Effect of Connecting Link Deformation on Stability of Balance Hoist Based on Multi-body Dynamic

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Abstract. Aiming at the instability problem of balance hoist in the loading process, this paper is to establish a dynamic simulation model of balance hoist by using ADAMS. Based on rigid-flexible coupling dynamics, flexible connecting link was modeled as Euler–Bernoulli beams. The stability and dynamic characteristics of two extreme working states were analyzed. The results showed that the vibration and elastic deformation of connecting link after loading have a great influence on the constraint force of each hinge and out-of-balance force, and caused slippage and instability of balance hoist, especially when the lifting weight of the balance hoist moved to the region around workspace. It can reduce the out-of-balance force and improve the stability of balance hoist to increase the stiffness of the connecting link properly, which will provide a better reference for the structure optimization and operational performance of balance hoist.

1. Introduction

As widely used mechanical power-assisted equipment, balance hoist is featured with simple structure, flexible operation, low price and convenient maintenance, so it is suitable for working conditions that frequent loading and unloading, such as machinery manufacturing workshops and docks. As the boom system of the balance hoist is a slender component, the rod will bear great constraint force and inertia force under the impact of heavy lifting weight and large external loading. Therefore, the out-of-balance force caused by the deformation of the links have a great adverse effect on neutral equilibrium characteristics of the balance hoist, which is easy to cause slippage and instability of balance hoist. This is also one of the reasons for limiting the load[1].

Ever since the balance hoist was created, there have been many achievements in the studies of problems of balance hoist imbalance, such as reducing the radial operating force through precise assembly[2], reducing deformation through the optimal design of rods and the reasonable arrangement of reinforcement. In practical applications, the friction force is limited to a certain range to obtain the best performance. Some scholars have found that the effect of unbalanced forces on balance hoist with a lifting weight of more than 1t is very obvious, while the effect by the original spring balance method and weight balance method can only play a very limited role[3]. Fang analyzed several key technical issues about the balance hoist by multi-rigid-body dynamics and finite element[4]. However, it was proven not accurate to calculate the influence of elastic deformation and vibration on the whole machine by the analysis of the static equivalent and dynamics for multi-rigid body[5]. Liu et al. established the
dynamic model of balance hoist based on the rigid-flexible coupling simulation method and analyzed the dynamic characteristics of the boom system, the results showed that the lifting weight has a great influence on the deformation and vibration of boom system[6]. In the study of multi-body system dynamics modeling, scholars at home and abroad have made in depth researches using different methods. Li established and analyzed the dynamic model of parallel robot with flexible link translation based on a combination of Euler-Lagrange formula and hypothetical model[7]. Zhu et al. analyzed the effect of links deformation on motion precision of parallel manipulator based on flexible dynamic model[8]. Zheng conducted a multi-body dynamics analysis before optimizing the front suspension of the car, and verified that the lateral load was generated at the top of the damping rod[9].

According to the working principle of the balance hoist, the force and kinematic of the boom system are analyzed. The influence of a connecting link deformation on the out-of-balanced force of the balanced hoist is analyzed by the graphic method. Based on rigid-flexible coupling dynamics, flexible connecting links are modeled as Euler–Bernoulli beams, and rigid-flexible coupling model of balance hoist was established by using ADAMS. The proposed model is analyzed the effect of connecting link deformation on out-of-balance force of balance hoist, and the effective measures are proposed to increase stability, which can provide reference for the structure optimization and performance of balance hoist.

2. Structure analysis of boom system

2.1. Structure and coordinate

The balance hoist is mainly composed of balance boom system, drive system, self-weight balance device of connecting link system and electric control device, as shown in Figure 1. The vertical lifting of the lifting weight is realized by the motor driving rotation of screw to force the nut move up and down. Moving objects on the hook horizontally is completed by the hand pushing and pulling at point F of the hook, and forcing the roller of point C to move in the horizontal guide groove. It can be combined oblique motion when the motor-driven lifting and hand push simultaneously. The boom system is also known as the parallel four-bar mechanism. In Figure 2, it consists of upright column and four connecting rods of BC, CE, ABD, DEF, these links are connected by four hinges B, C, D and E, especially, BD is parallel and equal to CE, BC is parallel and equal to DE. Meanwhile, the three points A, C and F are always in a straight line. In this paper, the ABD, DEF and CE rod of balance hoist are regarded as flexible-body due to slender and weak stiffness, while other mechanisms are regarded as rigid-body without any deformation. The whole balance hoist is regards as a rigid-flexible coupling dynamics system.

