Analysis of the front carrier stability considering real-time offset of the spreader

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Abstract. Frontal carrier is often used to stack and transfer containers at freight terminals or inland transfer stations, and the requirement of its security is increasing. Since the lifting point is located in front of the vehicle body, it is also necessary to move the spreader left or right in real time to adjust the position of the lifting point during the lifting process. While the boom extends forward and the lifting load is large, the front carrier will be in a state of unbalanced stress, which increases the hidden danger of the front carrier overturning forward. This paper analyzes the influence of spreader offset on the change of overturning line of the frontal carrier while the frontal carrier is lifting a large load, establishes the coefficient to measure the anti-overturning stability of the frontal carrier, calculates the real-time lifting point position of the frontal carrier, and analyzes the spatial force system of the frontal carrier. By comparing the influence of spreader offset on the anti-overturning stability coefficient of the frontal carrier under different typical lifting conditions, this paper analyzes the change of anti-overturning stability coefficient, and gives the stability area diagram under given load, which provides a certain judgment basis for the safe operation of the frontal carrier.

1 Introduction

The Frontal Carrier (FC), which is equipped with a lifting boom structure on its body, installed with extension and pitch cylinders as well as a spreader that can be moved from side to side so that the lifting point (point of action of the load) can be moved in the front space of the body to reach a large operation area [1]. The front boom extends forward when lifting the container load. Long boom and large load make the vehicle body to bear a large load moment, and left and right movement of spreader to adjust the lifting point position makes the FC force unbalanced, which increases the hidden overturning danger of the FC. Therefore, analyzing the FC anti-overturning stability is essential for the safety operation [2].

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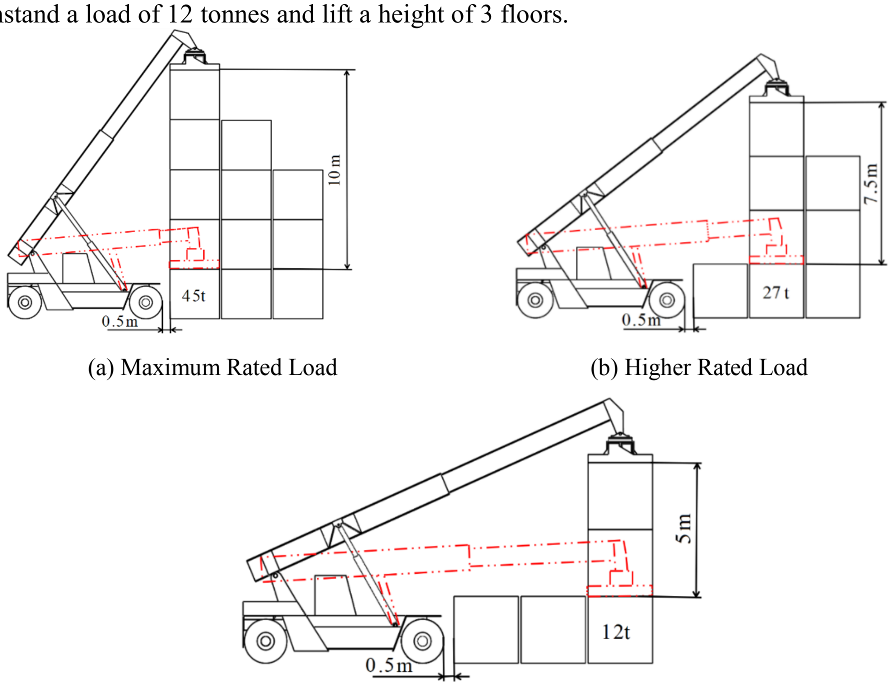
The displacement equations for the boom system of the FC had been generated by Shun Long et al. who had analyzed the position change of the lifting point [3]. The force on the boom system of the FC with a plane force system had been analyzed by Ning Tao et al. who had derived the force on the connection points of each member [4]. The operational stability coefficients of container the FC had been solved by Zhao Yang et al. under various working conditions based on Adams simulation [5]. A weighing algorithm for the FC had been designed by Yu Zhang et al. based on plane moment [6].

