A Numerical Model for the Attitude Manipulation of Twin-Hoisted Object

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Abstract –

Hoisting an object with two crane hooks is sometimes applied when the pitch attitude of the hoisted object is necessary to be adjusted. The pitch attitude can be manipulated by changing the length difference of the two crane cables that connect the object with two hooks at two different positions. However, this twin-hoisted approach is impractical for crane operators who must be highly experienced and capable of adjusting the crane based on their visual measurement. This implies that the safety of workers and operation efficiency may rely on the physical and mental state of the operator. Furthermore, for the automation of the hoisting process, the method to precisely adjust attitude is required. In this research, a numerical study is carried out by a model that enables the attitude manipulation of a twin-hoisted object. By specifying a pitch attitude and lifting height of the object, the model can take the geometrical limitations of hoisting process into consideration and then determine the lengths of the two crane cables in real-time. In this study, the developed model is validated using a mobile crane both through a virtual environment and a lab-scale experiment. The proposed model not only can be implemented with a guiding interface established to guide crane operators in real time but also contributes to the development of automated crane control method.

Keywords –

Twin-Hoisting; Attitude Manipulation; Crane Control; Authors; Automation

1 Introduction

Conventionally, if the manipulation of the pitch attitude of a hoisted object is necessary, three approaches can be applied. The first approach is to hang the object with one crane using one single cable. This requires nearby workers adjusting the pitch angle of the hoisted object. The second approach is to hang the object by two cranes. These cranes hang each sides of the object and adjust its pitch angle through changing the length of their cables. The last approach hangs the object with two cables on one crane. By using both cables of the main boom and the auxiliary jib, adjustment can be achieved similarly to second approach. However, the former two approaches are limited in many ways. The first approach requires space for workers to adjust the attitude of the object. This may be hazardous when the attaching point is located high where there are only uncomplete structures for workers to stabilize themselves. Moreover, the object hanging in the air can also pose dangerous to nearby workers by striking them [1]. As for the second approach, requiring an additional crane implies that extra space and rent are needed. This may increase the total cost of the project and hinder its progress as well. Moreover, the coordination of the two cranes may be troublesome when attempting to reach the desired attitude by respectively changing the length of their cables.

While the first and the second method face those issues, the third method avoids them. As a result, demands on controlling the pitch attitude with the third approach is reported to be rising [2]. Furthermore, similar approaches in the field of manufacturing have been developed. Sawano et al. proposed a power-assisted attitude control system that hangs an object with one cable and a linear cylinder. In their study, the attitude of the object can be controlled through expanding and contracting the cylinder [3]. Hence, we aim to further improve the third method for a better controlling of the pitch attitude of the object hung by a crane.

Although the third method has some advantages over other methods, it still has a few disadvantages. This practice relies heavily on the experience of the crane operator. Also, the operator has to estimate the angle of the object by sight, which is not intuitive and precise. In the case that the operator cannot see the object, a voice guidance from other workers is needed. However, this may be sometime confusing to the operator. In addition, if an autonomous crane control system is to be developed, a precise approach to determine the pitch attitude will be necessary.

Therefore, we propose a numerical model to aid the manipulation of the pitch attitude using one crane and two cables. The telescopic boom of crawler cranes and a beam-type object are selected in this model. Formulas are also developed basing on the geometry of the crane and the hoisted object. By specifying the desired attitude, the corresponding lengths of the two cables can be obtained. Then, the cables of the crane are adjusted without changing the posture of the crane. An assigned attitude includes the pitch angle and the height of the hoisted object. As a result, a desired pitch attitude at a certain elevation can be reached. Finally, we inspect the validity through a virtual experiment and a lab-scale experiment.

2 Numerical Model and Formulas

The model considers the geometry of a crane to calculate the proper length of the crane cables to achieve specified pitch attitude of the object hoisted. In our study, A mobile crane with a telescoping boom and an auxiliary jib attached on the top of the boom is considered. A simplified mobile crane is illustrated in figure 1 with a set of parameters representing the geometry of the crane. As the figure shows, l_1, l_2, a and b respectively represents the length of the main cable, the length of the auxiliary cable, the distance between the left hooked point on the object to the center of mass of the object and the distance between the right hooked point on the object to the center of mass of the object. The distance between the sheaves of the main boom and the auxiliary jib is assigned as D. The angle of elevation of the auxiliary jib, main cable, auxiliary cable and the object are respectively defined as φ, α, β and θ. Furthermore, we defined a set of constraints to these angles. That is, $0° \leq \varphi \leq 90°$, $0° \leq \alpha \leq 90°$, $90° \leq \beta \leq 180°$ and $-90° \leq \theta \leq 90°$. This is to prevent unreasonable attitudes of the system.