The coordinate system $xoy$ is established in the boom system depicted in Figure 2. The $y$-axis is pointing vertically downward and passes point A. The $x$-axis is perpendicular to the $y$-axis and passes through point C, horizontally to the left, and the $x$-axis and $y$-axis intersect at the origin $o$. The angle $\alpha$ is the angle between the DEF rod and the vertical direction, and the external pendulum is positive, and
the internal pendulum is negative. The $\beta$ angle is the angle between the ABD rod and the horizontal direction, the upper pendulum is positive, and the lower pendulum is negative.

2.2. Equilibrium condition and kinematic

The neutral equilibrium characteristic of balance hoist refers to no matter the with or without load, the lifting weight at point F of the hook can stop freely and keep balance at any position within the workspace. For the sake of analysis, it is assumed that the self-weight of the rods, the friction and clearance of each kinematic pairs, the deformation of the rods, the error of manufacturing and installation are ignored.

According to the principle of the balance hoist, the motion of point A is controlled by the transmission part. The point A can be regarded as a fixed hinge pedestal when it stays at a certain height, the horizontal movement of point C is the reason for the horizontal movement of point F. If the hook F is at any position (load or no load), the point A, C, and F have only vertical reaction force and the resultant force is zero, then the horizontal resultant force at point C is zero, and the balance hoist has reach a balance state.

From the knowledge of engineering mechanic, in a plane force system, a member is subjected to three forces at the same time, then the three forces must be transferred to one point, which is called a three-force bar. When a certain member is simultaneously subjected to two forces and the point of action of the two forces are at the two end point, the two forces must be equal in magnitude and opposite in direction, called the two-force rod. Therefore, ABD and DEF are three-force rod, BC and CE are two-force bar. The acting forces on the parallel four-bar mechanism of the balance hoist are shown in Figure 3. $G$ is the gravity of lifting weight at point F, the direction is vertically downward. The force $FE$ of the CE rod on the DEF rod pass through the hinge E and along the direction of CE line, $G$ and $FE$ intersect at point J, the force $FD$ from the ABD rod to the DEF rod must through the hinge D and point J. According to the principle of action and reaction, obviously, the force $FD'$ of the DEF rod to the ABD rod must through the hinge D and the direction is shown in Figure 3. The force $F_B$ of the two-force BC rod to the ABD rod through the hinge B is along the BC direction and intersect with the force $FD'$ at point K, however, the reaction force $F_A$ at hinge A must through hinge A and point K. For the balance hoist to achieve balance, the reaction force $F_A$ must be a force in the vertical direction. The mechanism satisfy the geometric condition of $\triangle EFJ \sim \triangle BKA$ and $\triangle DEJ \sim \triangle KDB$, that is the horizontal component force of $FE$ and $F_B$ is equal and opposite, so the horizontal resultant force of point C is zero.

![Figure 3. Balance hoist boom structure force diagram.](image)

As shown in Figure 2, assuming the lengths of AD, AB, DF and DE are $H$, $h$, $L$ and $l$, respectively. Based on the force triangle and moment principle, with $\alpha$, $\beta$ as independent variables, the force of the BC and CE rods can be expressed as:

$$\begin{align*}
F_B &= G\alpha \frac{\cos \beta}{\cos(\alpha - \beta)} \\
F_E &= G\alpha \frac{\sin \alpha}{\cos(\alpha - \beta)}
\end{align*}$$

(1)
where $\lambda$ is the proportional amplification factor of the balance hoist, according to the principle of neutral equilibrium, $\lambda = H/h = L/l$. While the balance hoist is suspended at any position, the position of point F during the work process can be described as:

$$
\begin{align*}
    x &= L \sin \alpha + H \cos \beta \\
    y &= (L - l) \cos \alpha - (H - h) \sin \beta
\end{align*}
$$

(2)

According to equation (1), when the DEF rod is vertical to the ground and the CE rod is not stressed, we have: $\alpha = 0$, $F_E = 0$. Elliptic equation with centre Q (0, $L - l$), long axis is $H$, and short axis is $L - l$ by substituting value of $\alpha$ and $F_E$ into equation (2) can be obtained:

$$
\frac{x^2}{H^2} + \frac{(y - L + l)^2}{(H - h)^2} = 1
$$

(3)

The position of the ellipse relative to the workspace is shown in Figure 4. When $\alpha < 0$, $F_E < 0$, the CE rod is subjected to tension, and the F point is within the elliptic curve; when $\alpha > 0$, $F_E > 0$, the CE rod is compressed, and the F point is outside the elliptic curve, the elliptic curve is the boundary between the tension zone and compression zone.