Although many force analysis of the FC have been conducted in the above studies, they are all based on the plane force system, rather than focus on the influence of spreader offset on the establishment of the force system and stability analysis of the FC. In this paper, the spatial force system is directly used to establish the stability coefficient expression on the basis of considering the real-time offset of the spreader. The position of the lifting point and the corresponding force needed in the calculation process are all derived based on the spatial force system model.

2 Anti-overturning stability model of frontal carrier

2.1 Typical lifting conditions for a frontal carrier

The FC can be used for stacking and transferring containers. A certain type of the FC is classified into three typical lifting conditions according to the distance of the point of action of the load from the vehicle body. Figure 1(a) shows that the FC lifts the first row of containers, which can withstand a load of 45 tonnes and lift a height of 5 floors; (b) shows that the FC lifts the second row of containers, which can withstand a load of 27 tonnes and lift a height of 4 floors; (c) shows that the FC lifts the third row of containers, which can withstand a load of 12 tonnes and lift a height of 3 floors.



(a) Maximum Rated Load

(b) Higher Rated Load

(c) Lower Rated Load

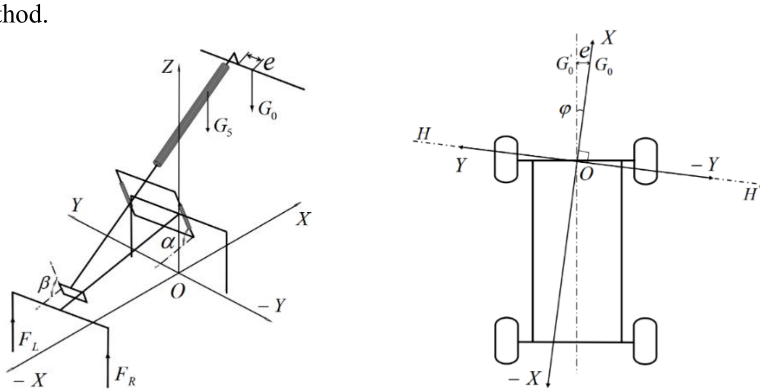
Fig. 1. Schematic diagram of typical lifting condition of a certain type of frontal carrier.

2.2 The establishment of the frontal carrier anti overturning stability expression

According to GB / T 3811 "Crane Design Code" for the moment method of solving the crane stability provisions, when the body by the weight and counterweights and other components of the stability of the moment is greater than by the load and other components of the overturning moment, it can be assumed that the body is stable and will not be overturned forward, and the stability of the moment and the overturning moment are the results of corresponding force on the body of the overturning line to find moments. The overturning line is the axis of rotation around which the vehicle body overturns. The overturning line affects the calculation of stabilizing moment and overturning moment, which in turn affects the calculation of the anti-overturning stability of the FC, and it is crucial to analyze the change of the position of the overturning line for the establishment of the stability coefficient of the FC.

Generally speaking, the overturning line of the FC passes through the line between the contact points of the front wheels and the ground on both sides. However, the spreader will be offset to both sides to adjust the lifting point position, when lifting large loads, the boom outstretched distance is too long and the spreader to one side offset distance is too large, the load action point will be too biased towards one side of the front wheel, so that the other side of the front wheel has a tendency to buckling, the FC may flip along the single side of the front wheels to the side of the front[7]. At this time, the overturning line is only over the contact point between the unilateral front wheel and the ground, compared with the previous rotation that is, as the load action point moves to both sides of the overturning line will have a tendency to rotate [8].

The coordinate system XYZ is established in Fig. 2(a), where the projection point G_0 of the axis X overload point on the surface XOY is shown in Fig. 2(b). From this, a dynamic coordinate system XYZ can be obtained which varies with the deflection e, where the overturning line HH' is on the axis Y, and the angle of rotation φ is related to the boom elongation and the deflection e. The trend of the overturning line can be described by the above method.



