

Study on Anti-sway Control of Jib Crane

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Abstract

The jib crane will cause the suspended load to swing two-dimensionally during the slewing motion; this swing not only reduces the work efficiency, but also may collide with surrounding objects or people, causing safety accidents; in order to prevent safety accidents, Crane operation puts high demands on the operating level of operators. In order to reduce the burden on operators, it is very important to develop a control system that can simultaneously control crane movement and suppress load swing. In previous studies, in order to suppress the two-dimensional swing of the load, it is often necessary to control the rotary motion of the turntable and the pitch motion of the boom at the same time. Such a control method not only increases the complexity of the controller, but also increases the cost. . For this reason, this paper designs a nonlinear controller that can realize positioning and anti-sway only by controlling the rotation movement, and then proves the stability of the controller through the Lyapunov stability theory. Finally, the effectiveness of the controller is verified through simulation experiments.

Keywords

Swing jib crane; Anti-swing control; Slewing anti-swing; Nonlinear controller.

1. Introduction

As an important basic equipment for the construction of offshore wind farms, offshore wind power installation ships will still have broad development space in the future [1]. The jib crane is the type of crane with the highest proportion among the ship cranes for wind power installation. This type of crane is constantly developing in a fast, intelligent and stable direction. The movement of the jib crane mainly includes the pitching movement of the boom and the slewing movement of the turntable [2]. However, when the turntable is in a rotary motion, due to the centripetal force, the one-dimensional rotary motion often produces a two-dimensional load swing. This swing not only reduces the operating efficiency of the crane, but also may collide with surrounding objects or people, causing Serious safety incident. In order to prevent the occurrence of safety accidents, crane operation puts forward high requirements on the operating level of operators [3]. In order to reduce the workload of the operators, many scholars have carried out research on the anti-sway control of the load, and have proposed many control schemes, including optimal control [4], sliding mode control [5], adaptive control [6], input shaping control [7], and nonlinear control based on Lyapunov stability [8], etc.

In previous studies, in order to suppress the two-dimensional swing of the load, it is necessary to simultaneously control the pitching motion of the boom and the rotary motion of the turntable to achieve the purpose of anti-swing. This increases the complexity of the controller on the one hand, and on the other hand, because the boom needs to overcome the gravity of the load when the boom is tilted, the crane consumes more energy and increases the cost. Considering that this kind of swing is caused by one-dimensional rotary motion, it is very important to study a controller that can realize the positioning and anti-sway of the turntable only by controlling the rotary motion of the turntable.

For this reason, this paper designs a nonlinear controller that can realize positioning and anti-sway only by controlling the rotary motion, and proves the stability of the controller through

the Lyapunov stability theory. The simulation experiment verifies the effectiveness of the designed controller.

2. Modeling of Jib Crane System

The structure of the jib crane is shown in Figure 1. The load is suspended on the top of the boom by a steel cable. The boom can achieve pitching motion in the vertical plane under the action of the motor, and the turntable can also realize the slewing motion in the horizontal plane under the action of the motor.



Figure 1. Jib crane

The swing of the load in space can be described by the in-plane swing angle θ_1 and the out-of-plane swing angle θ_2 of the boom. For the actual crane pendulum system, its structure is very complicated. In addition to its own nonlinear components, it will also be affected by various external disturbances, including various frictions and air resistance. In order to facilitate the analysis of the dynamic characteristics of the system, and then to study the anti-sway control, the actual crane system is abstracted and simplified as follows.

- (1) Simplify the suspended load of the rope to a mass point, assuming that the rigidity of the rope is large enough, and ignore its mass;
- (2) Assuming that the load swing angle θ_1 and θ_2 both are measurable, and its angular velocity is bounded;
- (3) Ignore the friction and external interference between the various agencies in the system.

According to the above simplified hypothesis, the crane can be abstracted into a simplified model as shown in Figure 2.