The aim of the model is to obtain the length of the cables, l_1 and l_2, when a certain pitch angle θ and the vertical length $l_1 \sin\alpha$ of the main cable are assigned. Here we assume that the height of the main boom sheave is readily known, thus setting the vertical length of the main cable is equivalent of setting the height of the object. In this regard, we view D, a, b and φ as known parameters. On the other hand, the angle of the two cables, α and β will be calculated in the process as well. Therefore, a set of attitude calculation formulas are proposed.

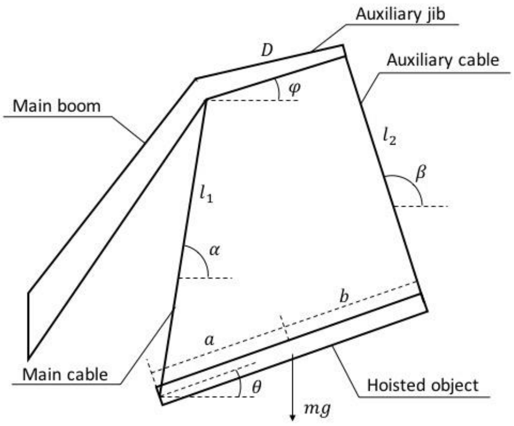

Figure 1. Simplified crane geometry

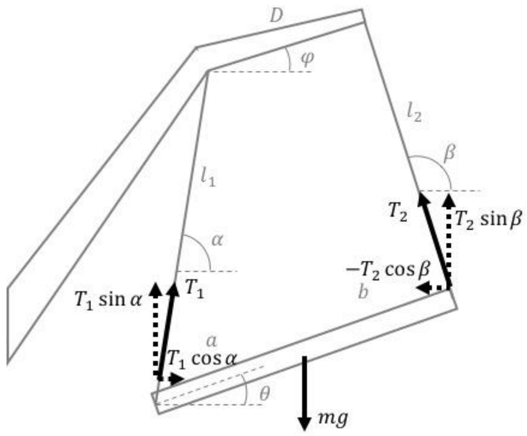

Figure 2. Forces acting on the object

Here we illustrate the formulation of the attitude calculation formulas of the model. The forces acting on the hoisted object in mechanical equilibrium are shown in figure 2. T_1 and T_2 are the tension of the main cable and the auxiliary cable. mg is the gravitational force acting on the hoisted object. Since the object is in mechanical equilibrium, vertical and horizontal forces in the system balance each other. Therefore, we can yield:

$$T_1 \sin\alpha + T_2 \sin\beta = mg \text{ and} \tag{1}$$

$$T_1 \cos\alpha + T_2 \cos\beta = 0. \tag{2}$$

In addition, the hooked points on the left and right side of the object are free to spin. This indicates that the moment on both side should be zero in mechanical equilibrium. Therefore, we can yield:

$$T_1 = m \cdot \frac{b}{a+b} \cdot \frac{\cos\theta}{\sin(\alpha-\theta)} \text{ and} \tag{3}$$

$$T_2 = m \cdot \frac{a}{a+b} \cdot \frac{\cos\theta}{\sin(\beta-\theta)}. \tag{4}$$

From Equation (1), (2), (3) and (4), we obtain a relationship between α and β:

$$\tan\alpha = \frac{a+b}{a} \cdot \tan\theta - \frac{b}{a} \cdot \tan\beta. \tag{5}$$

From the geometry relationship between the vertical distance of the upper and lower ends of D, l_1, l_2 and $(a+b)$, we get:

$$l_1 \sin\alpha = l_2 \sin\beta - D\sin\varphi + (a+b)\sin\theta. \tag{6}$$

Similarly, from the geometry relationship between the horizontal distance of the upper and lower ends of D, l_1, l_2 and $(a+b)$, we get:

$$l_1 \cos\alpha = l_2 \cos\beta - D\cos\varphi + (a+b)\cos\theta. \tag{7}$$

Finally, through Equation (5), (6) and (7), we yield:

$$\begin{aligned} & l_1 \sin\alpha \\ &= \Bigg((a+b)\sin\theta - D\sin\varphi \\ &+ \big((a+b)\cos\theta - D\cos\varphi\big) \\ &\cdot \left(\frac{a}{b} \cdot \tan\alpha - \frac{a+b}{b} \cdot \tan\theta\right) \cdot \sin\alpha \Bigg) \\ &\div \left(\sin\alpha + \cos\alpha \cdot \left(\frac{a}{b} \cdot \tan\alpha - \frac{a+b}{b} \cdot \tan\theta\right)\right) \end{aligned} \tag{8}$$