(a) Space coordinate system XYZ. (b) Projection on XOY plane.

Fig. 2. Schematic diagram of the overturning line of the frontal carrier affected by the offset of the lifting point.

When the stabilizing moment of the FC is greater than the overturning moment, that is, the ratio $M_{\mathrm{W}}/M_{\mathrm{q}} > 1$, the FC will not overturn forward. The stabilizing moment includes the self-weight of the vehicle body, counterweight, basic boom and tilting cylinder, etc., and the overturning moment includes the self-weight of the telescopic boom and the load, etc., and the moment of the overturning line. The overturning moment M_{q} will make the FC have the tendency to flip forward along the overturning line HH', and the stabilizing moment M_{W} will make the FC have the tendency to keep stable backward along the overturning line HH', and the ground support force on the rear wheels for the overturning line moment can be equated to the stabilizing moment minus the surplus moment of the overturning moment, that is, $M_{\mathrm{F}} = M_{\mathrm{W}} - M_{\mathrm{q}}$. When the ratio of $(M_{\mathrm{W}} + M_{\mathrm{q}})/M_{\mathrm{q}} > 1$, the vehicle is stabilized, and the rear wheels will not be affected. When $M_F = 0$, the rear wheels of the car body will be overturned forward without ground support force, thus the anti-overturning stability coefficient of the FC can be defined as:

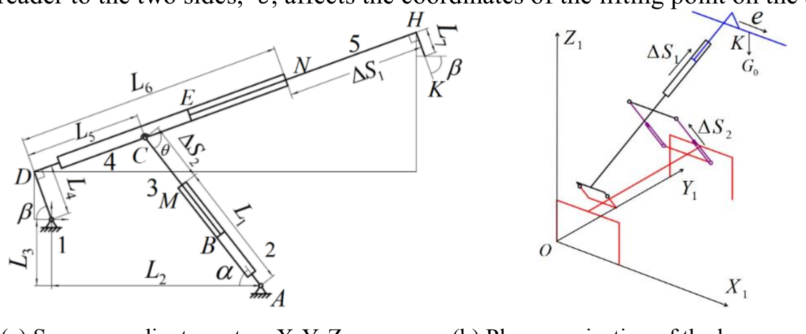
$$S = 1 + \frac{L_{F1L} \cdot F_{1L} + L_{F1R} \cdot F_{1R}}{2(L_{G01} \cdot G_0 / \cos\varphi + L_{G51} \cdot G_5 \cdot \cos\varphi)} \tag{1}$$

In the formula (1), $S > 1$ indicates that the FC is stabilized, and the larger its value is, the larger the surplus of stabilizing moment is, and the more unlikely that the vehicle body will overturn forward, and the above formula is based on the method of solving for spatial moment. In the fractional term, the numerator represents the arithmetic average of the surplus moment, that is, the average force on the rear wheel of a single side of the overturning line for the spatial moment, and the denominator represents the overturning moment, and the specific solution can be solved by the FC spatial force system model.

2 Frontal carrier space force system model

2.1. Position analysis of load action point

The boom part of the container is composed of extension boom, fixed boom, extension rod of pitch cylinder, and pitch cylinder barrel, and the active parts are the two cylinders of extension and pitch, which make the position of the lifting point change through the coordinated movement of the two cylinders [9]. In Figure 3 (a), the lifting point, that is, the point of action of the load is located in the center of the spreader, with the left side of the rear wheels and the ground contact point for the origin O, the two sides of the rear wheels and the ground contact point line for the axis X_1, the establishment of coordinate system $X_1Y_1Z_1$. Figure (b) shows the projection of the boom section on the Y_1OZ_1 surface, and it can be seen that the expansion of the extension and pitch cylinders, ΔS_1 and ΔS_2 variation, affects the coordinates of the lifting point K on the surface Y_1OZ_1, and the distance of movement of the spreader to the two sides, e, affects the coordinates of the lifting point on the axis X_1.



