Radius survey of crawler crane base on total station

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Abstract. The process of surveying crane parameters has been continually refined due to the competitive situation, modern surveying instruments and more powerful softwares. As the radius is the crucial parameter to determine the jib crane’s safety, a survey scheme is put forward to solve the problem that the rotary axis can’t be determined on-site in the paper, which measures the coordinate data of marked points by utilizing the total station, then the plane fitting method and the space analytic geometry method are adopted to determine the revolving centre axis. The proposed method is simple and easy to implement with acceptable accuracy in the field.

1. Introduction

Alignment surveys have been carried out by various means and for a variety of applications for decades. As to the crane’s parameters surveys, the theodolites or the total stations is preferred by surveyors, and many researchers have carried out the meaningful survey works on the crane runway[1,2,3,4,5]. In [1], a combined of angular triangulation and distance survey with an accuracy of one millimetre on the 300m long crane rails was described, and the main survey was carried out on three intersection total stations with some position targets evenly distributed on the full length of rails, the data of targets about two rails were measured by total stations, then the preliminary calculation was performed to obtain the mean horizontal alignment of each rail, the mean height of all positions, the lateral deviation from the standard gauge and the difference in height between two rails, meanwhile, the diagram of gauge and height deviations were plotted by CAD software. The survey methodology of [1] could archive the satisfied accuracy at cost of complex steps and multiple instrument stations. In [2], a comprehensive measurement named The Advanced Rail Track Inspection System (ARTIS) was developed to solve the recording of crucial parameters, e.g., the wear of the rail, or the condition of the rail fastening and rail joints. And the system also consists of a monitoring vehicle and an external tracking sensor; it could make kinematic observations with the tracking sensor from outside the rail run, e.g., the floor of an overhead crane runway, possible. The system had the advantages of the high accuracy and the comprehensive measurement of track parameters; however, its structure is complex with the high cost, and is also had certain on-site requirements, which is difficult to promote the implement.

Although there are many references on crane parameter survey, little literature about the crane Radius survey is seldom published and available, as to the jib crane, the Radius is the crucial parameter which determines the safety of crane. The inaccurate radius would lead the lifting moment limiter couldn’t stop the jib luffing towards unsafe direction in time, which causes many overturning accidents. For the mobile crane and the tower cranes, overturning is the most common accident. In the paper, we focus on the jib crane parameter of the radius survey, which is required by two inspection
rules (TSG 7015-2016[6], TSG 7016-2016[7]). As to large crane, the large-scale monitoring system should be installed, and the contents and the requirements of supervision and inspection of large-scale monitoring system are clearly stipulated. Therefore, a survey methodology combined the total station and the MATLAB software is put forward to deal with the Radius survey of crawler crane, which is easy to implement in the site inspection with less labour and acceptable precision.

2. Definition of jib crane radius

According to the definition of radius in GB 6974.1-2008 "Crane Terminology Part 1: General Terminology"[8], when a jib crane is placed on a horizontal site, the horizontal distance from the revolving centre line of its rotary platform to that of the pick-up device (no-load) is the radius. As to the crawler crane, the distance between the revolving centre line and the centre line of the hook is the radius. The working radius of the jib crane is varied with the position of the lifting load, which is realized by changing the angle of the lifting arm by the luffing mechanism, thus the lifting moment is also varied with the working radius. And the different types of jib cranes have their individual lifting performances curves, which are the important parameters reflecting the lifting capacity of cranes. When the jib lifts a load, its lifting moment should not exceed the overturning moment, which is achieved through restricting the maximum working radius by the lifting moment limiter.