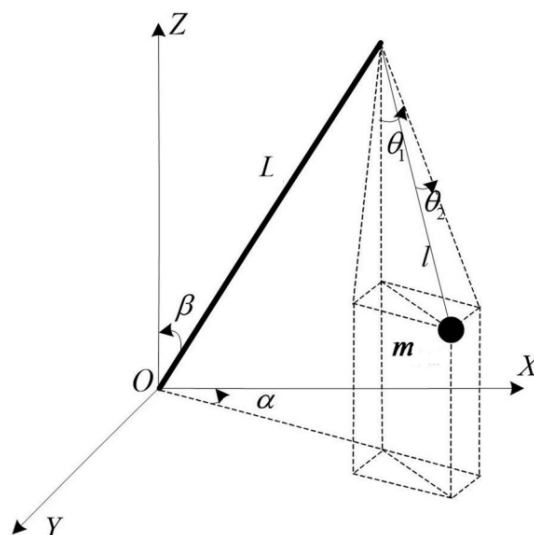


Figure 2. Model of jib crane

Assume that the mass of the load is m , the boom length is L , the rope length is l , the rotation angle is α , and the pitch angle is β .

When only the rotary motion of the turntable is considered, the dynamic model of the jib crane can be obtained by using the Lagrangian method as shown in the following formula:

$$\begin{cases} \ddot{\theta}_1 + (-\dot{\alpha}^2 + \frac{g}{l})\theta_1 - \dot{\alpha}\dot{\theta}_2 - \ddot{\alpha}\theta_2 = \frac{L}{l} \dot{\alpha}^2 \sin\beta \\ \ddot{\theta}_2 + (-\dot{\alpha}^2 + \frac{g}{l})\theta_2 + \dot{\alpha}\dot{\theta}_1 + \ddot{\alpha}\theta_1 = -\frac{L}{l} \ddot{\alpha} \sin\beta \\ J\ddot{\alpha} = Ku_\alpha \end{cases} \quad (1)$$

Among them: u_α is the control input of the slewing motion, K is the gain, J is the moment of inertia of the slewing motion, assumes that J is constant, and external interference such as friction during the slewing motion is ignored. In order to design the anti-sway controller, it is assumed that the load swing angle θ_i and the swing angular velocity $\dot{\theta}_i$ are very small, ($i=1,2$), so in the formula (1), there is, therefore, the formula (1) can be further simplified as:

$$\ddot{\theta}_1 = -a\theta_1 + b\dot{\alpha}^2 \quad (2)$$

$$\ddot{\theta}_2 = -a\theta_2 - b\frac{K}{J}u_\alpha \quad (3)$$

Among them: $a = \frac{g}{l}$, $b = \frac{L \sin \beta}{l}$

3. Controller Design and Stability Analysis

When designing the controller, consider two issues. One is that the controller must enable the turntable to reach the desired position specified by the reference trajectory r as soon as possible, that is, the positioning problem; the other is the swing of the load during and after the rotation of the turntable. As small as possible, that is, the problem of anti-swing. It is assumed that the first derivative $\dot{r}$ and the second derivative $\ddot{r}$ of the reference trajectory r of the movement of the turntable exist and are continuous. In order to design the controller, consider the following Lyapunov function:

$$V_e = \frac{1}{2} K_e s_e^2 + \frac{1}{2} K_{\theta_1} s_1^2 + \frac{1}{2} K_{\theta_2} s_2^2 \quad (4)$$

Among them: $e = r - \alpha$, $s_e = \dot{e} + \lambda e$, $s_1 = \dot{\theta}_1 + \lambda_1 \theta_1$, $s_2 = \dot{\theta}_2 + \lambda_2 \theta_2$, K_e , K_{θ_1} , K_{θ_2} , λ , λ_1 and λ_2 are all normal numbers. Derivation of the above formula can be obtained:

$$\begin{aligned}\dot{V}_e = & K_e s_e (\ddot{r} + \lambda \dot{e}) + K_{\theta_1} s_1 (-a\theta_1 + \lambda_1 \dot{\theta}_1) + \\ & K_{\theta_2} s_2 (-a\theta_2 + \lambda_2 \dot{\theta}_2) + \\ & K_{\theta_1} b s_1 \dot{\alpha}^2 - (K_e s_e + K_{\theta_2} b s_2) \frac{K}{J} u_\alpha\end{aligned}\quad (5)$$

