

# Load's Swing Angle Equation and Structure Parameter for Container Crane Hydraulic Anti-sway System

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**Abstract.** The container crane may damp the container swing with hydraulic anti-sway system. The container may be accurately located and promptly placed. To obtain the load's swing angle equation when the crane trolley is stationary after braking for the container crane's hydraulic anti-sway system on the basis of structural characteristic of the anti-sway system and its trolley-load system's moving characteristic and engineering practice. The system's structure Parameter is one of influencing factors on the anti-sway system's performances when the hydraulic cylinder system's design is accomplished. Through analyzing anti-swing rope's spatial arrangement characteristic and simulating, simulation results show that changing fixed blocks' lateral distance may obviously change the system's structure parameter when the fixed blocks' lateral distance is less than 2.5 m. And changing anti-swing crown blocks' longitudinal distance can not obviously improve the anti-sway system's performances.

**Keywords:** Container crane, hydraulic anti-sway system, dynamic analysis, swing angle equation, structure parameter

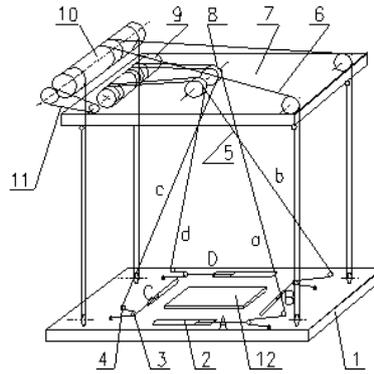
## 1. Introduction

Rail-mounted container gantry crane (hereinafter referred to as container crane for short) is one of the main logistics equipment for loading and unloading railway containers in railway goods site [1]-[3]. An anti-sway system (device) that is installed between the trolley and container spreader can rapidly attenuate container spreader's swing; make spreader stationary relative to the trolley in shorter time. The spreader can be accurately positioned and the container can be rapidly palletized. So the anti-sway system can improve container's loading and unloading operation efficiency and safety. Therefore, anti-sway technology is one of the key technologies for container crane [4]-[6]. In numerous anti-sway types [7] and [8], hydraulic cylinder type anti-sway system (hereinafter referred to as hydraulic anti-sway system for short) has the characteristic of simple structure and good anti-swing effect. Hydraulic anti-sway system is widely applied in the container crane. When no consideration of factors including wind load, air damping and system's friction, anti-sway system's structure parameter, lifting load, lifting rope and lifting speed is the main factors that impact on anti-swing effect. Among factors structure parameter is the key parameter [9], [10] for designing anti-sway system. When the hydraulic cylinder system's design is accomplished, the structure parameter is only determined by crown blocks' location parameter. Theory analysis for crown blocks' location parameter's influence rule on the system structure parameter and anti-swing effect can provide certain theoretical basis for reasonable design of whole anti-sway system structure in engineering practice.

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## 2. Anti-sway System



1. Spreader 2. Anti-swing cylinder 3. Movable block 4. Spreader anti-swing crown block 5. Anti-swing wire rope 6. Hoisting wire rope 7. Trolley frame  
8. Crown block 9. Anti-swing roll 10. Hoisting roll 11. Chain transmission device 12. Hydraulic pump station