There are two points for the jib crane radius parameters in the inspection regulations, one is to do the luffing movement on site, checking the corresponding position on the display with the metric survey retained two decimal points at least; the other is that the comprehensive error of radius is less than 5%, as to the mobile crane, the radius test under rated load should also be carried. In the inspection process, the first is the on-site confirmation without survey; the second is the on-site survey. According to the item 7.2 in the standard GB/T 28264-2012 "Safety Monitoring and Management System of Lifting Machinery"[5], the measuring radius ranges are selected 30%, 60% and 90% maximum operating Radius under no-load condition, and the luffing mechanism of crane should be stopped after running twice in a small area near the pick-up point. Then the actual radius $R_{0.3a}$, $R_{0.6a}$ and $R_{0.9a}$ are measured three time respectively with the average values obtained, and the corresponding data of Radius $R_{0.3a}$, $R_{0.6a}$ and $R_{0.9a}$ displayed on the crane monitoring system are also recorded three time with the average values obtained. According to the formula of comprehensive error:

$$E_R = \frac{|R_s - R_i|}{R_i} \times 100\%$$

Where $E_R$ is the comprehensive error of Radius, and $R_s$ is the average value of actual Radius, $R_i$ is the average value of the crane monitoring system.

3. Measuring object and instruments

Table 1. Main technical parameters of QUY700.

| items                      | unit | value   |
|----------------------------|------|---------|
| Standard conditions        |      |         |
| Heavy Main Arm Length      | m    | 24-84   |
| Light Main Arm Length      | m    | 66-102  |
| Length of tower auxiliary arm | m | 24-84 |
| Guying condition           |      |         |
| Light Main Arm Length      | m    | 90-138  |
| Length of tower auxiliary arm | m | 24-96 |
3.1. Measuring object
In order to explore the actual radius survey method of the crawler crane, we select the QUY700 crawler crane produced by Xuzhou Engineering Group Co. Ltd. as the measuring object, and its main technical parameters are listed in Table 1. In Figure 1 the actual working condition of QUY700 crawler crane is shown, and the length of its heavy main arm is 36m.

3.2. Measuring instrument and PC software
The measuring instrument is Leica TPS1200(Figure 2), which can be operated either manually or automatically with excellent accuracy of angle and distance survey, its accuracy level is 1' and distance error is 1 mm + 1.5 ppm (1 km 2.5 mm error). Therefore, the accuracy of the radius survey can be fully satisfied by that of total station. During the survey, the coordinate of the total station is taken as the reference coordinates, and all the coordinate data of the marked points are measured in one instrument station.

The PC software used as data processing is MATLAB, which has the powerful function about the matrix calculus, the drawing functions and the data, implementation Algorithms. And the program to process the survey data is complied with MATLAB in the paper.

4. Survey scheme
For most crawler cranes, the revolving centre axis is hardly determined directly on site, so the alternative method is adopted to measure the coordinates of the relevant points from the surrounding position, which could be accurately accomplished by total station. Then the revolving centre line could be determined by the space analytical geometry method. During the process of solving the coordinate equation and the plane fitting, the powerful data analysis and processing function in MATLAB software is used.

4.1. Geometric Characteristics of Marked Points
As shown in Figure 1, the main arm is located in front of the crawler crane, which guarantees the axis of main arm is parallel to the side of crawler crane chassis. In Figure 3, four points are marked on the side of crawler crane chassis with the line segment 13 being parallel to the revolving centre line as possible. Figure 4 is the schematic diagram of the survey process. As can be seen from the figure, plane A is established by fitting the four points, then plane B is built to parallel with plane A through point a at the centre bottom of hook, and point d is the midpoint of line segment 13, the normal vector of plane A through point d is intersected to plane B at point c. Point 11 and point 11’ are the same marked point with the different height whose coordinate data are measured by the total station, so are...
to point 12 and point 12’, then the average of coordinate difference of the same points is taken as the vertical vector. Therefore, the angle between vector and vertical vector could be calculated by the spatial analytic geometry method. At last, the radius R is obtained by projecting line segment on horizontal plane.

Figure 3. Four marked points of the side of crawler crane chassis.

Figure 4. Schematic diagram of survey process.

4.2. On-site measurement steps
The on-site measurement steps are as follows:
1) Four points are marked on the side of crawler crane chassis with the line segment 13 being parallel to the revolving centre line o-o as possible, each point coordinate is measured three times by the total station;
2) Measuring point a on the central bottom of hook;
3) Marking point 11 and point 12 on the side of the hook, measuring their coordinate, lifting the hook to another height, then measuring their coordinates again.