Combining formula (2) and formula (3), the following control law is proposed:

$$u_\alpha = \begin{cases} \frac{J}{K} \left(K_1 p + \frac{\omega}{p} + \frac{K_2 K_{\theta_1} b |s_1 \dot{\alpha}^2|}{p} \right) & |p| \geq \varepsilon \\ \frac{J}{K} \left(K_1 p + \frac{\omega}{\varepsilon} + \frac{K_2 K_{\theta_1} b |s_1 \dot{\alpha}^2|}{\varepsilon} \right) & |p| < \varepsilon \end{cases} \quad (6)$$

Among them: $p = K_e s_e + K_{\theta_2} b s_2$,

$\omega = K_e s_e (\ddot{r} + \lambda \dot{e}) + K_{\theta_1} s_1 (-a\theta_1 + \lambda_1 \dot{\theta}_1) + K_{\theta_2} s_2 (-a\theta_2 + \lambda_2 \dot{\theta}_2)$,

K_1 and K_2 are normal numbers, ε is a small constant.

At that time $|p| \geq \varepsilon$, equation (6) was substituted into equation (5), after sorting out, getting:

$$\dot{V}_e = -K_1 p^2 + K_{\theta_1} b (s_1 \dot{\alpha}^2 - K_2 |s_1 \dot{\alpha}^2|) \quad (7)$$

Suppose $\dot{\alpha} \neq 0$, if $K_2 > 1$, then $V_e^{\dot{\alpha}}$ is negative definite.

If $|p| < \varepsilon$, formula (6) is substituted into formula (5), after simple sorting, getting:

$$\dot{V}_e = -K_1 p^2 + \omega \left(1 - \frac{p}{\varepsilon} \right) + K_{\theta_1} b \left(s_1 \dot{\alpha}^2 - \frac{p}{\varepsilon} K_2 |s_1 \dot{\alpha}^2| \right) \quad (8)$$

And can get:

$$\dot{V}_e \leq -\eta_1 V_e + \eta_2 \quad (9)$$

Among them: $\eta_1 = 2K_1 \bullet \min(K_e, K_{\theta_2} b^2)$,

$$\eta_2 = -2K_1 K_e K_{\theta_2} b s_e s_2 + \frac{1}{2} m K_{\theta_1} s_1^2 + \omega \left(1 - \frac{p}{\omega} \right) + K_{\theta_1} b \left(s_1 \dot{\alpha}^2 - \frac{p}{\omega} K_2 |s_1 \dot{\alpha}^2| \right)$$

According to the assumptions of the anti-sway control research, θ_i and $\dot{\theta}_i$ ($i=1,2$) are bounded, and d , so d is bounded. By adjusting the parameters of the control law, the ideal control effect can be achieved.

4. Simulation Analysis

In order to verify the effectiveness of the proposed control method, the following simulation experiments are carried out. The parameters of the controller and model parameters are shown in Table 1.

Table 1. Simulation parameters

$J/(\text{kg} \cdot \text{m}^2)$	1.02	$\beta(^{\circ})$	45	K_2	1.2
K	2.06	K_e	1	ε	0.005
L_B/m	0.65	K_{θ_1}	1	λ	0.01
l/m	0.25	K_{θ_2}	0.3	λ_1	3
$g/(\text{m} \cdot \text{s}^{-2})$	9.81	K_1	50	λ_2	3

In order to verify the performance of the proposed controller's anti-sway control, a common PD controller is used for comparative research.

The structure of the PD controller is as follows:

$$u_{\alpha} = K_p e + K_v \dot{e} \quad (10)$$

Among them: $e = r - \alpha$, $K_p = 40$, $K_v = 20$;

Consider the reference trajectory as a fifth degree polynomial:

$$r = 0.2909t^3 - 0.1454t^4 + 0.0194t^5 \quad (11)$$

The control result of the PD controller is shown in Figure 3. In Figure a, the solid line is the reference trajectory, and the dashed line is the turntable rotation angle α . It can be seen that α can track the reference trajectory well. Figure b is the swing angle θ_1 of the load in the plane of the boom. It can be seen from the figure that when the turntable rotation angle α turns to 45° , the swing angle θ_1 has a constant amplitude oscillation; Figure c is the swing angle θ_2 of the load outside the plane of the boom. It can be seen from the figure that there is also a constant amplitude oscillation in θ_2 . Therefore, the traditional PD controller and the turntable rotation angle α as feedback can only achieve the tracking of the reference trajectory, but cannot achieve effective swing suppression.