Figure 1. Hydraulic anti-sway system structure

The hydraulic anti-sway system structure is shown in figure 1. The system is composed of anti-swing roll 9 that synchronously lifts and lands with lifting mechanism, anti-swing wire ropes 5 (including a, b, c and d), hydraulic cylinders 2 (including A, B, C and D, 4 cylinders), hydraulic pump station 12 and pulley block. The hydraulic system is composed of hydraulic pump station and hydraulic cylinders. Anti-swing wire ropes 5 are wound on the trolley frame's crown blocks 8 and the ropes are across connected with crown blocks 4 on spreader 1. The left and right crown blocks among crown blocks 4 on spreader are symmetrically installed relative to the trolley frame's crown blocks' axis. Anti-swing roll 9 is synchronously rotating with the hoisting roll 10 through the chain transmission device 11. When the container with the spreader is swinging because of starting or braking for the crane or trolley, the swinging of the load including container and spreader can be attenuated to zero because the anti-swing rope's cross connection and hydraulic system's role. For example, when the load's initial swing is right, the pulling force of rope a and b is increasing and rope a and b is in tightening state; on the contrary, the pulling force of rope c and d is decreasing and rope c and d is in losing state. The A and B hydraulic cylinders' piston rods respectively stretch out to the cavity with piston rod, and then cylinder cavity pressure will increase. When the pressure reaches the overflow valve's setting pressure, the overflow valve will be opened, and the pressure oil will return to the tank through overflow valve. At the same time, the piston rods in the C and D hydraulic cylinders that are connected by the wire rope c and d in losing state move to the cavity without piston rod, so rope c and d in losing state will be changed into tightening state to a certain extent. When the load's swing left, the state of rope a and b, the state of rope c and d, the moving directions of piston rods in hydraulic cylinder A and B, C and D are contrary to the condition on the load's swing right. Through the process of left and right swinging, the pressure oil constantly flows out from the overflow valves; the load's swinging energy is changed into pressure oil's buffering energy because of the pressure oil's damping. So the objectives of the load's anti-swing and crane's fast contraposition are attained. The schematic diagram of the hydraulic anti-sway system was shown in reference [10].

## 3. System Dynamic Analysis And Load's Swing Angle Equation

### 3.1 Dynamic analysis on hydraulic anti-sway system

In general, crane's or trolley's running will have a same effect on the load's swinging [11], [12]. In order to study conveniently, the trolley-load's structural coupling system is only considered [13]. Make hypothesis that anti-swing ropes a, b, c and d are suspended at a point on the trolley frame's crown blocks, and this suspension point's projection on the spreader is a rectangle diagonal intersection that is determined by the spreader's crown blocks 4. The structure scheme is shown by figure 2, among which  $\varphi$  is the load's swing angle and  $\varphi$ 's dimension is radian. The schematic diagram of anti-swing ropes' spatial arrangement drawn by figure 2 is shown by figure 3. In figure 3: rectangular edge length  $e$  and  $f$  are determined by the installation position of anti-swing crown blocks on the spreader;  $e$  is the installation distance along the trolley's running direction, called crown blocks' longitudinal distance;  $f$  is the installation distance vertical to the trolley's

running direction, called crown blocks' lateral distance;  $\theta_1$  is a angle between anti-swing rope and installing plane of anti-swing crown blocks,  $\theta_2$  is a angle between the crown blocks' longitudinal distance and the rectangle diagonal.  $G(t)$  is sum of tension in two anti-swing ropes being in the tightening state;  $F_x$  is sum of horizontal component of the two anti-swing ropes' tension. Make some assumptions: the load is a free suspended pendulum without installing anti-sway system and without considering other resistances; the load's horizontal swing is only considered, and swing angle  $\varphi$  is relative less;  $F_x$  is proportional to the load's velocity, and its direction is contrary to the trolley's velocity direction; the anti-swing ropes' acting force to the load in the ropes being in the loosing state is neglected considering the anti-sway system's structure characteristic and the retardation influence on the ropes' tension because of the damping action during hydraulic oil's buffering process; the anti-swing ropes' acting force direction to the load keeps constant because  $\varphi$  is relative less to  $\theta_1$  and  $\theta_2$ . The anti-swing ropes' weight, friction between wheel rails, windage resistance and air damping are all neglected.