5. Surveying Data Processing

5.1. The measured data
The measured coordinate data of marked points are shown in Table 2, which is as follows,

5.2. Plane fitting
The fitting plane equation is supposed as $p = A(x - \bar{x}) + B(y - \bar{y}) + C(z - \bar{z})$, where $\bar{x}$, $\bar{y}$ and $\bar{z}$ are the average measured data of each coordinate. And the least square method[9] is adopted to fit the plane and the objective function equation [6] is set as
\[ F = \frac{1}{2N} \sum_{i=1}^{N} (Ax_{io} + By_{io} + Cz_{io})^2 \]  

(2)

Where \( x_{io} = x_i - x \), \( y_{io} = y_i - y \), \( z_{io} = z_i - z \), and \( N \) is the total number of data, let \( W = [A B C]^T \) and \( X = [x_{io} y_{io} z_{io}]^T \). Therefore, the matrix function is expressed as

\[ F = W^T X(W^T X)^T = W^T XX^T W \]

(3)

Take the partial derivative of \( W^T \) and make it equal to zero,

\[ W^T(XX^T) = 0 \]

(4)

| Marked points | Location of points               | The coordinate data of points (m) |
|---------------|----------------------------------|-----------------------------------|
| 1             | Horizontal midpoint chassis      | x | y | z |
|               |                                  | 14.0748 | 36.4558 | 5.2339 |
|               |                                  | 14.0743 | 36.4555 | 5.2333 |
|               |                                  | 13.4379 | 37.4143 | 5.2236 |
| 2             | Horizontal right point chassis   | x | y | z |
|               |                                  | 13.4380 | 37.4140 | 5.2246 |
|               |                                  | 13.4391 | 37.4161 | 5.2241 |
|               |                                  | 14.0740 | 36.4562 | 5.6192 |
| 3             | Upper point chassis side         | x | y | z |
|               |                                  | 14.0738 | 36.4577 | 5.6175 |
|               |                                  | 14.0758 | 36.4568 | 5.6185 |
|               |                                  | 14.6114 | 35.6458 | 5.2374 |
| 4             | Horizontal left point chassis side| x | y | z |
|               |                                  | 14.6128 | 35.6435 | 5.2336 |
|               |                                  | 14.6127 | 35.6435 | 5.2353 |
| a             | Bottom of hook                   | x | y | z |
|               |                                  | 6.3377  | 32.9898 | 15.8169 |
| 11            | upper point of hook(before hoist)| x | y | z |
|               |                                  | 38.1521 | 8.0977  | 37.5699 |
| 12            | upper point of hook(before hoist)| x | y | z |
|               |                                  | 38.3081 | 8.2149  | 36.7637 |
| 11’           | upper point of hook (after hoist)| x | y | z |
|               |                                  | 38.0750 | 8.1239  | 6.1166 |
| 12’           | upper point of hook (after hoist)| x | y | z |
|               |                                  | 38.2460 | 8.2161  | 5.3093 |

Then perform eigen decomposition on \((XX^T)^T\), obtain eigenvalue matrix \( \Lambda \) and eigenvector matrix \( V \), and the eigenvector corresponding to the minimum eigenvalue is the coefficient of the fitting plane, that is \( v_{\min} = [A_{\min} B_{\min} C_{\min}] \).

In the paper, the equation of plane A fitted by four point coordinate data on the side of crawler is

\[ 0.6671x+0.4907y+0.5605z-30.3161 = 0 \]

, and the fitting result is shown in Figure 5.