By inputting a set of known value of D, a, b and φ and assigning a set of $l_1 \sin\alpha$ and θ, a set of αs satisfying the constraint of α can be obtained through Equation (8). In addition, the corresponding l_1s can also be calculated. Through Equation (5), a set of corresponding βs can be obtained. By checking if β meets its constraint, we can get the only set of α and β. With the particular set of α and β, l_1 and l_2 can be calculated through Equation (6) or (7). In this study, the process of finding l_1 and l_2 is carried out by Matlab.

3 Experiment and Result

To examine the validity of the proposed model and formulas, we conducted several tests with a virtual crane. In the tests, we specified 6 different attitudes of the hoisted object. Which are, respectively, 1. $\theta = 30°$, $l_1 \sin\alpha = 30cm$, 2. $\theta = 45°$, $l_1 \sin\alpha = 30cm$, 3. $\theta = 60°$, $l_1 \sin\alpha = 30cm$, 4. $\theta = -30°$, $l_1 \sin\alpha = 30cm$, 5. $\theta = -45°$, $l_1 \sin\alpha = 30cm$ and 6. $\theta = -60°$, $l_1 \sin\alpha = 30cm$. First, we calculated the corresponding set of α, β, l_1 and l_2 basing on the formulas through Matlab. Then, we adjusted the l_1 and l_2 of the virtual model according to the result of the previous calculation. Finally, we compared the resulting αs, βs, l_1s and l_2s. In addition, tests are also conducted with a lab-scale crane shown in figure 3. The feasibility of applying our method was expected to be inspect through these tests.

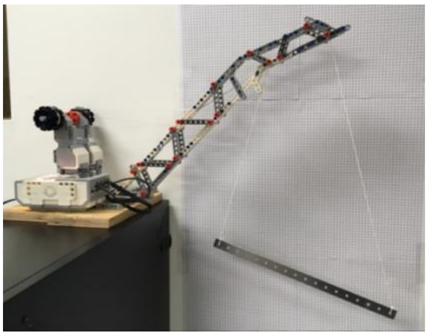

Figure 3. Lab-scale crane

In both virtual and lab-scale tests, the geometry parameters of the crane models are set identically as follows: $D = 9.7cm$, $\varphi = 26.04°$, $a = b = 13.65cm$. The corresponding αs, βs, l_1s and l_2s calculated basing on our formulas are listed in table 1.

Table 1 The calculated corresponding αs, βs, l_1s and l_2s

Attitude	$\alpha(°)$	$\beta(°)$	$l_1(cm)$	$l_2(cm)$
1	75.8	109.6	30.9	21.9
2	79.0	107.7	30.6	15.7
3	84.0	99.5	30.2	10.8
4	97.7	99.9	30.7	48.6
5	81.6	96.5	30.3	53.9
6	86.4	93.0	30.1	58.0

In the virtual crane test, we built a crane in Unity 3D, which is a physic engine as well as a game engine. We adjusted the length of the cables to the calculated l_1s and l_2s of the six specified attitudes in the virtual environment. Then, we measured the resulting θs and $l_1 \sin\alpha$s as well as αs and βs. Noted that we did not precisely set the lengths to the precise numbers but manually adjust them to simulate the crane operating process. Thus, slight difference of l_1s and l_2s between the calculated result and experimental result can be noticed. The result of the virtual test is list in table 2.

In the lab-scale crane test, we built a crane boom and an auxiliary jib attached on its top with LEGO Mindstorms EV3. We also adjusted the length of cables l_1 and l_2 and measured the resulting θs and $l_1 \sin\alpha$s as well as αs and βs. Similarly, we did not precisely set the length but manually adjust their lengths. Thus, slight difference of l_1s and l_2s between the calculated result and experimental result can also be noticed. The result of the lab-scale test is list in table 3.