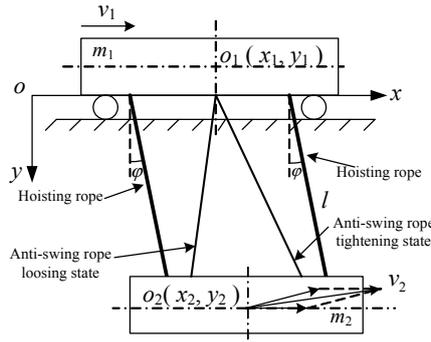


Figure 2. Simplified structure schematic diagram

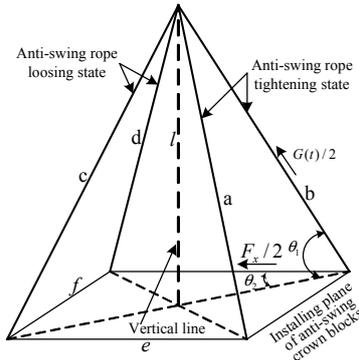


Figure 3. Schematic diagram of anti-swing ropes' spatial arrangement

Figure 2 shows the coordinate system. The following notations will be used:  $m_1$  is the trolley's mass,  $m_2$  is the load's mass,  $o_1(x_1, y_1)$  is the trolley's barycenter coordinate,  $o_2(x_2, y_2)$  is the load's barycenter coordinate,  $l$  is the hoisting rope length,  $v_1 = \dot{x}_1$  is the trolley's velocity. Figure 4 shows the load's velocity vector, the load's velocity  $v_2$  is vector sum of swing load's tangential velocity  $v_r$  with radius  $l$  and horizontal velocity  $v_x$ , and according to the geometric relation we have

$$v_2 = \sqrt{\dot{x}_1^2 + 2\dot{x}_1\dot{l}\sin\varphi + 2l\dot{x}_1\dot{\varphi}\cos\varphi + \dot{l}^2 + l^2\dot{\varphi}^2} \quad (1)$$

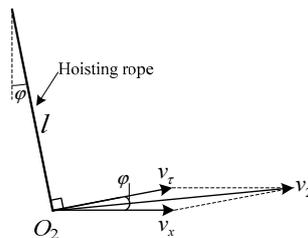


Figure.4 Load's velocity vector schematic diagram

The system's Lagrange equations are

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = F_{q_i}, (i=1,2,3) \quad (2)$$

where  $q_i (i=1,2,3)$  is generalized coordinate,  $q_1=x_1$ ,  $q_2=\varphi$ ,  $q_3=l$ ;  $F_{q_i}$  is generalized force,  $F_{q_1}=F(t)$  is the trolley's driving force, and  $F_{q_3}=F_l(t)$  is load's hoisting force;  $L$  is Lagrange function

$$L = \frac{1}{2}(m_1 + m_2)\dot{x}_1^2 + m_2\dot{x}_1\dot{\varphi}\sin\varphi + m_2\dot{x}_1\dot{\varphi}\cos\varphi + \frac{1}{2}m_2\dot{l}^2 + \frac{1}{2}m_2l^2\dot{\varphi}^2 - m_2g(1 - \cos\varphi) \quad (3)$$

where  $g$  is gravity acceleration,  $g=9.81\text{m/s}^2$ .

According to [9] and [10]

$$F_{q_2} = F_\varphi = G(t)l \quad (4)$$

where  $G(t)$  is the sum of tension in two anti-swing ropes being in the tightening state, according to the structure in figure 3,

$$G(t) = \frac{F_x}{\cos\theta_1 \cos\theta_2} \quad (5)$$

where  $F_x$  is sum of horizontal component of the two anti-swing ropes' tension. According to above assumptions, we have

$$F_x = -\lambda v_2 \quad (6)$$

where  $\lambda$  is a proportional coefficient, is only related to hydraulic system,  $\lambda>0$ , and  $\lambda$ 's dimension is  $\text{N}\cdot\text{s}\cdot\text{m}^{-1}$ . When the hydraulic system's design is accomplished,  $\lambda$ 's value is just determined.

According to (5) and (6), suppose

$$k = \frac{\lambda}{\cos\theta_1 \cos\theta_2} \quad (7)$$

where  $k$  is hydraulic anti-sway system structure parameter, called structure parameter for short, and  $k>0$ ,  $k$ 's dimension is same as  $\lambda$ . From (7), when the hydraulic system's design is accomplished,  $k$  is only determined by crown blocks' installing position.

