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Calculation method and control value of static stiffness of tower crane

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Abstract

The static stiffness of tower cranes is studied by using the proposed formulations and finite element method in this paper. A reasonable control value based on theoretical calculation and finite element method is obtained and verified via collected field data. The results by finite element method are compared with the collected field data and that by the proposed formula. Corresponding to theoretical formulations and field data, it is found that the results by finite element method are closer to the real data.

Keywords: Tower crane; Static stiffness; Control value; Static displacement

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1. Introduction

Sagirli, Bococlu and Omurlu (2003) realized the simulation of a rotary telescopic crane by utilizing an experimental actual system for geometrical and dynamical parameters [1]. With the intention of comparing the real system and the model and of verifying the sufficiency of the model accuracy, various scenarios were defined corresponding to different loading and operating conditions. Of the scenarios defined, impulse response, time response and static response are used to experimentally gather such system parameters and variables as damping coefficient, cylinder displacements, and stiffness of the telescopic boom, respectively. Following are the simulations for two dissimilar scenarios which are static response and impulse response and the results that were presented. Barrett and Hrudey (1996) performed a series of tests on a bridge crane to investigate how the peak dynamic response during hoisting is affected by the stiffness of the crane structure, the inertial properties of the crane structure, the stiffness of the cable-sling system, the payload mass, and the initial conditions for the hoisting operation [2]. These factors were varied in the test program, and time histories were obtained for displacements, accelerations, cable tension, bridge bending moment, and end truck wheel reactions. Values for the dynamic ratio, defined as peak dynamic value over corresponding static value, are presented for displacements, bridge bending moment, and end truck wheel reactions. A two degree of freedom analytical model is presented, and theoretical values for the dynamic ratio are calculated as a function of three dimensionless parameters that characterize the crane and payload system. Grierson (1991) considered the design under static loads whereby the members of the structure are automatically sized by using commercial steel sections in full conformance with design standard provisions for elastic strength/ stability and stiffness [3]. This problem was illustrated for the least-weight design of a steel mill crane framework comprised of a variety of member types and subject to a number of load effects. Huang et al (2005, 2006, 2007) analyzed the static and dynamic characteristics of mechanical and structural systems using fuzzy and neural network methods [4-11].

For static stiffness of a tower crane, the requirements of GB 3811-1983 “Design rules for cranes” and GB/T 13752-1992 “Design rules for tower cranes” of China are as follows. “Under the rated load, the horizontal static displacement of the tower crane

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body $\Delta\chi$ at the connection place with the jib (or at the place of rotary column with the jib) should be no larger than $H/100$. In which H is the vertical distance of the tower body of the rail-mounted tower crane from the jib connection place to the rail surface, and the vertical distance from the jib connection place of the attached tower crane to the highest adhesion point".

In this paper a special research on the static stiffness of tower cranes was carried out aimed at relieving the over-strict control on the static stiffness ($\Delta\chi \leq H/100$) in the rules above, so as to meet the requirement for revising GB/T 3811-1983 "Design rules for cranes".

The remainder of this paper is organized as follows. Section 2 gives the suggested control value of static stiffness of a tower crane. Section 3 verifies the static stiffness control value. Theoretical calculation method of static displacement of the tower body corresponding to the static stiffness control value is provided in Section 4. Section 5 compares various methods for calculation of static displacement with the actually measured values. A brief conclusion is given in Section 6.

2. The suggested control value of static stiffness of tower crane

Because of the wide use of high-strength steel, it is not difficult to meet the structural strength and stability. Requirements on structural stiffness are becoming a dominant factor restricting tower crane development of towards the lightweight. The revised control value of static stiffness of tower crane should not only meet requirements of the current product development, but also should be suitable for future development. Based on the actual situation in China to ensure tower crane quality, so that design and inspection of the tower crane could have rules to follow, proper widening of the control value of static stiffness is the inevitable trend.

On the basis of a large number of investigations and visits to tower crane manufacturers and users, Yu, Wang, Zheng, and Wang proposed the recommended the control value of the tower crane static stiffness and the corresponding inspection method, i.e., taking the hinge-connection point of the jib end under no-load condition (at this moment there is an absolute backward displacement of the jib end hinge-connection point in relation to the theoretic centerline of the non-deformed tower body as shown in Fig.1) as the reference, and taking the absolute displacement $\Delta\chi$ at the jib end hinge-connection point after loading as the measurement value of static displacement. This value will be used to measure the static stiffness [12]. For measuring static displacement this is the method used in inspection and acceptance of the tower crane. This value can be easily measured, and the measured value has basically eliminated the verticality deviation of the tower crane. Yu, Wang, Zheng, and Wang recommended that the static displacement control value corresponding to this measuring method is $\Delta\chi \leq 1.33H/100$, i.e., the static stiffness control value is 1/3rd larger than the control value specified in the mentioned "rules" [12].