(a) Space coordinate system $X_1Y_1Z_1$. (b) Planar projection of the boom system.

Fig. 3. Schematic diagram of frontal carrier displacement analysis.

The following trigonometric relationship can be established in the quadrilateral ODCA:

$$\begin{cases}(L_1+\Delta S_2)\cos(\alpha)+L_5\sin(\beta)-L_4\cos(\beta)=L_2\\(L_1+\Delta S_2)\sin(\alpha)+L_5\cos(\beta)-L_4\sin(\beta)=L_3\end{cases} \tag{2}$$

In the formula: ΔS_1、ΔS_2- Expansion amount of extension and pitch cylinder;

α- The angle between the pitch cylinder and the horizontal plane;

β- Angle between fixed arm cylinder and horizontal plane;

L_1- Cylinder length of pitch cylinder;

L_2- The horizontal distance between the lower hinge point of the pitch cylinder and the lower hinge point of the fixed arm;

L_3- The vertical distance between the lower hinge point of the pitch cylinder and the lower hinge point of the fixed arm;

L_4- The distance between the centre line of the fixed arm and its lower hinge point along the width of the fixed arm;

L_5- The distance between the middle and lower hinge points of the fixed arm along the length of the fixed arm;

L_6- Length of the fixed arm;

L_7- The distance between the lifting point K and the centre line of the fixed arm along the width of the fixed arm.

Then the coordinates of the lifting point K can be expressed as:

$$\begin{cases}L_{Kx}=1.53+e\\L_{Ky}=(L_6+\Delta S_1)\sin(\beta)-L_4\cos(\beta)+L_7\cos(\beta)+0.48\\L_{Ky}=(L_6+\Delta S_1)\cos(\beta)+L_4\sin(\beta)-L_7\sin(\beta)+3.34\end{cases} \tag{3}$$

In the formula: L_{Kx}, L_{Kx} and L_{Kx}- The coordinates of point K in the space coordinate system $X_1Y_1Z_1$.

The relevant parameter values of a certain type of the FC are brought into the formula, and the displacement area that can be reached by the lifting point K can be solved by MATLAB programming.

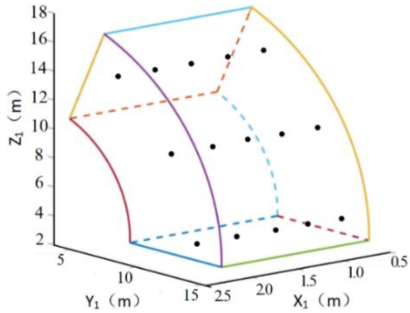


Fig. 4. Schematic diagram of the spatial location of lifting point K.

As shown in Fig. 4, in the spatial coordinate system $X_1Y_1Z_1$, the space reachable by the lifting point K is a spatial region with a fan-shaped cross-section through the coordinated movement of the pitch and expansion oils as well as the cylinders of the spreader.

2.2. Analysis of spatial force system of frontal carrier members.

In the process of travelling and lifting containers, the travelling speed of the FC and the lifting speed of the boom are relatively slow and uniform, which is similar to the uniform motion. For the mechanical analysis of the FC, the spatial moment balance equation of the whole vehicle can be solved. The spatial force system balance equation is shown as follows, indicating that in the state of space force on the FC, to satisfy the equilibrium of forces in the axes X, Y and Z of the space coordinate system, and each force for the three axes of the moment is also balanced [10], that is

$$\sum X = 0, \sum Y = 0, \sum Z = 0, \sum M_X = 0, \sum M_Y = 0, \sum M_Z = 0 \tag{4}$$

Using the matrix solution of the spatial force system, Equation (4) can be expanded into Equation (5).

