Position control and vibration suppression of a flexible overhead crane system

Điều khiển vị trí và dập dao động tải trọng cho hệ thống nâng hạ

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Abstract:
Trolley positioning and payload swinging control problem of a flexible overhead crane system is addressed in this paper. The system's equations of motion that couple the crane's cable and actuators dynamics are derived via extended Hamilton's principle. The control signal is designed based on the Lyapunov direct method and backstepping control. The stability of the closed loop system is proven. Numerical simulations are included to demonstrate the effectiveness of the proposed control.
Keywords: Flexible systems, overhead crane, field oriented control, Lyapunov direct method.

Tóm tắt
Bài báo đề cập đến vấn đề điều khiển vị trí và dập dao động phụ tải trong cầu trục. Phương trình chuyển động bao gồm động học của dây tời và cơ cấu truyền động được tổng hợp thông qua nguyên lý Hamilton mở rộng. Luật điều khiển được thiết kế nhờ phương pháp Lyapunov trực tiếp và backstepping. Tính ổn định của hệ thống kín được chứng minh, một số mô phỏng cũng được đưa ra nhằm minh họa tính đúng đắn của nghiên cứu.
Từ khóa: Hệ mềm, hệ thống nâng hạ, điều khiển tựa từ thông, ổn đinh Lyalunov

1. INTRODUCTION

Due to the flexibility in handling loads, gantry crane systems are essential in industrial and logistic applications. Expected operating condition of the gantry system is the desired positions of the trolley and the pay-load is coinciding. In practice, this is impossible because of swinging motion of the payload. Swinging payload phenomenon slows down goods handling operations and can be a potential threat to human and surrounding devices. Certain types of payload can ignite multi-modes or double-link pendulum effects [1] -[4]. In addition, characterized as a class of under-actuated systems, precisely controlling trolley position and suppressing payload vibration simultaneously pose many challenges for control engineers.

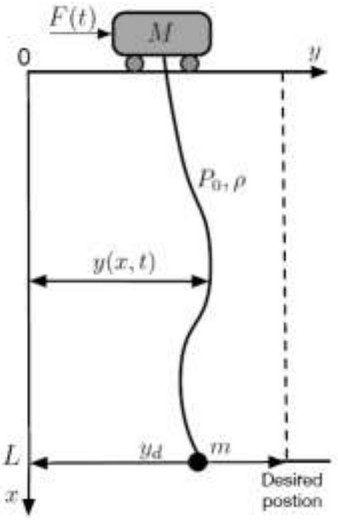
In order to find a solution for the aforementioned control problem, a decoupling control law is proposed in [5] to asymptotically stabilize trolley position and swing angle of the payload. Actually, the designed control only guarantee bounded swing angle. An improvement is made in [6] with a gantry system with varying rope length. A switching control action is derived based on feedback lineariazation technique. Position control and vibration suppression of gantry crane is considered in [7], the control problem is partly solved with the coupling effect between trolley and payload motions are taken into account. However, the obtained results are relatively limited in practice since the variance of system's parameters and actuator's dynamics are not considered. Practically, parameters of a gantry system is varying and challenging to identify due to hydrodynamic forces acting on the payload and the variance of payload mass and geometry. In order to deal with system uncertainty, an adaptive mechanism is integrated in proposed control law suggested in [8]. Well-known with its robustness against system uncertainty and disturbances, sliding mode control is applied in gantry control in [9]. However, it is need to cooperate with a pre-shape input to gain better performances [10]. Several adaptive schemes for gantry control also presented in [11] and [12].

Although having some promising results, feedback control seems to be suitable with automated gantry systems (where desired payload positions are pre-defined via a human machine interface). The reason is when in manual operating modes, human-in-the-loop actions may interfere with control decision of the feedback controller and deteriorate system responses. Instead of feedback controls, control actions from operators are modified before sending to the gantry actuators as shown in [13] and [14]. The advantage of pre-shape input technique over feedback control is that measurement of system states is not required but a full knowledge of the system must be available. To rectify this drawback, pre-shape input method can be hybridised with a robust control as indicated in [14]-[16]. A brief literature review above shows that the limitation of aforementioned researches rooted in the modeling step. Gantry control problem are solved with an assumption of pendulum motions of the payload that results in a system of ordinary differential equations govern system motions. Practice has shown that it is not the case, and gantry cable actually considered as a flexible systems whose motions are modeled as a system of partial differential equations.

