AL-MUKHTAR JOURNAL OF ENGINEERING RESEARCH ISSN online: 2519-6839 // ISSN Print 2519-6820
Vol. 6, No. (1): 77-86 Available at mjer.omu.edu.ly
Received October 6, 2022, Accepted November 11, 2022, Published December, 2022 DOI: https://doi.org/10.54172/ve5s7j61

MODELING AN ANTI-SWING CONTROLLER OF AN OVERHEAD CRANE BY USING MATLAB SIMULINK

Abdalkaleg Hamad[1], Hafeth Bu Jldain[2], Gebreel Abdalrahman [3]

[1] Department of Mechanical Engineering, Omar Al-Mukhtar University, Libya, *Email: abdalkaleg.hamad@omu.edu.ly*
[2] Department of Mechanical Engineering, Omar Al-Mukhtar University, Libya, *Email: hafeth.bujldain@omu.edu.ly*
[3] Department of Mechanical Engineering, Omar Al-Mukhtar University, Libya, *Email: gebreel.abdalrahman@omu.edu.ly*

Abstract

An overhead crane is one of the most common types of loading and unloading equipment. It can be used in civil engineering, metallurgical manufacturing, river, and seaports, and so on. It allows for cargo ascent and descent as well as distance transfer employing lifting and traveling equipment. The equation of motions of the system (crane mechanisms) in this paper has been derived based on Newton's laws. The crane overhead consists of a pendulum and a moving cart. Such a system is unstable without control, and it is nonlinear. A linearizing dynamic feedback procedure is deduced from its general implicit differential model. In crane overhead systems, the suspended load (by cable) is subject to swing caused by improper control input, which may even cause accidents. The Crane controller system is able to move the trolley fast enough and suppress the payload swing at the final position. This is so-called anti-swing control. The aim of this paper is to design a control system for the overhead system that can smoothly position the trolley while minimizing the swing of the load at the destination by using MATLAB Simulink to meet some of the specification requirements.

الملخص العربي

الرافعة العلوية هي واحدة من أكثر أنواع معدات التحميل والتفريغ شيوعًا. يمكن استخدامها في الهندسة المدنية، في التصنيع المعدني، على ضفاف الأنهار، وفي الموانئ البحرية، وما إلى ذلك. إنها تسمح بصعود ونزول البضائع وكذلك نقلها لمسافة باستخدام معدات الرفع والازاحة. في هذه الورقة تم اشتقاق معادلة حركة النظام بناءاً على قوانين نيوتن. تتكون الرافعة العلوية من بندول وعربة متحركة. مثل هذا النظام غير مستقر بدون تحكم وهذا النظام غير خطي. في أنظمة الرافعة العلوية، يخضع الحمل المعلق (بواسطة الكابل) للتأرجح الناتج عن إدخال تحكم غير صحيح، مما قد يتسبب في وقوع حوادث. نظام التحكم في الرافعة قادر على تحريك العربة بسرعة كافية وتخفيف تأرجح الحمولة في الموضع النهائي. هذا ما يسمى بنظام السيطرة المضاد للتأرجح. الهدف من هذه الورقة هو تصميم نظام للتحكم بنظام الرافعة العلوية يمكنه تحريك العربة إلى موضعها النهائي بسلاسة مع تقليل تأرجح الحمولة باستخدام **MATLAB Simulink** لتلبية بعض المواصفات.

Keywords: linearizing, nonlinear, crane, pendulum, Simulink.

1. Introduction

Overhead cranes allow them to lift and move heavy loads which makes them very useful to be used in the transportation and construction fields. Cranes consist of a cable-hook assembly that is suspended on a support mechanism which could be a trolley-girder, a trolley-jib, or a boom. The type of support mechanism defines the movement degrees of freedom of the overhead crane system.

Cranes are typically a damped system [1-3] and any transient motion can cause oscillation or pendulation motion of the payload and it takes a long time to dampen out this swinging motion of the payload. The movement of the cable-hook-payload assembly of the overhead crane system can result in an excitation of the suspension point. This external excitation caused by cable-hook assembly movement results in oscillations of the payload. Also, the motion of the crane itself can induce inertia forces causing significant payload peculations. Suppression of pendulation and oscillation of the crane during motion will decrease the damping of loads and increase the safety of operations. Most crane system controllers developed and tested in actual operation were found to be ineffective [4].

Various attempts have been made to control the pendulation and oscillation of the payload through different anti-swing control systems. However, a skilled human operator still performs much better than a control system. Usually, the control system is designed according to a given application and can not adapt to any changes that may occur during actual operation [5,6].

The anti-swing control system module in this paper will focus on the overhead crane system, which has two main moving parts namely, the trolly and the cable-hook assembly. The control system will be able to move the trolley from rest to the desired position and stabilize the vibrations of the cable-hook assembly induced by this movement.