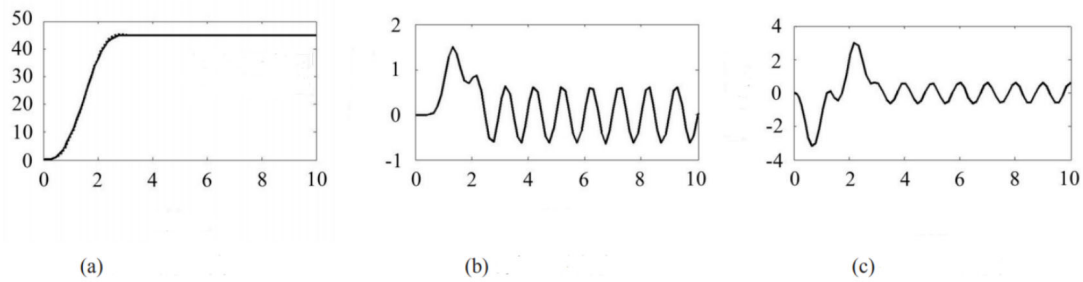


Figure 3. Using PD controller

The control result of the controller designed in this paper is shown in Figure 4.

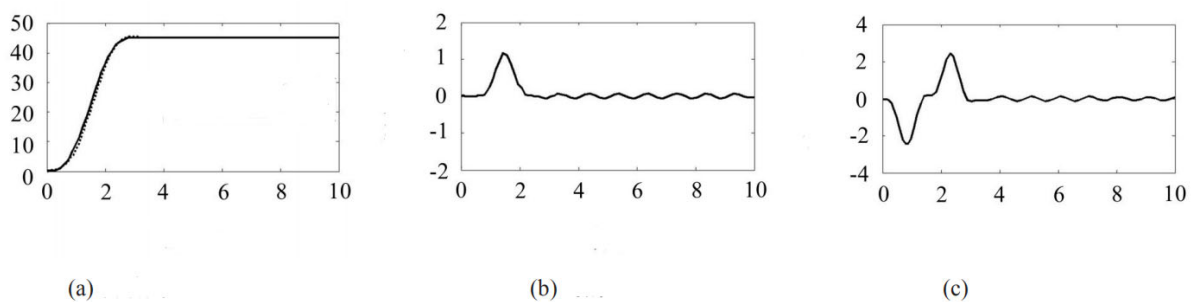


Figure 4. Controller using design($\alpha = 45^\circ$)

In Figure 4(a), the solid line is the reference trajectory, and the dashed line is the turntable rotation angle α . It can be seen that α can also track the upper reference trajectory well. Figure 4(b) is the swing angle θ_1 of the load in the plane of the boom. It can be seen from the figure that after the turntable rotation angle α reaches 45° , the angle θ_1 is basically 0; Figure 4(c) is the swing angle θ_2 of the load outside the plane of the boom. It can be seen from the figure that θ_2 is basically 0 after the turntable rotation angle α reaches 45° ; it can be seen that using the controller designed in this article, α , $\dot{\alpha}$, θ_1 , $\dot{\theta}_1$, θ_2 , $\dot{\theta}_2$ are all used as feedback, which can realize tracking The purpose of referring to the trajectory can also achieve the purpose of load anti-sway.

5. Conclusion

The jib crane will cause the suspended load to swing two-dimensionally during the slewing motion; in order to suppress the two-dimensional swing, this paper proposes a control method that can achieve positioning and anti-swing only by considering the slewing motion. First, the Lagrangian method is used to model the jib crane to obtain its dynamic model; then based on this model, a nonlinear controller is designed using the Lyapunov stability theory; finally, the simulation experiment verifies the proposed Effectiveness of the method.

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