Effect of Operation Environmental Uncertainties on Cargo Sway Characteristics of Tower Cranes

Mingxiao Dong[1, a], Haiping Dong [2,b], Bo Pang [1,c] and Jiyong Wang [1,d]

[1] Mechatronic Engineering School, Shandong Jianzhu University, Jinan, 250101, China

[2] Industrial Technology Department, Weihai Vocational College, Weihai, 264210, China

[a] mxdong@sdjzu.edu.cn, [b]dhp223@163.com, [c] pl-plcn@sdjzu.edu.cn, [d] wjyhjn@sdjzu.edu.cn

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Abstract. Tower crane operating environment uncertainties include lifting sway, wind load and air resistance and other factors. If we ignore these factors, it is difficult to accurately describe dynamic characteristics of the real system and difficult to realize automation of the tower cranes. This paper reveals the influence of the operating environment uncertainties on sway characteristics of cargoes by quantitatively analyzing the operating environmental uncertainty for tower cranes.

Introduction

At present, there are many researches on the sway characteristics of the cargoes and anti-sway control strategies of the tower crane. And the uncertainties of the operation environment are a main factor to hinder the crane automation. If we neglect the influence factors, then we also neglect the dynamic characteristics of the real systems, so that the high precision tracking control algorithm is difficult to achieve [1-5].

Lifting Sway

Tower cranes transport cargoes by rotation of crane jib and trolley motion along the jib. According to the motion characteristics, we set up a polar coordinate system $\{e_\rho, e_\psi\}$ whose coordinate origin is located at the intersection of the rotary center line of the tower body and the rotary surface of the crane jib. The cargoes, moving along with the hanging point, sway in space pendulum and pendulum length changes. Based on this, a non-inertial Cartesian coordinate system {i,j,k} and non-inertia spherical coordinate system $\{e_\theta, e_\varphi, e_l\}$ are set up[6]. The origin of coordinates is located at cable suspension point [4]. The origin moves with the trolley and rotates synchronously with the lifting jib. The coordinate system of the tower crane is shown in Fig. 1.

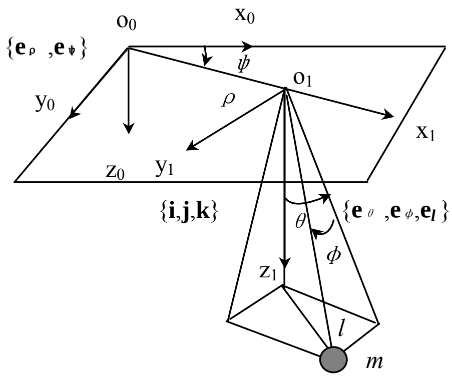
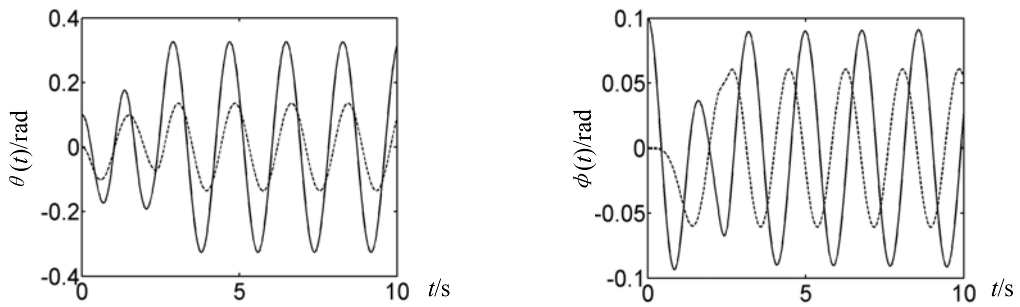


Fig. 1 The coordinate system of the tower crane

The cargo suspension point is located at position (ρ, ψ) in the polar coordinates, where ρ and ψ are respectively displacement of the trolley and the rotation angle of the jib. The position of the cargo in the non-inertia spherical coordinate system is described by three generalized coordinates (l, θ, φ), where, l is hoisting cable length, φ is the angle between hoisting cable and $x_1o_1z_1$ plane, θ is the angle between the projection of the hoisting cable in $x_1o_1z_1$ plane and plumb line through the cargo hanging point. The crane system has five parameters which are the trolley velocity or acceleration, the rotary angular velocity of the jib or the angular acceleration, cargo lifting velocity, or acceleration, cargo sway angles θ and φ. In this paper, the first three variables are control variables and the latter two are controlled variables.