Martindale et al. [7], and Rahn et al. [8] developed a linear feedback controller to move the trolley to a desired position and stabilize the cable-hook assembly at the end position. The controllers in all of these systems were sensitive to changes in the cable length and traveling speed of the trolly during operation. Lee [9,10] introduced a controller to the hoisting motor to track the cable length and accordingly adapt to fix the payload pendulation by slowing the changing in cable length. Experiments verify that low travel speed minimizes transient pendulations to less than 2◦. M´endez et al. [11] used Two neural networks to enhance the performance of a state feedback controller. networks used to generate and adjust each trolley and the payload. experiments verify that this strategy can produce a smooth positioning of the trolley and suppress residual pendulations at low travel speeds.

Fliess et al. [12,13] proposed a nonlinear dynamic feedback technique. The technique Substitutes a mathematical representation of nonlinear expressions and produced a linear relationship between the state and input variables. Then a controller is used to drive the trolley to these predefined input accelerations. Computer simulations showed that payload pendulations were reduced to a maximum of 1.7 ◦ during the motion.

d’Andrea-Novel et al. [14-16] proposed two feedback controllers assuming a flexible cable and a payload mass of the same magnitude as the cable. In the first controller, the dynamics of the trolley are ignored, and nonlinear feedback was used to stabilize the cable-payload assembly. In the second controller, the dynamics of the trolley included nonlinear feedback used to stabilize the cable-payload assembly. Both strategies proven to have the ability to stabilize the payload assembly.

In section 2, the equation of motion for the hanging crane system is driven and the equations of the motion are linearized. In section 3, to solve both linear and nonlinear differential equations and simulate the motion of the pendulum MATLAB Simulink is used.

2. Over-Head Crane Dynamics

The crane over-head system has two masses m_t cart’s mass and m pendulum’s mass as shown in figure (1).

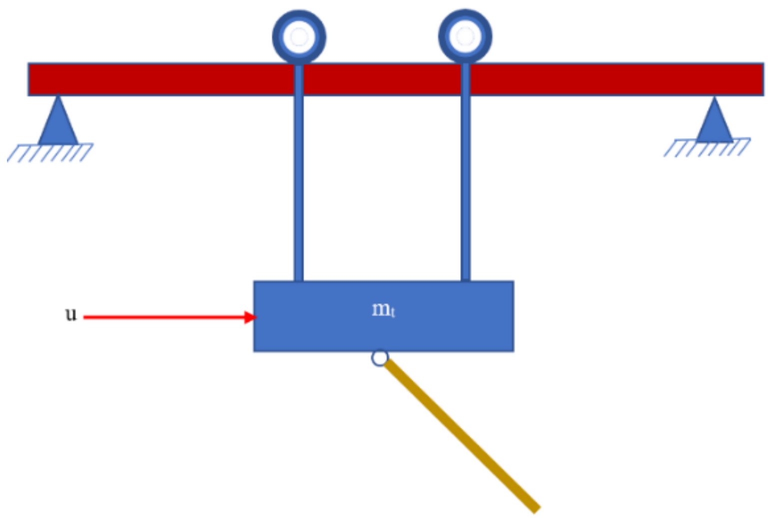

Fig. 1 The crane over-head system

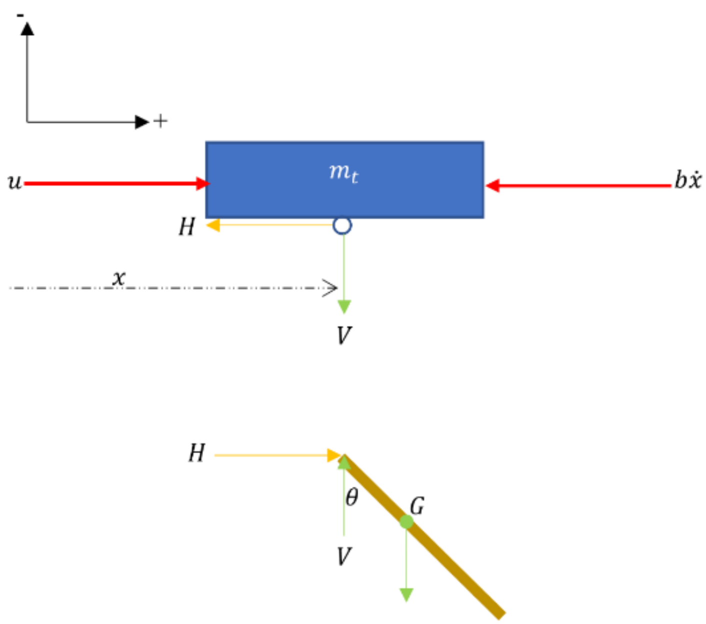

Fig. 1 shows the free-body diagrams of the two elements of the inverted pendulum system

Figure 2 shows the free-body diagrams of the two elements of the inverted pendulum system.