Table 2 Result of virtual test

Attitude	$\theta(°)$	$l_1 \sin\alpha\ (cm)$	$\alpha(°)$	$\beta(°)$	$l_1(cm)$	$l_2(cm)$
1	29.4	29.8	74.8	108.6	30.9	21.8
2	46.1	30.3	79.1	106.4	30.8	15.5
3	59.6	30.1	83.7	99.1	30.3	11.0
4	-29.3	30.4	97.4	99.8	31.1	48.7
5	-45.4	29.9	80.4	95.8	30.3	53.9
6	-59.6	30.1	86.6	93.3	30.2	58.1

Table 3 Result of lab-scale test

Attitude	$\theta(°)$	$l_1 \sin\alpha\ (cm)$	$\alpha(°)$	$\beta(°)$	$l_1(cm)$	$l_2(cm)$
1	26.9	26.1	74.1	108.7	30.2	22.0
2	43.2	26.6	77.6	107.0	30.0	15.4
3	55.5	26.9	81.2	101.9	29.2	10.6
4	-32.4	26.4	77.5	99.0	29.9	48.2
5	-51.5	27.0	83.0	94.6	29.9	54.8
6	-66.2	27.0	87.7	90.9	30.0	58.7

Table 4 Gap between test results and calculated results

Attitude		Gap ($\|1 - TestResult \div CalculatedResult\| \times 100\%$)			
		θ	$l_1 \sin\alpha$	α	β
1	Virtual Test	2.1%	0.6%	1.3%	1.0%
	Lab-scale Test	10.3%	13.1%	2.2%	0.8%
2	Virtual Test	2.4%	0.9%	0.2%	1.2%
	Lab-scale Test	3.9%	11.4%	1.8%	0.7%
3	Virtual Test	0.6%	0.5%	0.3%	0.4%
	Lab-scale Test	7.6%	10.2%	3.3%	2.4%
4	Virtual Test	2.5%	1.2%	0.3%	0.1%
	Lab-scale Test	7.8%	12.1%	20.6%	0.9%
5	Virtual Test	0.8%	0.4%	1.5%	0.7%
	Lab-scale Test	14.5%	10.1%	1.7%	1.9%
6	Virtual Test	0.6%	0.5%	0.2%	0.3%
	Lab-scale Test	10.4%	9.8%	1.6%	2.3%

4 Discussion

The gap of the geometry parameters between the results calculated through the formulas and the results obtained through the tests is listed in table 4. The gaps between the θs of the virtual tests and the calculation are less than 2.5%. Also, $l_1 \sin\alpha$s, αs and βs of the virtual tests also show matching results with gaps no more than 1.5%. This indicates that the corresponding l_1 and l_2 calculated through proposed model and formulas are able to form the specified attitude. On the other hand, the results of the lab-scale tests show larger gaps. However, since the main purpose of the lab-scale tests are not evaluating the formulas, precise measure methods were not applied. Therefore, we believe this is because of the errors of the measurement of these parameters. Also, deformation of the crane boom caused by weight was noticed and may also lead to the inaccuracy of the attitude of the object.

We observed several facts during the lab-scale tests. 1. Some geometry constraints are necessary to be added into our model. 2. The swaying pattern of a twin-hoisted object is complicated. 3. Physical factors are necessary to be considered. For the first observation, we noticed that the hoisted object may strike the crane boom in certain critical condition. This is especially likely to occur when the length $(a + b)$ of the object is sizable or the object is close to the boom. Therefore, geometry constraints are needed to avoid collisions between the object and the boom. For the second observation, we noticed that the swaying of the twin-hoisted object is apparently different from single-hoisted objects.

Referring to the study of Maleki et al., a two-mode oscillation occurs when a motion perpendicular to the boom is performed with unequal cable lengths [4]. Reduction of the oscillation may be needed to allow more rapid operation and further applications. Finally, for the third observation, we found that deformation of the boom caused by weight can affect the accuracy of the resulting attitude. This issue should also be considered to allow a precise control of the hoisted object.

Although several problems were observed in the tests, the proposed method is still able to provide useful indication to adjust the cable lengths for an assigned pitch attitude of the hoisted object. Also, we believed that allowing users to assign the height of one side of the beam-type object is considerably convenient. In a case of attaching a beam to the structure, the operator may first lift the beam horizontally to the desired height near the attaching point on the structure. Then, he or she can adjust its attitude without changing the height of the attaching point on the beam. Consequently, the effort and time of readjusting the height of the beam can be saved.

5 Conclusion

A numerical model of a twin-hoisted beam-type object hoisted by a crane is proposed. In the model, the object is hoisted by a main boom and an auxiliary jib attached on the boom with two cables. Formulas are also proposed to calculate the corresponding cable lengths which can lead to specified attitude of the object under certain conditions. Furthermore, several issues were observed in lab-scale test, which indicate several necessary enhancements to further improve the safety and precision of such practice. Finally, the results of our tests suggest that the proposed model and formulas are capable to aid the manipulation of the pitch attitude of the hoisted object using one crane and two cables. Future works can be focused on implementing the proposed method on real cranes, while simultaneously addressing the observed issues.

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