The sway phenomenon may appear when cranes lift cargoes. Namely, the initial sway angles of the cargo sway are not zero. Fig. 2(a) and Fig. 2(b) describes sway states of cargoes respectively considering the initial lifting sway angles and ignoring the initial lifting sway angles with the same initial lifting sway angle 0.1rad. When taking initial lifting sway angles into account, the cargo residual sway angles $\theta(t)$=20°, $\varphi(t)$=4.5°that are respectively 233% and 133% times comparing with ignoring the initial sway angles. Thus, the lifting initial sway angles seriously affect the cargo sway characteristics. Therefore, when there is a lifting initial sway angles, we should consider its impact on the characteristics of cargo sway [7].



----- Ignoring initial sway angle
—— Taking initial sway angle into account

(a) Sway angle $\theta(t)$ (b) Sway angle $\varphi(t)$

Fig. 2 Cargo sway states respectively considering the initial lifting sway angles and ignoring the initial lifting sway angles

Wind Load

Wind load is horizontal force acting on the crane in any direction that is an important factor to cause the rotary tower crane tilting over. The wind load magnitude is relative with the air density and the wind speed and too large wind load will increase the risk of crane dump. Therefore, crane design specification stipulates that when the wind speed exceeds 6 levels, we should stop all operations

$$F_{\mathrm{w}} = C_{\mathrm{w}} P_{\mathrm{W}} A \quad (1)$$

Where, C_{w} is wind coefficient, P_{w} is wind pressure, A is the windward area of the cargo.

Assuming that the wind is along o_0x_0 direction, F_{w} is discomposed along e_θ direction and e_φ direction, the force moment M_θ and M_φ are calculated as following,

$$M_\theta = F_{\mathrm{w}} l \cos\psi \cos\phi \cos\theta \quad (2)$$

$$M_\phi = -F_{\mathrm{w}} l \sin\psi \cos\phi \quad (3)$$

The linear models of tower crane are

$$M\ddot{\rho} - M\rho\dot{\psi}^2 - mg\theta + b_\rho \rho = F_\rho \quad (4)$$

$$(J_m + M\rho^2)\ddot{\psi} + 2M\rho\dot{\rho}\dot{\psi} - m\rho g\phi + b_\psi \dot{\psi} = F_\psi \quad (5)$$

$$m(\ddot{l} - g) + b_l \dot{l} = F_l \quad (6)$$

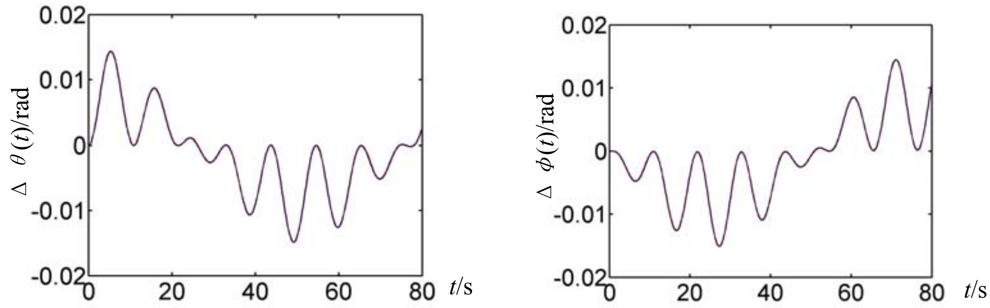
$$l\ddot{\theta} + 2\dot{l}\dot{\theta} + (g + l\dot{\psi}^2)\theta - 2l\dot{\psi}\dot{\phi} - l\ddot{\psi}\phi = -\ddot{\rho} + \rho\dot{\psi}^2 - 2\dot{\rho}\dot{l} \quad (7)$$

$$l\ddot{\phi} + 2\dot{l}\dot{\phi} + (g - l\dot{\psi}^2)\phi + 2l\dot{\psi}\dot{\theta} + l\ddot{\psi}\theta = -\rho\ddot{\psi} - 2\dot{\rho}\dot{\psi} \quad (8)$$

M_θ and M_φ are substituted into the linear models, the sway angular displacement of the cargo and angular velocity are calculated as following.

Where $r = \omega / \omega_{\mathrm{n}}$, is crane rotating angular velocity, ω_{n} is natural frequencies of cargo oscillation.

Fig. 3 depictures the error curves of cargo sway respectively when there is 6 levels wind load and no wind load when the tower crane transports and rotates at the same time. The rotary motion causes periodic wind load that acts on the cargo. The wind load causes the sway angular displacement and the angular velocity changing in periodicity and the degree of change is proportional to the wind load.