For the cart

For the cart there is no motion in y direction (vertical) then one can write:

$$\sum f_y = 0 \quad (1)$$

The horizontal motion of the cart is descrbing can be found by summing the forecs in x-dirction as follows

$$\sum f_x = m_t\ddot{x} \quad (2)$$

$$m_t\ddot{x} = u - H - b\dot{x}$$
$$\ddot{x} = \frac{1}{m_t}(u - H - b\dot{x})$$

For the pendulum

For obtaining the equation of motion of the pendulum $(\boldsymbol{x}, \boldsymbol{y})$ coordinates are defined as in figure 1 and the center gravity of the pendulum as $(\boldsymbol{x_G}, \boldsymbol{y_G})$:

$$x_G = x + l\sin(\theta) \qquad y_G = l\,cos(\theta) \tag{3}$$

The motion of the pendulum can be obtained by taking the moment about an axis passing through the center of gravity of the pendulum.

$$\sum M_G = I\,\ddot{\theta}$$
$$I\,\ddot{\theta} = -Hlcos(\theta) - Vlsin(\theta) \tag{4}$$
$$\ddot{\theta} = \frac{1}{I}(-Hlcos(\theta) - Vlsin(\theta))$$

The horizontal motion of the pendulum can be obtained as follows

$$\sum f_x = m_p\,\ddot{x_G} \qquad m_p\ddot{x_G} = H \tag{5}$$

The vertical motion of the pendulum can be obtained as follows

$$\sum f_y = m_p\,\ddot{y_G} \qquad m_p\ddot{y_G} = V - m_p g \tag{6}$$

The acceleration of the centerty gravity can be obtained by differentiating equation (3) twice

$$\ddot{x_G} = \ddot{x} - l(\dot{\theta})^2\sin(\theta) + l\ddot{\theta}\cos(\theta) \qquad \ddot{y_G} = l(\dot{\theta})^2\cos(\theta) + l\ddot{\theta}\sin(\theta) \tag{7}$$

Now, taking equation 7 into 5 and 6 equations

$$H = m_p(\ddot{x} - l(\dot{\theta})^2\sin(\theta) + l\ddot{\theta}\cos(\theta)), \tag{8}$$

$$V = m_p(l(\dot{\theta})^2\cos(\theta) + l\ddot{\theta}\sin(\theta)) \tag{9}$$

The two governing equations

The two governing equations for this system can be obtained by substituting and with a few algebraic manipulations of the previous equations (from 1 to 9):

The system of equations given in 8 is a nonlinear system that describes the motion of the crane with its hanging load.

These equations can be linearized for small motions

about $\boldsymbol{\theta(t) \approx \dot{\theta}(t) \approx 0}$ which would typically be valid for the hanging crane system.

Such a system needs to be linearized because the control system design is based on linear techniques. These two equations will be linearized about the downward vertical equilibrium position $\boldsymbol{\theta(t) \approx \dot{\theta}(t) \approx 0}$. Consquenly, $\boldsymbol{sin\theta \approx \theta}$,$\boldsymbol{cos\theta \approx 1}$, and $\boldsymbol{\dot{\theta} \approx 0}$.

This assumption should be reasonably valid since under control the pendulum must be in a vertical position i.e., $\boldsymbol{\theta(t) = 0}$

$$(m_t + m_p)\ddot{x} + b\dot{x} + m_p\,l\,\ddot{\theta}\,\cos\theta - m_p l\,(\theta)^2\,\sin\theta = u$$
$$(I + m_p l^2)\ddot{\theta} + m_p g\,l\,\sin\theta = -m_p l\,\ddot{x}\,\cos\theta \tag{10}$$

After substituting the above approximations into the nonlinear governing equations, the equations of motion for both the cart and the pendulum become.

$$\ddot{x} = \frac{1}{m_t}(u - H - b\dot{x}) \tag{11}$$

$$\ddot{\theta} = \frac{1}{I}(-Hl - Vl(\theta)) \tag{12}$$

$$H = m_p(\ddot{x} + l\,\ddot{\theta}) \tag{13}$$

$$V = m_p(l\,\ddot{\theta}\,\theta + g) \tag{14}$$

Equations 11-14 represent the linearized differential equations for the crane over-head system.
Note that the above linear equations are valid when is θ varies a small amount of θ.

3. Simulation of Over-Head Crane System

In this section, MATLAB Simulink blocks shown in Figure 2 are used to solve both linear and nonlinear differential equations of motion and simulate the motion of the pendulum to a low amplitude square wave force input on the trolley (u) with the frequency of 0.05 Hz. Also, the results of the solutions of nonlinear and linearized equations are compared with each other. All the parameters used in the simulation of the overhead crane system are listed in table 1.

Figure 3 shows the Simulink block for both linearized and nonlinear systems used to simulate and compare the linearized and nonlinear responses.