This paper directly designs a gantry control when taking flexibility of the cable into consideration. Trolley position and swinging payload suppression control is design based on Lyapunov's direct method. Finally stability of the closed-loop system is proven analytically and numerically.

2. MATHEMATICAL MODEL

An overhead crane system is illustrated in Fig. 1, where



H. 1 *An overhead crane system.*

$y(x,t)$ and y_d are the transverse motion of the crane's cable and target position of the payload, respectively. P_0 is the cable tension, ρ is the mass per unit length of the cable, L is the length of the cable. M and m are trolley's and payload's masses, respectively. The force $F(t)$ is generally generated by an induction motor. The kinetic energy of the system is

$$T=\frac{M}{2}\left(\frac{\partial y\ \ 0}{\partial t}\right)^2+\frac{\rho}{2}\int_0^L\left(\frac{\partial y}{\partial t}\right)^2 dx+\frac{m}{2}\left(\frac{\partial y\ \ L}{\partial t}\right)^2, \quad (1)$$

In (1) and from now onward the argument (x,t) is omitted for neat representation. In addition $y(0)$ and $y(L)$ are used to denote $y(0,t)$ and $y(L,t)$, respectively. The potential energy can be expressed as

$$P=\frac{P_0}{2}\int_0^L\left(\frac{\partial y}{\partial x}\right)^2 dx \quad (2)$$

where P_0 is the tension of the cable. The work done by the external control force is given as

$$\mathrm{W}=F(t)y(L) \quad (3)$$

Remark 1. Bending stiffness of the cable is considerably small so that potential energy due to bending stiffness can be ignored. The cable is assumed to be inextensible. The extended Hamilton's principle is expressed as follows

$$\int_{t_1}^{t_2}\delta\ \ T-P+\mathrm{W}\ \ dx \quad (4)$$

Substituting (1), (2) and (3) into (9) results

$$\int_{t_1}^{t_2}\int_0^L\left[\left(-\rho\frac{\partial y^2}{\partial t^t}+P_0\frac{\partial^2 y}{\partial x^2}\right)\delta dx-P_0\frac{\partial y}{\partial x}\bigg|_0^L\right.$$
$$+M\frac{\partial y^2(0)}{\partial t^2}\delta y(0)dt+m\frac{\partial y^2(0)}{\partial t^2}\delta y(0) \quad (5)$$
$$+F(t)\delta y(0)\ \ dt=0$$

Using integration by parts, the equations of motions and boundary conditions of the crane system can be given as

$$\rho y_{tt}-P_0y_{xx}=0$$
$$My_{tt}(0)+P_0y_{\mathrm{x}}(0)=F(t) \quad (6)$$
$$my_{\mathrm{tt}}(L)-P_0y_{\mathrm{x}}(L)=0$$

The force acting on the trolley $F(\mathrm{t})$ can be calculated in term of the motor torque as

$$F(\mathrm{t})=\frac{i\eta}{R_b}m_M\ , \quad (7)$$

where R_b is the radius of the drum, i is the transmission ratio of the gearbox and η is the efficiency of the transmission system. Mathematical model of the asynchronous motor can be written as follows