(a) Sway angle error (b) Sway angle error

Fig. 3 Wind load causes sway angle error of cargo

When the wind load is along the jib or vertical to the jib, there will is the maximum sway angle and speed. Thereby we can estimate the maximum pendulum angle θ_{max} and φ_{max} and the maximum sway angular speed $\dot{\theta}_{max}$ and $\dot{\phi}_{max}$. The maximum sway angle and the maximum sway speed are relative with wind speed, load windward area, cargo mass. When the wind load $F_w > \pi mg/18$, the cargo sway angle is larger than 10° that no longer meets the requirements of the engineering. Especially upwind operation, the wind load will cause more effect on the cargo sway.

$$\theta_{max} = F_w / mg . \tag{13}$$

$$\dot{\theta}_{max} = F_w \omega_n / mg . \tag{14}$$

$$\phi_{max} = F_w / mg . \tag{15}$$

$$\dot{\phi}_{max} = F_w \omega_n / mg . \tag{16}$$

Air Resistance

Cargoes oscillate in space pendulum with the tower crane transporting, rotating and lifting motion. All air resistances include the resistances to translation, rotation, listing motion, the cargo sway in e_θ direction and e_φ direction. The formula for calculating the air resistance is the same as the one calculating the wind load. The wind pressure is calculated based on $P_w = 0.613 v_{max}^2$, where v_{max} is the rated speed of the trolley. First we calculated the sway resistance moment of above 5 kinds of air resistances in e_θ direction and e_φ direction, then substituted the resistance moment in the linear models. The maximum sway angles θ_{max} and ϕ_{max}, the maximum sway speeds $\dot{\theta}_{max}$ and $\dot{\phi}_{max}$ are calculated as following

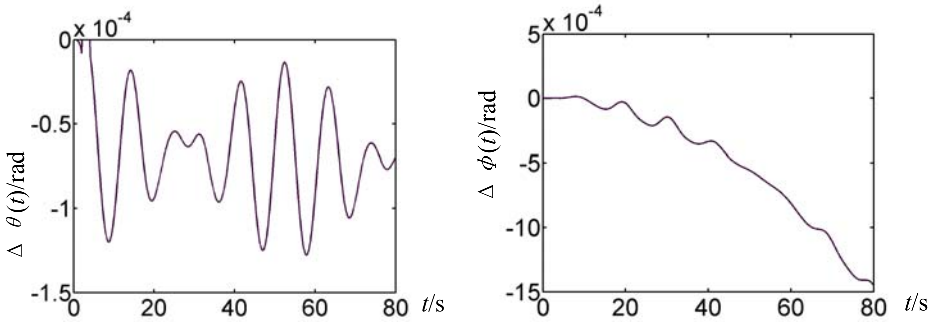
$$\theta_{max} = 1.226 C_w A v_{max}^2 l / mg . \tag{17}$$

$$\dot{\theta}_{max} = 1.226 C_w A v_{max}^2 l \omega_n / mg . \tag{18}$$

$$\phi_{max} = 1.226 C_w A(\rho \dot{\psi}_{max})^2 l / mg . \tag{19}$$

$$\dot{\phi}_{max} = 1.226 C_w A(\rho \dot{\psi}_{max})^2 l \omega_n / mg . \tag{20}$$

Fig. 4 shows the sway error curves of the cargo respectively taking the air resistance into account and ignoring the air resistance. With the tower crane's translation motion, the turning radius is increasing, the rotary air resistance is increasing, and the cargo sway angular error is increasing. It can be seen that the amplitude of the cargo sway caused by air resistance is related to the speed of translation motion and the speed of the rotary motion. The cargo sway angle caused by the air resistance is small and the influence of air resistance can be negligible for low speed cranes. For high speed and large cranes, when the hoisted cargoes are fluffy material and hoisting cables are long, the impact of air resistance on cargo sway is large and we should consider the action of the air resistance.



(a) Sway angle error (b) Sway angle error

Fig. 4 Sway angle error of cargoes caused by air resistance

Conclusion

When there is a lifting sway angle, its influence on the cargo oscillation should be considered. When the wind load $F_w > \pi mg/18$, cargo sway angle is greater than 10° and that no longer meet the engineering requirements. Especially upwind operation, wind load's effect on the load sway is greater. For low and medium speed cranes, air resistance has little effect on the cargo sway and the resistance can be negligible. For high-speed and large cranes, when the cargo density is smaller, hoisting cable length is long and the influence of air resistance should be considered.

Acknowledgements

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