Figure 4 and figure 5 show the responses of both systems the pendulum and the cart (angular position θ and translation position x) where the input magnitude is the small value (1 N). These results show that there are small variations in the two responses.

Clearly, in figures 6 to Figure 11 the variations between the nonlinear and the linearized system are increasing as the magnitude of the input force increases. Therefore, in the next section, the controller is designed by assuming the plant can be linearized at a small value of theta.

Table1: The parameters of the system

Parameter	**Symbol**	**Value**	**Unit**
The mass of the pendulum	m_p	100	kg
The mass of the trolley	m_t	240	Kg
Damping on the trolley track	b	100	$N.\frac{sec}{m}$
Pendulum moment of inertial around its center of gravity	I	100	$Kg.m^2$
Half-length of the pendulum	L	4	m
Gravity acceleration	g	9.81	$\frac{m}{sec^2}$

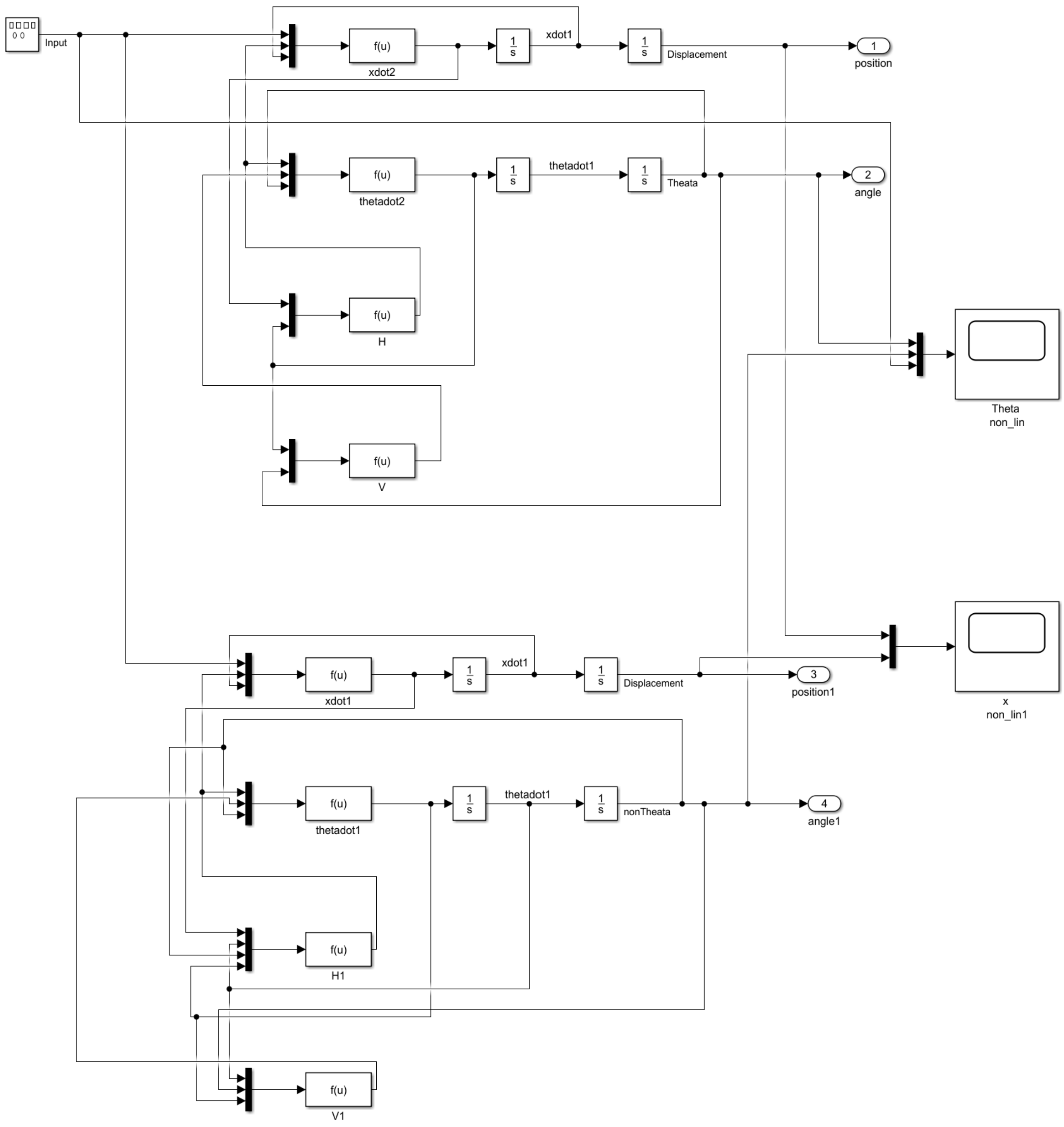