$$\dot{i}_{sd}=-\left(\frac{1}{\sigma}+\frac{1-\sigma}{\sigma T_r}\right)i_{sd}+\omega_s i_{sq}+\frac{1-\sigma}{\sigma T_r}\psi'_{rd}$$
$$+\frac{1-\sigma}{\sigma}\omega\psi'_{rd}+\frac{1}{\sigma L_s}u_{sd},$$
$$\dot{i}_{sd}=-\omega_s i_{sd}-\left(\frac{1}{\sigma T_s}+\frac{1-\sigma}{\sigma T_r}\right)i_{sd}-\frac{1-\sigma}{\sigma}\omega\psi'_{rd}$$
$$+\frac{1-\sigma}{\sigma T_r}\psi'_{rd}+\frac{1}{\sigma L_s}u_{sq},$$
$$\dot{\psi}'_{rd}=\frac{1}{T_r}i_{sd}-\frac{1}{T_r}\psi'_{rd}+\ \ \omega_s-\omega\ \ \psi'_{rd},$$
$$\dot{\psi}'_{rq}=\frac{1}{T_r}i_{sq}-\ \ \omega_s-\omega\ \ \psi'_{rd}-\frac{1}{T_r}\psi'_{rq},$$
$$m_M=\frac{3}{2}K_m z_p\psi_{rd}i_{sq}. \quad (8)$$

In (8), i_{sd} and i_{sq} are direct and quadrature components of stator current. T_r and T_s are rotor and stator time constants, z_p is number of pole pairs, σ is total magnetic leakage factor. $K_m=\frac{L_m}{L_r}$, where L_m and L_r are mutual and rotor inductance. $\psi'_{rd}=\frac{\psi_{rd}}{L_m}$ and $\psi'_{rq}=\frac{\psi_{rq}}{L_m}$, where ψ_{rd} and ψ_{rq} are *dq* components of the rotor flux. The coupled electrical-mechanical system is rewritten as follow

$$\rho y_{tt} - P_0 y_{xx} = 0,$$
$$My_{tt}(0) - P_0 y_x(0) = \Omega i_{sq},$$
$$\dot{i}_{sq} = -\theta_1 i_{sd} - \theta_2 i_{sq} - \theta_3 + \theta_4 u_{sq},$$
$$my_{tt}(L) + P_0 y_x(L) = 0. \qquad (9)$$

where

$$\theta_1 = \omega_s, \theta_2 = \frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_r}, \theta_3 = \frac{1-\sigma}{\sigma}\omega\psi'_{rd}$$
$$\theta_4 = \frac{1}{\sigma L_s}, \Omega = \frac{3}{2}\frac{i\eta}{R_b} K_m z_p \psi'_{rd} \qquad (10)$$

Remark 2. Equation (9) is derived under a condition that the rotor flux orientation is obtained, i.e., $\psi'_{rq} = 0$. Moreover, it is assumed that i_{sd} and ψ'_{rd} are kept constants by current and flux controllers and their values are available for feedback. In addition, the current controller has the ability of decoupling i_{sd} and i_{sq}.

It is noted that from this point onward, argument *t* is ignored where applicable.

3. CONTROL DESIGN

The control objective is to simultaneously stabilize the trolley and the payload at the desired position. An investigation of the system given in (9) shows that the system is of strict-feedback form. Hence, in this paper, backstepping technique will be employed to design the control input u_{sq}. The choice of back-stepping as a design tools make it ready if system parameters adaptation is needed. The control design process comprises of two steps. In order to satisfy the control objective, at first we take i_{sq} as a control and define

$$z = \Omega i_{sq} - \alpha \qquad (11)$$

where is α virtual control. Consider the following Lyapunov candidate function

$$W = \frac{\rho}{2}\int_0^L y_t^2 dx + \frac{P_0}{2}\int_0^L y_x^2 dx + \frac{m}{2} y_t^2(L) + \frac{M}{2} y_t^2(0) + \frac{\Delta}{2}\left(y(0) - y_d\right) \qquad (12)$$

where Δ is a strictly positive constant. It is straightforward to show that V can be lower and upper bounded as below

$$W \geq \gamma_1\left(\int_0^L y_t^2 dx + \int_0^L y_x^2 dx + y_t^2(L) + y_t^2(0) + \left[y(0) - y_d\right]^2\right) \qquad (13)$$

and

$$W \leq \gamma_2\left(\int_0^L y_t^2 dx + \int_0^L y_x^2 dx + y_t^2(L) + y_t^2(0) + \left[y(0) - y_d\right]^2\right) \qquad (14)$$