Substituting (1) and (3)-(7) in (2), we obtain the system's dynamic equation with state space form

$$A(q)\ddot{q} + B(q, \dot{q})\dot{q} + C(q) = u \quad (8)$$

where

$$q = [x_1 \quad \varphi \quad l]^T,$$

$$C(q) = [0 \quad m_2g\sin\varphi \quad m_2g(1 - \cos\varphi)]^T, u = [F(t) \quad -kv_2 \quad F_l(t)]^T, A(q) = \begin{bmatrix} m_1 + m_2 & m_2l\cos\varphi & m_2\sin\varphi \\ m_2\cos\varphi & m_2l & 0 \\ m_2\sin\varphi & 0 & m_2 \end{bmatrix},$$

$$B(q, \dot{q}) = \begin{bmatrix} 0 & m_2(\dot{l}\cos\varphi - l\dot{\varphi}\sin\varphi) & m_2\dot{\varphi}\cos\varphi \\ 0 & m_2\dot{l} & m_2\dot{\varphi} \\ 0 & -m_2l\dot{\varphi} & 0 \end{bmatrix}.$$

### 3.2 Load's swing angle equation

$\sin\varphi=\varphi$  and  $\cos\varphi=1$  are approximately regarded because of less load's swing, and the high order trace including  $\dot{\varphi}^2$  in (8) is also neglected. At the same time,  $\ddot{x}_1 = \dot{x}_1 = 0$  and  $F(t)=0$  are fact while the trolley being stationary after the trolley braking. In order to study conveniently, suppose that the load is hoisted with uniform speed, that is to say that  $\dot{l}$  is constant and  $\ddot{l}=0$ , we have  $v_2=l\dot{\varphi}$  according to (1). So from (8) we obtain the load's swing angle equation

$$\ddot{\varphi}(t) + \left(\frac{2\dot{l}}{l} + \frac{k}{m_2}\right)\dot{\varphi}(t) + \frac{g}{l}\varphi(t) = 0 \quad (9)$$

Take into account  $\varphi(t)=\varphi_0$  ( $\varphi_0$  is initial swing angle.) and  $\dot{\varphi}(t)=0$  while time  $t=0$ . From (9), we have

$$\varphi(t) = \xi_1 e^{u t} - \xi_2 e^{v t} \quad (10)$$

where

$$\xi_1 = \frac{\varphi_0(2\dot{l}m_2 + kl + \omega)}{2\omega}, \xi_2 = \frac{\varphi_0(2\dot{l}m_2 + kl - \omega)}{2\omega}, u = \frac{-(2\dot{l}m_2 + kl - \omega)}{2m_2l}, v = \frac{-(2\dot{l}m_2 + kl + \omega)}{2m_2l}, \omega = \sqrt{4\dot{l}^2m_2^2 + 4\dot{l}m_2kl + k^2l^2 - 4m_2^2gl}.$$

(10) is just the load's swing angle equation when the trolley is stationary after the trolley braking, so swing angle will be successively attenuated to zero with exponential function form. The load's anti-swing effect is shown in figure 5 ( $l=8\text{m}$ ,  $m_2 = 4 \times 10^4 \text{ kg}$ ,  $\lambda = 1\text{kN} \cdot \text{s} \cdot \text{m}^{-1}$ ) with  $k$ 's different value. It is known that  $k$ 's influence on the load's anti-swing effect is relatively obvious, and the load's swing angle will be attenuated to zero from oscillating attenuation form to non- oscillating attenuation form with  $k$ 's increasing.