Fig. 2 shows the Simulink block for both linearized and nonlinear systems

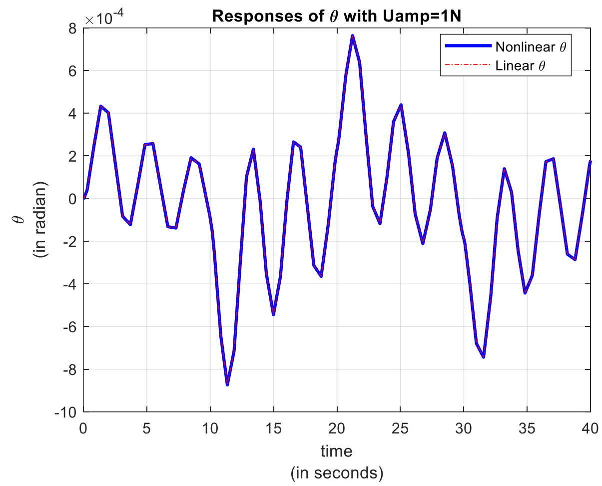

Fig. 3 pendulum position response with u amplitude =1N

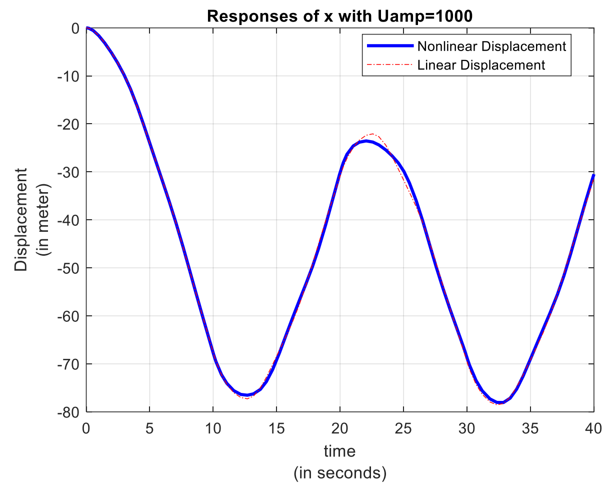

Fig. 6 Cart position response with u amplitude =4000N

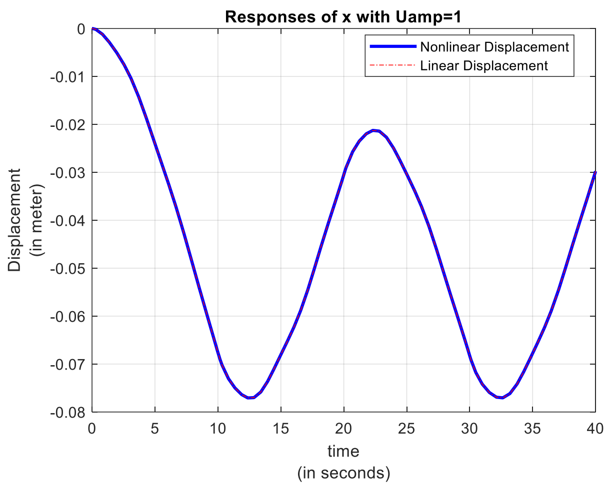

Fig. 4 Cart position response with u amplitude =4000N

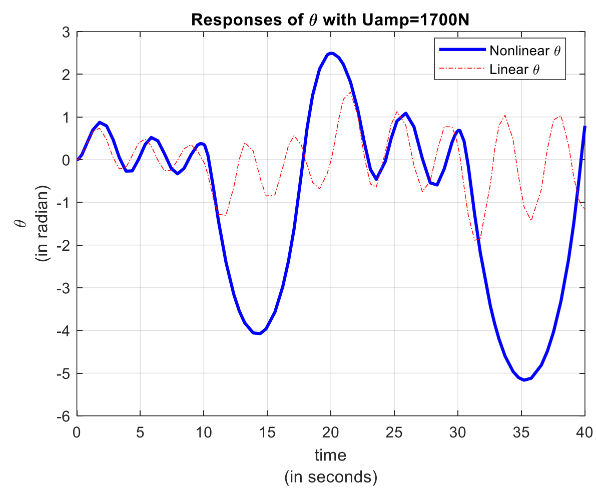

Fig. 7 pendulum position response with u amplitude =1700N

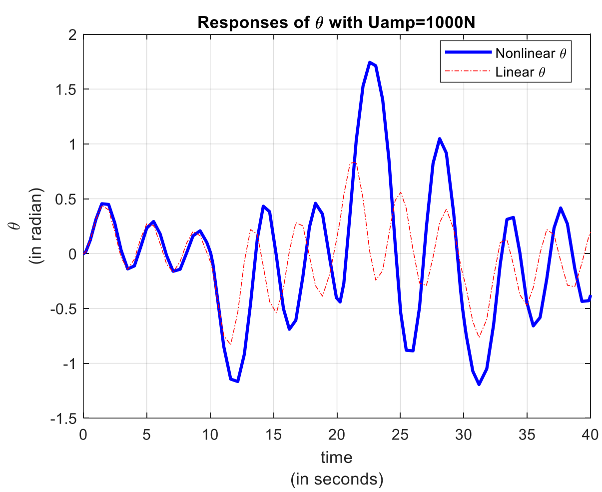

Fig. 5 pendulum position response with u amplitude =1000N

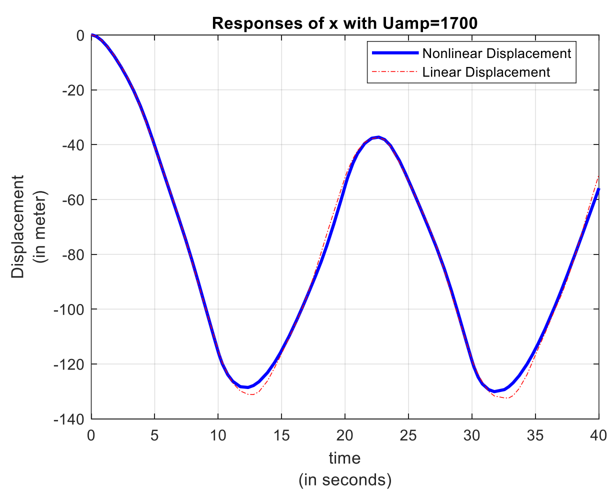

Fig. 8 Cart position response with u amplitude =1700N

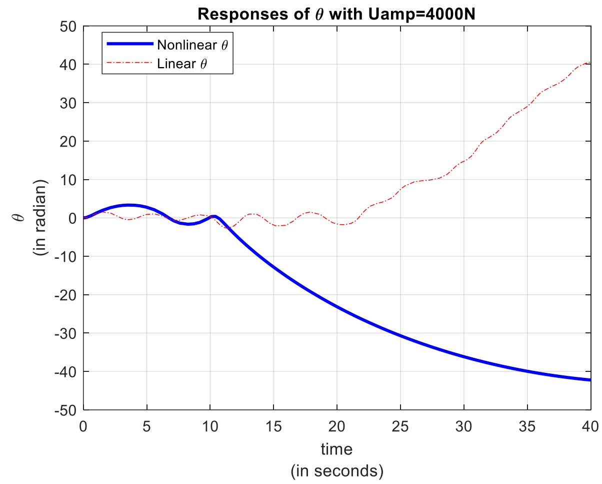

Fig. 9 pendulum position response with u amplitude =4000N

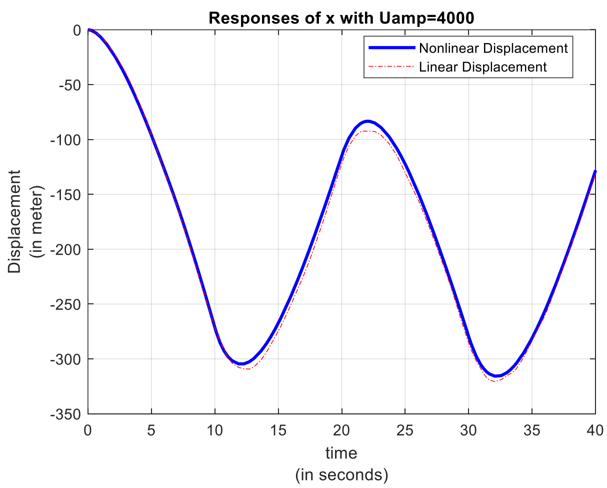

Fig. 10 Cart position response with u amplitude =4000N

4. Anti-Swing Controller Design Simulink

The goal of designing the controller here is to eliminate the oscillations of the pendulum which can be done by measuring and feeding back the angular velocity with a suitable again ($\boldsymbol{k_d = 100}$).

For the cart position, the basic proportional gain ($\boldsymbol{k_P = 6500}$) that gives a suitable overshot and fast response based on the rise time is chosen. This work was done by assuming the plant can be linearized at a small value of theta.

Figure 12 shows the Simulink block for the anti-swing controller's response to the pendulum by using MATLAB Simulink.

Figure 13 shows the Simulink block for the anti-swing controller's response for the cart by using MATLAB Simulink. Clearly, the oscillation of the pendulum is eliminated by the designed controller in this paper. Also, the desired position for the cart is reached. These results were obtained by using the input step function in the controller system.