![Figure 5. Result of plane fitting.](image-url)
5.3. Solving amplitude by space geometry analytic method

The plane B is made to parallel plane A through the central bottom point a (6.3377, 32.9898, 15.8169), whose equation is 
\[
0.6671x + 0.4907y + 0.5605z - 29.2826 = 0
\]
The coordinate of middle point d of the line segment 13 is (14.0745, 36.4559, 5.4260), and then the line \( cd \) is made from point d along the normal vector of plane A, which intersects plane B at point c, that is to solve equations 
\[
\begin{align*}
0.6671x + 0.4907y + 0.5605z - 29.2826 &= 0 \\
x - 14.0745 &= y - 36.4559 = z - 5.4260
\end{align*}
\]
(5)
The coordinate of point c is (13.3826, 35.9469, 4.8445), and the vector \( ac \) is (-7.0449, -2.9571, 10.9724) with \( |ac| = 13.3704 \). Meanwhile, the average of the vertical vector determined by the coordinate difference of point 11 and point 12 before and after lifting of hook is \((-0.0696, 0.0137, -31.4538)\), so the angle \( \alpha \) between \( ac \) and the mean vertical vector is calculated as 
\[
\cos \alpha = \frac{-7.0449 \times (-0.0696) - 2.9571 \times 0.0137 + 10.9724 \times (-31.4538)}{\sqrt{(-7.0449)^2 + (-2.9571)^2 + (10.9724)^2} \sqrt{(-0.0696)^2 + 0.0137^2 + (-31.4538)^2}} = 0.8196
\]
(6)
So \( \alpha = 34.96^\circ \), the measured radius could be obtained as 
\[ R = |ac| \sin \alpha = 7.6609m \].

5.4. Analysis of result

At first, the measured radius is compared with that of large-scale monitoring system, and the radius displayed on the monitoring system is 7.68m, which is slightly larger than the measured radius. Because the radius of the monitoring system is determined by the preset main arm length and the instantaneous angle between the main arm and the horizontal plane, and the deformation and bending of the main arm under load can’t be included in this case. Therefore, the radius of the monitoring system largely deviates from the actual value.

In order to validate the accuracy of this method, we also take another survey method, that is, to directly measure the diameter of the radius circle formed by the bottom point of the hook. On the spot, the main arm and the hook are driven to rotate one cycle by the rotary mechanism, and the coordinate data of point a are measured at about 30 degree of rotation. In this process, some influence factors, such as the wind blows and the main arm rotates, will lead the hook swaying. In order to eliminate the measure error of the hook swaying as far as possible, multiple measurements are used at each rotation position of 30 degree. In this way, there are ten groups of data in a circle of rotation. By the programming of MATLAB and the least square method, the circle fitting calculation of the ten groups of measured data is carried out, and the diameter of the fitting amplitude circle is obtained, and the calculated radius is 7.6553m.

Comparing the two survey methods, the second is based on the definition of the crane radius, which is directly measuring the coordinate data of points distributed around the circle of the crane radius and fitting this circle, avoiding the error produced by the auxiliary plane transformation, so its measuring accuracy is better than that of the first one. However, in the field testing more target point on the different positions need to be measured accompanying by the crawler crane’s operation, which takes a lot of labour and time. The first method is taking the side plane of the chassis of the crane as the reference plane, assuming that the line segment 13 in the side plane is parallel to the revolving axis, and the data distribution area for the plane fitting is small, therefore, the error of the first method is larger than that of the second method, but it is easy to implement with less measuring data, less labour and time consuming. Anyhow, the accuracy of the first method is better than that of monitoring system, therefore, it is easy to implement with the acceptable accuracy in the field.
6. Conclusion
In the paper, a survey methodology is proposed to measure the radius of the crawler crane, which basically solves the problem that the revolving axis is hardly determined on site. In the proposed survey scheme, the side plane of the chassis of the crane is selected as the reference plane, the radius is calculated by the plane fitting and the spatial analysis, the precise vertical vector is subtly obtained by the coordinate difference of the marked points before and after lifting the hook. In order to verify the accuracy of the proposed survey method, another method is adopted to directly measure the marked points distributed on the crane radius circle, and the circle is obtained by fitting the measured data, the two results are close to each other, the advantages and disadvantages of the two methods are analysed in detail, at last, it is pointed out that the proposed method in the paper is easy to implement with the acceptable accuracy in the field.

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