where

$$\gamma_1 = \frac{1}{2}\min\left\{\int_0^L y_t^2 dx, \int_0^L y_x^2 dx, y_t^2(L), y_t^2(0), \left(y(0) - y_d\right)^2\right\} \qquad (15)$$

and

$$\gamma_2 = \frac{1}{2}\min\left\{\int_0^L y_t^2 dx, \int_0^L y_x^2 dx, y_t^2(L), y_t^2(0), \left(y(0) - y_d\right)^2\right\} \qquad (16)$$

Time derivative

$$\dot{W} = P_0 y_t y_x \Big|_0^L - P_0 y_t(L) y_x(L) + y_t(0)\left(\alpha_1 + z_1 + P_0 y_x(0)\right) + \Delta\left[y(0) - y_d\right] y_t(0)$$
$$= y_t(0)\left(\alpha + z + \Delta\left[y(0) - y_d\right]\right) \qquad (17)$$

Equation (17) suggests that virtual control α_1 can be chosen as follows

$$\alpha = -k y_t(0) - \Delta\left[y(0) - y_d\right] \qquad (18)$$

where k is a strictly positive constant. In the second step, the actual control input u_{sq} is designed to regulate z_1 at the origin. To archive this target, we consider a Lyapunov candidate function

$$V = W + \frac{1}{2} z^2 \qquad (19)$$

Time derivative

$$\dot{V} = -k_1 y_t^2(0) + z\left[-\frac{\theta 1}{\Omega 1} i_{sd} - \frac{\theta 2}{\Omega} i_{sq} - \frac{\theta 3}{\Omega} + \frac{\theta 4}{\Omega} u_{sq} - k_1 y_{tt}(0) - (\Delta - 1) y_t(0)\right] \qquad (20)$$

The actual control input u_{sq} can be derived as

$$\frac{\theta_4}{\Omega} u_{sq} = \frac{\theta_1}{\Omega_1} i_{sd} + \frac{\theta_2}{\Omega} i_{sq} + \frac{\theta_3}{\Omega} + k_1 y_{tt}(0) + (\Delta - 1) y_t(0) \qquad (21)$$

where k_2 is positive constant.

Remark 3: The control input u_{sd} can be derived based on backstepping control method as follows

$$\frac{1}{s} u_{sd} = \frac{1}{T\sigma} i_{sd} - \omega_s i_{sq} - \frac{1-\sigma}{r}\hat{\psi}'_{rd} + \left(\frac{1}{T_r} - c_1\right)\left(i_{sd} - \hat{\psi}'_{rd}\right) + c_1 T_r \frac{d\hat{\psi}'_{rd}}{dt} + T_r \frac{d^2\hat{\psi}'_{rd}}{dt^2} - c_2 z_2 - \frac{1}{T_r} z_1 - d_2 z_2 \theta. \qquad (22)$$

where

$$\theta_2 = \left(\frac{1-\sigma}{\sigma T_r}\right)^2 + \left(\frac{1-\sigma}{\sigma}\omega\right)^2 \qquad (23)$$

c_1 and c_2 are strictly positive constant, z_1 and z_2 are errors between desired and virtual control when designing the flux controller.

The control design is complete and it is straightforward to to show that with the selected control input u_{sq} render the first time derivative of the Lyapunov candidate function $\dot{V}$ as

$$\dot{V} = -k_1 y_t(0) - k_2 z \le 0 \qquad (24)$$

Inequality () shows that $V(t)$ is upper bounded by $V(0)$. This consequently implies that $y_t(L)$, $y_t(0)$ and $y_t(0) - y_d$ are bounded. Further investigation of () can prove exponential convergence to y_d of $y(0)$ and $y(L)$.