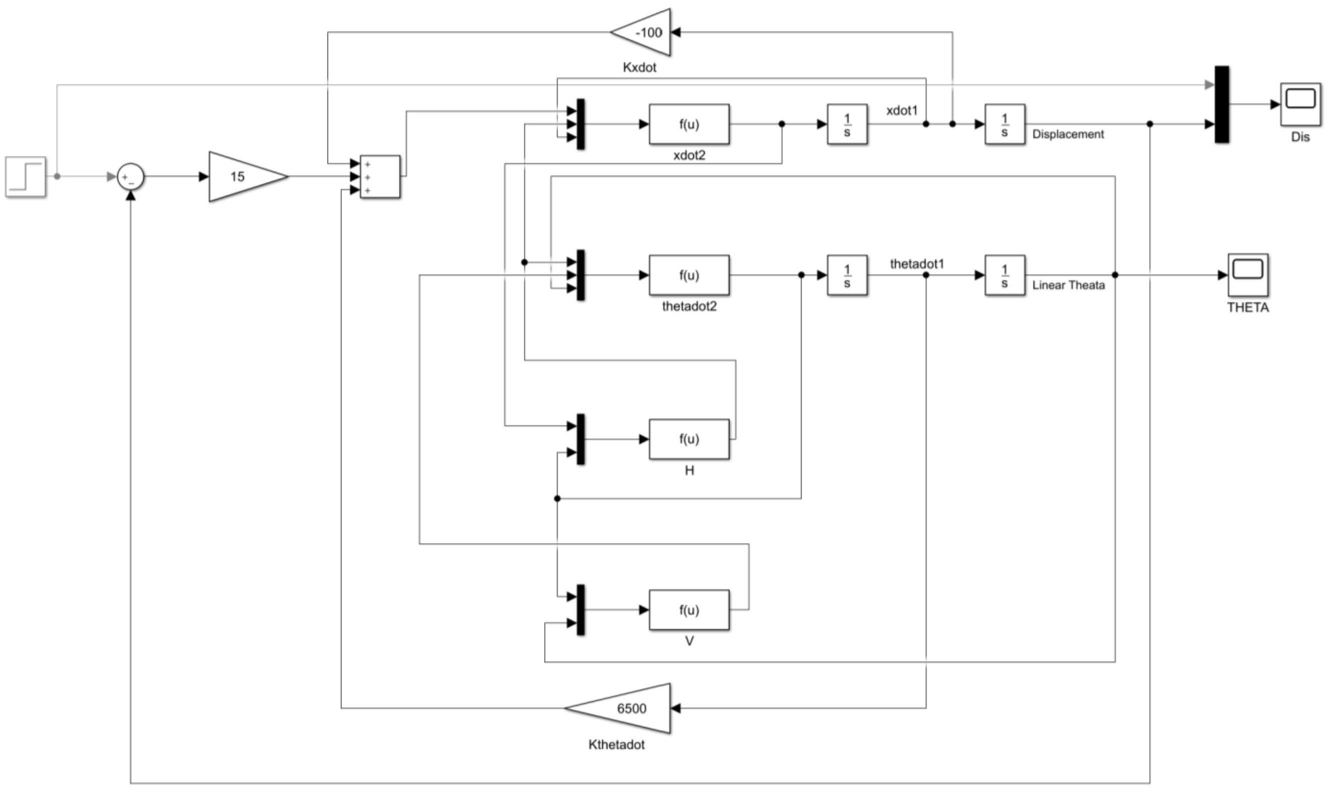

Fig. 11 The Simulink block for the controller

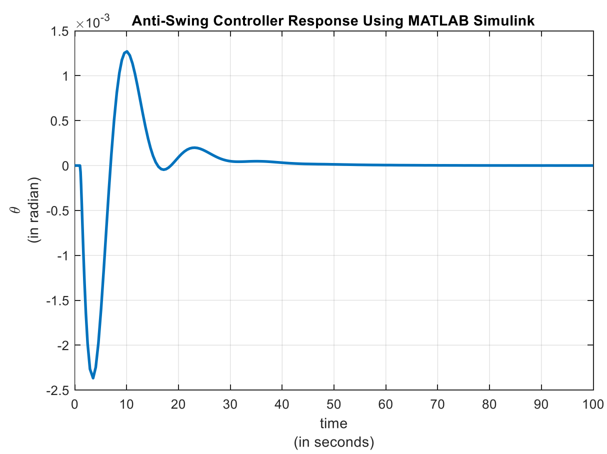

Fig. 12 Pendulum response

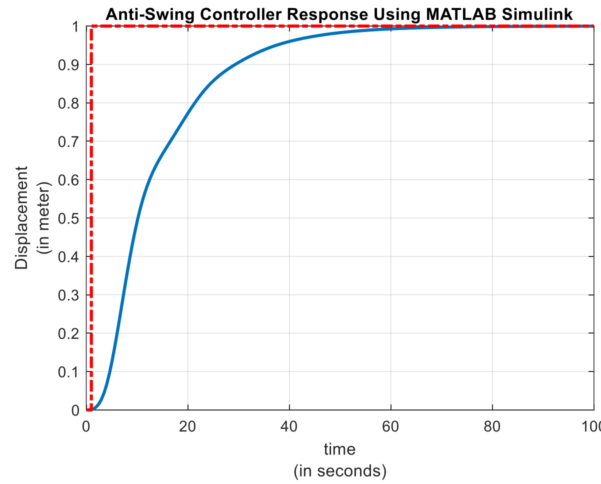

Fig. 13 Step response for Cart

5. Conclusion

A complete dynamic model for an overhead crane that includes the pendulum and moving cart based on Newton's laws has been derived. Increasing the magnitude of the input fore leads to an increase in the variations between the nonlinear and linearized system as the results are shown. The system stabilized by applying a force to the cart that the pendulum is attached to. The anti-swing controller was simulated by using MATLAB Simulink. The responses of the anti-swing controller are shown that the oscillation of the pendulum is eliminated and the desired position for the cart is reached. The gains are chosen to guarantee the desired response specifications. To improve the results linearization can be done using by different approaches, but it might be more complicated.

References

[1] Todd, M. D., Vohra, S. T., and Leban, F., "Dynamical measurements of ship crane load pendulation," in Oceans'97 MTS/IEEE: Conference Proceedings, Vol. 2, Halifax, Canada, pp. 1230–1236, 1997.

[2] Patel, M. H., Brown, D. T., and Witz, J. A., "Operability analysis for a monohull crane vessel," Transactions of the Royal Institution of Naval Architects 129, 103–113, 1987.

[3] van den Boom, H. J. J., Coppens, A., Dallinga, R. P., and Pijfers, J. G. L., "Motions and forces during heavy lift operations offshore," in Developments in Marine Technology, Proceedings of a Workshop on Floating Structures and Offshore Operations Vol. 4, Wageningen, The Netherlands, pp. 51–61, 1987.

[4] Ramli, L., Mohamed, Z., Abdullahi, A. M., Jaafar, H. I., & Lazim, I. M. Control strategies for crane systems: A comprehensive review. Mechanical Systems and Signal Processing, 95, 1-23, 2017.

[5] Abdel-Rahman, E. M., Nayfeh, A. H., & Masoud, Z. N. Dynamics and control of cranes: A review. Journal of Vibration and control, 9(7), 863-908, 2003.

[6] Lee, H. H., Cho, S. K., & Cho, J. S. A new anti-swing control of overhead cranes. IFAC Proceedings Volumes, 30(13), 115-120, 1997.