Figure 4. Analysis of workspace of balance hoist.

3. Effect of connecting link deformation on out-of-balance force

The neutral balance characteristic of the balance hoist is not practical under actual working conditions. Because the connecting links are bear large inertial force and constraint force when transmitting a larger lifting weight and being impacted by external loads, the parallel four-bar mechanism is destroyed by the vibration and elastic deformation of connecting links, eventually caused the instability of the balance hoist. Assuming that only the CE rod deform in the boom system, the influence of connecting link deformation on the out-of-balance force of balance hoist is analyzed by graphical method.

Assume that point F is working in the compressive zone of the workspace. As shown in Figure 5, the gravity of the lifting weight at hinge F is still $G$, and the direction is still vertically downward. Since the connecting link CE was effected by vibration and elastic deformation, the hinge E is moved to the point $E'$, and the angle $\alpha$ is reduced to the angle $\phi$. Same as the analysis method in the graphic diagram of 1.2, the direction of the force $F_E$ from the CE’ rod to the DE’F’ rod pass through the hinge $E’$ is along the direction of the CE’. $G$ and $F_E$ intersect at point $J'$, according to the principle of the force triangle, the force $F_D$ from the ABD rod to the DE’F’ rod must pass through the point $J'$ and the hinge D. Similarly, the ABD rod is also subjected to three forces, the reaction force $F_B$ of the BC rod to the ABD rod, and the reaction force $F_D'$ of the DE’F’ rod to the ABD rod, $F_D'$ intersects with $F_B$ at point $K'$, then the reaction force $F_A$ of the hinge A to the ABD rod must pass through the point $K'$. Thus, there is an angle $\gamma$ between the reaction force $F_A$ at point A and the vertical direction. From the analysis of the overall force, if the boom system is to reach equilibrium, there must be a horizontal resultant force at hinge C to offset the reaction force $F_A$ at hinge A, which is the out-of-balance force, then:
\[ P_x = F_{Ax} = F_{Bx} - F_{Ex} \]  

(4)

4. Simulations and results

According to the analysis of tension and compression zone in Figure 5 and the actual working conditions, the force of rods is larger and boom system is easy to be destroyed when the hook is in the region around workspace. Therefore, the effect of connecting link deformation on stability when the lifting weight move to region around the workspace will be mainly researched. The horizontal and vertical transport of objects with weighing 200, 500, and 800 kg were simulated respectively. As shown in Figure 4, first, horizontal transport of objects on the hook, assuming the point A is fixed, the drive is exerted in point F by force, the hook moves from point a to point b; second, vertical transport of objects on the hook, assuming the roller in point C is fixed in the guide groove and the hinge A is driven by a STEP function, the hook moves from point c to point d.

4.1. Influence of horizontal moving objects on stability of boom system

The simulation curve of the object on the hook being transported horizontally from point a to point b is shown in Figure 6. Figure 6 (a) shows the changing curve of the length of the CE rod under different lifting conditions. It can be seen that the shortening and amplitude of the connecting link start to be larger, and then gradually decrease and finally stabilize during the process of the hook horizontally moving from a to b, which is due to the greater inertia of the balance hoist system when it starts to carry objects, and the shortening tends to stabilize as the movement is conducted continuously. The initial length of CE rod is 1,750mm, but the length of the CE rod is shortening on the average by 0.6mm, 1.4mm and 2.5mm, when the lifting weight varies from 200kg, to 500kg and to 800kg respectively. Therefore, we can see that the resultant force of CE rod gradually decreases and then stabilizes from a to b, and the deformation and the amplitude of connecting link increase with the increase of cargo weight.

![Figure 6. Simulation curve of horizontal moving objects.](image)

The horizontal resultant force of the hinge C is shown in Figure 6(b), which is the out-of-balance force studied in this paper. It can be noticed from Figure 6(b) that the out-of-balance force fluctuates as a result of the elastic deformation of the CE rod. In the process of lifting weight conveyed from a to b, the out-of-balance force decreases first and then gradually increases. As can be seen, the closer the position of lifting weight approaches the both ends of a and b, the greater the fluctuation of the out-of-balance force becomes, which shows when the hook moves to both sides of the workspace, the out-of-balance force is larger than other positions, and the amplitude of the out-of-balance force increases significantly with the increase of the lifting weight. When the lifting weight is 200kg, 500kg, and 800kg, the maximum amplitude of the out-of-balance force are 60N, 184N and 237N respectively. It is observed that the force and deformation of the connecting link, with the increase of the lifting weight, cause the increase of out-of-balance force and the possibility of out-of-balance in the balance hoist will also be increased greatly.
4.2. Influence of vertical moving objects on stability of boom system