$$\begin{cases} \sum_{i=1}^{n} F_{i1} = 0 \\ \sum_{i=1}^{n} F_{i2} = 0 \\ \sum_{i=1}^{n} F_{i3} = 0 \\ \sum M_{\mathrm{X}} = \sum_{i=1}^{n} \left(R_{i2}F_{i3} - R_{i3}F_{i2} \right) = 0 \\ \sum M_{\mathrm{Y}} = \sum_{i=1}^{n} \left(R_{i3}F_{i1} - R_{i1}F_{i3} \right) = 0 \\ \sum M_{\mathrm{Z}} = \sum_{i=1}^{n} \left(R_{i1}F_{i2} - R_{i2}F_{i1} \right) = 0 \end{cases} \tag{5}$$

According to Fig. 2(a), list the matrix of partial forces and the matrix of force action points on the coordinate axis XYZ for the ground support force on the rear wheels as well as for the loads.

$$F_F = \begin{bmatrix} F_{1L} \\ F_{1R} \\ F_{2L} \\ F_{2R} \end{bmatrix} = \begin{bmatrix} 0 & 0 & F_{1L} \\ 0 & 0 & F_{1R} \\ 0 & 0 & F_{2L} \\ 0 & 0 & F_{2R} \end{bmatrix}, \quad R_F = \begin{bmatrix} r_{F_{1L}} \\ r_{F_{1R}} \\ r_{F_{2L}} \\ r_{F_{2R}} \end{bmatrix} = \begin{bmatrix} -L_{FL1} & L_{FL2} & 0 \\ -L_{FR1} & L_{FR2} & 0 \\ -1.53\sin\varphi & 1.53\cos\varphi & 0 \\ 1.53\sin\varphi & -1.53\cos\varphi & 0 \end{bmatrix}$$

$$F_G = \begin{bmatrix} G_0 \\ G_5 \end{bmatrix} = \begin{bmatrix} 0 & 0 & -G_0 \\ 0 & 0 & -G_5 \end{bmatrix}, \quad R_G = \begin{bmatrix} r_{G_0} \\ r_{G_5} \end{bmatrix} = \begin{bmatrix} L_{G01}/\cos\varphi & 0 & L_{G03} \\ L_{G51}\cdot\cos\varphi & L_{G51}\cdot\sin\varphi & L_{G53} \end{bmatrix};$$

$$\begin{cases} L_{F1L1} = 6.5\cos\varphi + 1.525\sin\varphi \\ L_{F1L2} = -6.5\sin\varphi + 1.53\cos\varphi \\ L_{F1R1} = 6.5\cos\varphi - 1.525\sin\varphi \\ L_{F1R2} = -6.5\sin\varphi - 1.53\cos\varphi \end{cases}, \quad \begin{cases} L_{G01} = (7.85 + S_1)\sin\beta + 0.3\cos\beta - 6.03 \\ L_{G03} = (7.85 + S_1)\cos\beta - 0.3\sin\beta + 3.34 \\ L_{G51} = (3.925 + S_1)\sin\beta - 0.55\cos\beta - 6.03 \\ L_{G53} = (3.925 + S_1)\cos\beta + 0.55\sin\beta + 3.34 \end{cases}$$

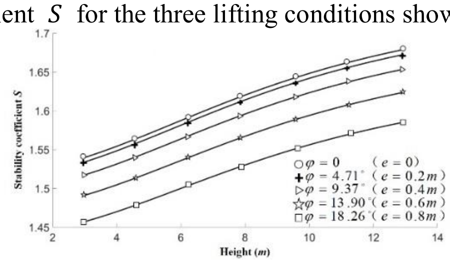
Bringing the above matrix of forces and force points into equation (5) yields four equations corresponding to four sets of wheel support forces from the ground, and given a load, the ground support force on the rear wheels can be derived.

The support force on the rear wheel is matrixed to the axis Y(HH’) as the surplus moment, and the load is matrixed to the axis Y(HH’) as the overturning moment.

