniques. For further investigation, parameter identification should be optimized by minimization of a cost function.

Figure 6. Showing of static and dynamic error

During the trial and error process, the natural frequency of the TF block and the velocity switch of the SW block depends on velocity command input. Therefore, the system parameters should be identified within a specific input range.
5. Conclusion

This paper investigated the model of drives and motors of an overhead crane, which was previously proposed by Sorensen and Singhose [8]. The modelling method was described to provide an understanding of the basic idea. The model was intently extended due to the hardware configuration, in the way that the crane position was measured instead of the crane velocity. The proposed model was verified by an industrial-grade 1-ton overhead crane. By using the trial and error method, the result showed that the proposed model provided a good prediction of the crane position. The static and dynamic errors were less than 20 and 40 mm, respectively. Inside the proposed model, it was found that natural frequency and velocity switch were input dependent, varying by velocity command inputs. To use this model, its parameters should be identified within a velocity command range.

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