The simulation curve of the object on the hook being transported vertically from point c to point d is shown in Figure 7. It can be noticed from Figure 7(a) that the changing trend of the CE rod length in the vertical resembles that in the horizontal movement. On average, the variation of the CE rod length for different lifting weights varies 0.6mm, 1.4mm, and 2.2mm respectively. In the process of lifting weight from point c to point d, the length of the CE rod shortens gradually and then decreases slightly, which shows that the resultant force of CE rod is larger when the lifting weight at both upper and lower ends of the workspace, and the shortening and amplitude of the connecting link increase with the increase of the cargo weight.

Figure 7(b) shows the curve of out-of-balance force for the horizontal movement. It can be seen that the amplitude of the out-of-balance force increases with the lifting weight increases. When the lifting weight is 200, 500, and 800kg, the maximum amplitude of the out-of-balance force are 80, 176 and 402N, respectively. It is observed that the force and the deformation amount of connecting link increase with the increase of the lifting weight, which lead to the increase of out-of-balance and the possibility of unbalance in the balance hoist will also be increased greatly. In particular, with the increase of the cargo weight, the center of the out-of-balance force wave shifts and the closer it is to the lower end, the greater the shift become. It shows when the lifting weight reach the outside of the lower end of the workspace, the balance hoist is extremely easy to lose its balance, which is also consistent with the research results — "underside and external end" as the most dangerous position, illustrated in the literature[6].

4.3. Effect of connecting link stiffness on out-of-balanced force

Figure 6(b) and 7(b) shows when the CE rod is a rigid body, the out-of-balance force is a smooth straight line. It can be seen that the rigid connecting link is not deformed in the process of motion, the component force in horizontal direction of CE and BC rod to hinge C is equal in magnitude and opposite in direction. When the CE rod is a flexible body, the out-of-balanced force curve of the balance hoist fluctuates up and down and the fluctuation center is shifted, from the analysis of the first two sections, it can be seen that the deformation of the connecting link lead to a large out-of-balanced force at hinge C. Therefore, the analysis shows that increasing the stiffness of the connecting link can reduce the out-of-balanced force, thus improving the stability of the balance hoist.

From the above results, the vibration and elastic deformation of the connecting link loading weight have a great influence on out-of-balance force of the balance hoist. First, when the hinge F of the balance hoist moves horizontally, the shortening and amplitude of the connecting link increases significantly with the increase of the cargo weight. The closer the lifting weight position is to the both ends of the workspace, the greater the amplitude of the out-of-balance force and the risk of out-of-balance increase. Second, when the hook F of the balance hoist moves vertically, the shortening and amplitude of the connecting link increase significantly with the increase of the cargo weight. The center of the out-of-balance force wave shifts when the lifting weight reach the lower end of the workspace and the closer it is to the lower end, the greater the shift become, the balance hoist is extremely easy to lose its balance. Third, comparing horizontal and vertical movements, we can see that the amplitude of the out-of-balance...
force in vertical movements is larger than that in horizontal movements and the center of the wave is shifted, so we should focus on the risk of out-of-balance in vertical movement. Finally, the analysis shows that increasing stiffness of the connecting link can reduce the out-of-balanced force, thus improving the stability of the balance hoist.

Therefore, try to avoid the lifting weight reaching the limit in actual work. During the production and design process, the out-of-balance force of the balance hoist can be reduced by increasing the stiffness of the connecting link, changing the curvature of the horizontal guide rail and appropriately reducing the workspace, and effectively reduce the risk of unbalance of the balance hoist.

5. Conclusions
Based on the rigid-flexible coupling dynamics, the effect of connecting link deformation on stability of balance hoist was investigated under different working conditions. According to the balance principle and kinematics of the boom system, the force of connecting links and the workspace of balance hoist were analyzed. The influence of the deformation of a rod in the boom system on the out-of-balance force was analyzed using the graphical method. It was found that the closer the hook is to the boundary of the workspace, the greater influence of connecting link deformation on stability of balance hoist. The largest out-of-balance force is at the lower outside edge of the balance hoist workspace. According to the results, the dangerous workspace should be avoided during the working process. It is also possible to reduce the out-of-balance force by appropriately increasing the stiffness of connecting link, increasing the length of pressure rod and changing the shape of guide rail, thereby improving the stability of balance hoist. It can be used as a reference for optimal design of the structure, the operational performance and the study of the dynamics characteristics of balance hoist.

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