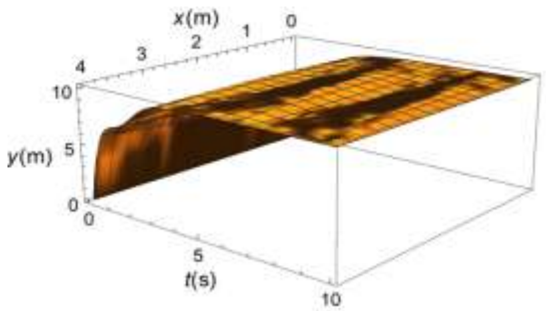
4. NUMERICAL SIMULATIONS

To verify the effectiveness of the proposed control. Simulations are carried out using an asynchronous motor of 7.5kW (other motor power ranges can be applied with no loss of generality). The closed loop system is simulated in Matlab/Simulink environment. Simulation parameters are given in Table 1.

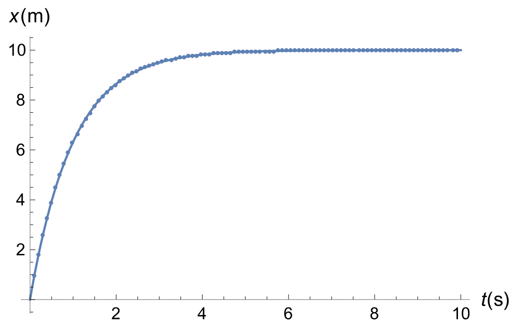
Table 1. *Induction motor parameters*

Parameter	**Value**
Nominal power	PN = 7,5kW
Pairs of pole	Pc = 2
Nominal current	UN = 340V
Nominal speed	n = 1400 rpm
Stator resistance	RS = 2.521Ω
Stator inductance	LS= 0.1825 H
Rotor resistance	RS = 0.976
Rotor inductance	LR = 0.1858 H
Inertial moment	J = 0,117 kg.m2

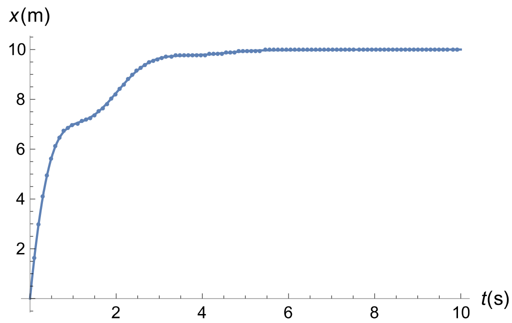
The mass of the trolley and the payload are 500kg and 1000kg, respectively. The cable length is of 10m. Simulation scenario is to regulate trolley and payload position at a position of 10m from the initial condition. It is assumed that initially the positions of the trolley and payload are coinciding.



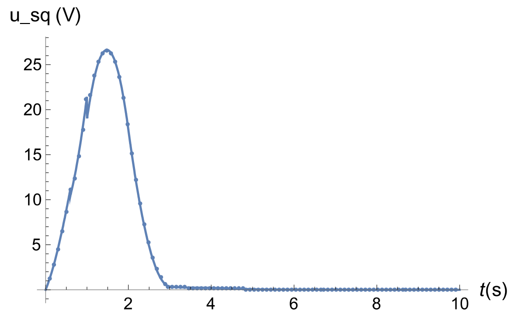
H. 2 *System response of the trolley, the flexible cable and the payload.*



H. 3 *Position response of the trolley.*



H. 4 *Position response of the payload.*



H. 5 *Control input.*

Numerical sumulation indicates that the effectiveness of the proposed control design. Trolley position is regulated at the desired value after 6s, and the payload also reach the target after a few oscilations. In addition, the control input is of the applicatble in practice range.

5. CONCLUSION

A design of a position and vibration suppression control of a gantry crane system is designed in this paper. Based on energy approach, a system of partial differential and ordinary differential equations that govern the system's motions including cable and actuator dynamics are derived. The Lyapunov direct method and backstepping technique are employed to design the controller. Stability and the effectiveness of the closed-loop system are verified analytically and illustrated numerically.

Acknowledgment

The authors would like to thank Institute for Control Engineering and Automation (ICEA), Hanoi University of Science and Technology for supporting this work.

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