[7] Martindale, S. C., Dawson, D. R., Zhu, J., & Rahn, C. D. (1995, June). Approximate nonlinear control for a two degree of freedom overhead crane: Theory and experimentation. In Proceedings of American Control Conference-ACC'95 (Vol. 1, pp. 301-305). IEEE, 1995.

[8] Rahn, C. D., Zhang, F., Joshi, S., & Dawson, D. M. Asymptotically stabilizing angle feedback for a flexible cable gantry crane, 1995.

[9] Lee, H.-H., "Modeling and control of a 2-dimensional overhead crane," in Proceedings of the ASME Dynamic Systems and Control Division DSC-Vol. 61, Dallas, TX, pp. 535–542, 1997.

[10] Lee, H.-H., "Modeling and control of a three-dimensional overhead crane," Journal of Dynamic Systems, Measurement, and Control 120, 471–476, 1998.

[11] M´endez, J. A., Acosta, L., Moreno, L., Hamilton, A., and Marichal, G. N., "Design of a neural network based self-tuning controller for an overhead crane," in Proceedings of the IEEE International Conference on Control Applications, Trieste, Italy, pp. 168–171, 1998.

[12] Fliess, M, L´evine, J., and Rouchon, P., "A simplified approach of crane control via a generalized state-space model," in Proceedings of the 30th Conference on Decision and Control, Brighton, England, pp. 736–741, 1991.

[13] Fliess, M, L´evine, J., and Rouchon, P., "Generalized state variable representation for a simplified crane description," International Journal of Control 58(2), 277–283, 1993.

[14] d'Andrea-Novel, B., Boustany, F., and Conrad, F., "Control of an overhead crane: Stabilization of flexibilities," in Boundary Control and Boundary Variation: Proceedings of the IFIP WG 7.2 Conference, Sophia Antipolis, France, pp. 1–26, 1990.

[15] d'Andrea-Novel, B. and Boustany, F., 1991b, "Control of an overhead crane: Feedback stabilization of an hybrid PDE-ODE system," in Proceedings of the 1st European Control Conference: ECC'91, Grenoble, France, pp. 2244–2249, 1991.

[16] d'Andrea-Novel, B., Boustany, F., Conrad, F., and Rao, B. P., "Feedback stabilization of a hybrid PDE-ODE system: Application to an overhead crane," Mathematics of Control, Signals, and Systems 7,1–22, 1994.