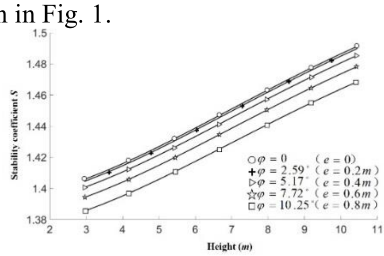
$$M_F = L_{FL1} \cdot F_L + L_{FR1} \cdot F_R$$

$$M_F = L_{G01} \cdot G_0 / \cos\varphi + L_{G51} \cdot G_5 \cdot \cos\varphi$$

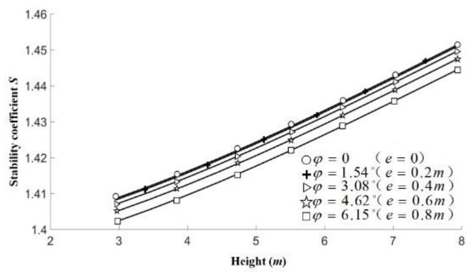
Write the programme using MATLAB and run it to solve for the variation of stability coefficient S for the three lifting conditions shown in Fig. 1.



(a) Lifting the first row of containers.



(b) Lifting the second row of containers.



(c) Lifting the third row of containers.

Fig. 5. Schematic diagram of the variation of stability coefficient S under the influence of offset e.

From Fig. 5, it can be seen that the stability coefficient S becomes larger with the increase of the lifting height of the FC for each working condition, and the vehicle body becomes more stable. The distance e of the load action point from the symmetry plane of the FC becomes larger, which will make the deviation angle φ of the overturning line increase, and eventually make the stability coefficient S become smaller. This effect is bigger and bigger with the increase of the deviation e, and with the smaller rated load of the crane (the number of rows increases), the influence on the stability is weakened. Among the three conditions, the stability of the container of the second row of the crane is small in general. Comprehensive stability coefficient of the three conditions, the lowest value is 1.38, the permissible value of the anti-overturning stability coefficient S, which is 1.38 will be taken.

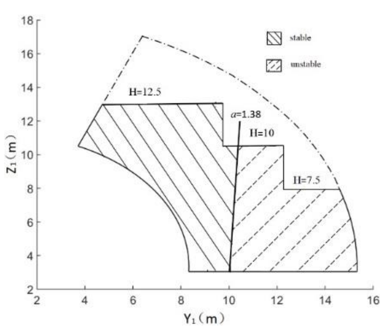


Fig. 6. Schematic diagram of the stabilisation zone for lifting 40 ft containers.

Project the spatial position of lifting point K in Fig. 4 onto the vertical plane Y_1OZ_1, and extract the height lines of the three rows of typical lifting conditions of the FC in Fig. 1, and take the permitted value of stability coefficient of 1.38 selected in Fig. 5 as the limit, and then draw a schematic diagram of the stability area of 40-foot containers (with a total load capacity of 30 tonnes) lifted when the offset distance of the lifting point is 0.8m at the maximum value, as shown in Fig. 6.

The area enclosed by the height line and the solid part of the fan in Fig. 6 is the working area of the lifting point. When the lifting point is located in the area of the solid diagonal line, it means that the FC has good working stability; when the lifting point is located in the area of the dotted diagonal line, it means that the FC is unstable, and there is a danger of overturning forward. For any lifting load, it is convenient to draw a stability area schematic diagram, which directly shows the safety area of the FC under the load, and can provide a basis for judgement of the FC's safe operation.

3 Conclusion

Through the above analysis, it can be concluded that as the spreader offset increases, the anti-overturning stability coefficient of the FC decreases, and at the same time, as the lifting point extends to a longer distance, the influence of the spreader offset on the stability of the FC is weakened. Based on it, this paper proposes a schematic diagram to facilitate the judgement of stability, which can be convenient to judge the safety of the FC operation.

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