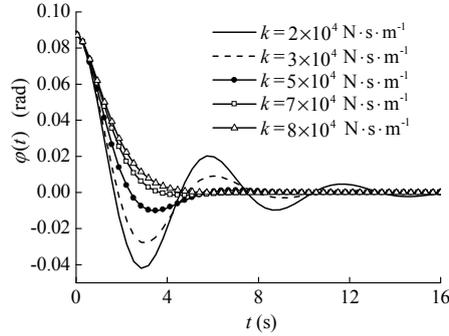


Figure 5. Simulation results of load's anti-swing

#### 4. Influence Factors of Anti-Sway System Structure Parameter

From figure 3, we have

$$\cos\theta_1 = \frac{\sqrt{e^2 + f^2}}{\sqrt{4l^2 + e^2 + f^2}} \quad (11)$$

$$\cos\theta_2 = \frac{f}{\sqrt{e^2 + f^2}} \quad (12)$$

From (7), (11) and (12), according to [9] and [10], take  $\lambda = 1\text{kN} \cdot \text{s} \cdot \text{m}^{-1}$ , we have

$$k = 1000 \sqrt{4\left(\frac{l}{f}\right)^2 + \left(\frac{e}{f}\right)^2 + 1} \quad (13)$$

When the container is positioned and palletized for crane's practical operation, the trolley is in stationary state after the trolley braking, and  $l$  is regarded as constant. It is known from (13) that  $e$  and  $f$  is main influencing factors on the structure parameter, that is to say that  $k$  is determined by rectangular size determined by anti-swing crown blocks' longitudinal distance and lateral distance.

Now suppose  $l=8\text{m}$ , figure 6 and 7 show  $k$ 's change trend toward  $e$  and  $f$ .

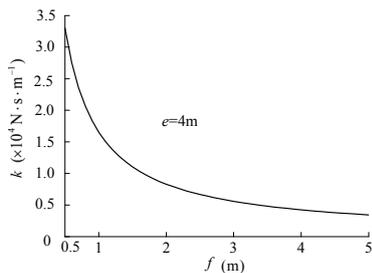


Figure 6.  $f$ 's influence on  $k$

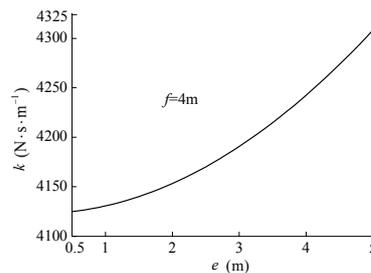


Figure 7.  $e$ 's influence on  $k$

From figure 6 it is known that  $k$ 's change trend toward  $f$  is  $k$  decreasing with  $f$  increasing when  $e$  is determined;  $k$ 's change is changing mildly with  $f$  increasing when  $f$  is more than 2.5m, so this time the system's anti-swing effect can not be obviously improved by increasing the lateral distance of the anti-swing crown blocks, that is to say that the anti-swing effect can be obviously changed by changing the longitudinal distance of the anti-swing crown blocks only when  $f$  is less than 2.5m. From figure 7 it is known that  $k$ 's general change trend toward  $e$  is  $k$  increasing with  $e$  increasing, but this change rate of  $k$  toward  $e$  is obviously less than the change rate of  $k$  toward  $f$ . So  $k$  can not be obviously changed by changing longitudinal distance of the anti-swing crown blocks, and system's anti-swing effect also can not be obviously improved. Computer simulation experiments also show that hoisting rope's length  $l$  almost has no effect on  $k$ 's above change trend.

## 5. Conclusion

While the trolley being stationary after the trolley braking, the load's swing angle equation was obtained from the system's dynamic equations through dynamic analysis on hydraulic anti-sway system for container crane. The load's swing angle would be successively attenuated to zero according to exponential function form. The system structure parameter was the key parameter affecting the anti-swing effect. When the hydraulic cylinder system's design was accomplished, the anti-swing crown blocks' longitudinal distance and lateral distance are main influence parameters on the system structure parameter. The dynamic simulation results' guiding significance for engineering design of anti-sway system is that the system's anti-swing effect will be obviously improved by changing the lateral distance of the anti-swing crown blocks only while the lateral distance of the anti-swing crown blocks is less than 2.5 m. Simulation results also show that the system structure parameter can not be obviously changed by changing the longitudinal distance of the anti-swing crown blocks, that is to say that the system's anti-swing effect can not be obviously improved by changing the longitudinal.

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