According to opinion of the experts of "Appraisal & evaluation meeting on special research project Revision of Rules on Crane Design," Yu, Wang, Zheng, and Wang recommended that the static stiffness control value is a proper limit value meeting the voice of the tower crane industry for revising and widening the $\Delta\chi$ limit value [12]. Moreover, this method is convenient for inspection. However, in order to be consistent with the coefficient value specified in international standard, it is recommended to take the static stiffness control value of the tower crane $\Delta\chi \leq (1.34/100)\, H$.

Widening the static stiffness control value ($1.34H/100$) of the tower crane can reduce the tower crane production cost, so that the tower crane can develop towards lightweight in favor of the technical progress of this industry.

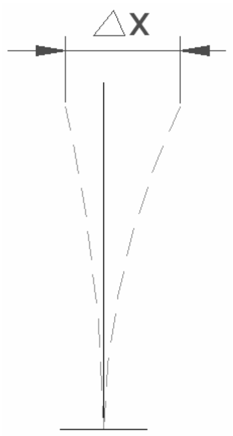

Fig. 1. Schematic diagram of static displacement of the tower crane.

3. Verification of the static stiffness control value

In order to make the revised static stiffness control value of the tower crane really reflect the current actual situation of the static stiffness, a special research group carried out measurements of static stiffness of 20 types of representative tower cranes which are within the period of their lifespan (see Table 1). The measurement results have shown that if measured according to the current measurement method, only one type of tower crane (sequence no. 5) can meet the static stiffness control value H/100, accounting for 5%, but 15 types of tower crane show a static stiffness control value of no more than 1.34*H*/100, accounting for 75%. It can be seen that proper widening the static stiffness control value of tower crane can let most of tower cranes, which meet the usage requirements, pass the inspection and acceptance conducted by the test & inspection authority.

It should be explained that all these 20 types of tower cranes are in excellent working condition.

Table 1. The actually measured static stiffness control value and the original control value of 20 types of tower cranes.

No.	Maximum lifting moment (Q×R)	Type	Height at the hinge-connection point of the tower H (m)	Original control value (mm) (H/100)	Actually measured value (mm) ($\triangle x$)	Actually measured value /height ($\triangle x/H$)
1	16.0t×15.1m	Rail-mounted	57.2	572	655	1.15%
2	16.0t×16.0m	Rail-mounted	57.2	572	768	1.34%
3	20.0t×22.4m	Rail-mounted	83.83	838	962	1.15%
4	32.0t×28.7m	Rail-mounted	91.3	913	1092	1.2%
5	10.0t×20.0m	Stationary	51.65	517	382	0.74%
6	12.0t×16.3m	Rail-mounted	47.3	473	573	1.21%
7	10.0t×11.8m	Stationary	57.1	571	678	1.19%
8	10.0t×13.9m	Stationary	57.1	571	686	1.20%
9	2.5t×12.18m	Rail-mounted	28.291	283	325	1.15%
10	4.0t×11.84m	Stationary	31.3	313	425	1.36%
11	4.0t×13.4m	Stationary	36.8	368	495	1.35%
12	6.0t×13.98m	Stationary	40.5	405	536	1.32%
13	6.0t×18.0m	Rail-mounted	31.36	314	360	1.15%
14	8.0t×18.6m	Stationary	30.55	306	373	1.22%
15	8.0t×12.5m	Rail-mounted	47.14	471	585	1.24%
16	50.0t×19.9m	Rail-mounted	110	1100	1600	1.45%
17	16.0t×16.0m	Rail-mounted	51.7	517	730	1.41%
18	20.0t×30.0m	Stationary	115	1150	1700	1.48%
19	4.0t×10.0m	Stationary	37.2	372	480	1.29%
20	20.0t×22.4m	Climbing	32	320	395	1.23%

4. Theoretical calculation method of static displacement of the tower body corresponding to the static stiffness control value

The static displacement calculation methods include the traditional mechanics method or finite element methods. The calculation model of the traditional mechanics method can be divided into mechanics model of continuum pressed-bending member and lattice-type frame mechanics model. The first one is simple and practical, while the second one is more accurate but the calculation is more complicated.

4.1 Theoretical model for continuum pressed-bending

According to the mechanics model of continuum pressed-bending member shown in Fig. 2, it is possible to obtain the theoretical calculation value corresponding to the static displacement measurement value described in this paper. According to the measurement method described in this paper, the bending moment caused by the self-load of the tower crane under no-load and loaded conditions can be balanced theoretically. Besides, the wind load and other horizontal loads are not considered during measuring static displacement. Therefore, in the calculation model there are only vertical load *N* and the bending moment *M* caused by the hoisting weight; the differential equation of column bending is as below.

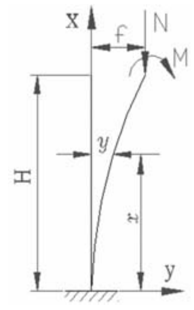

Fig. 2. Mechanical model of static displacement of the tower crane.

$$EIy'' = M + N(f - y) \tag{1}$$

Finding the solution of the above equation, we can obtain a precise calculation method of static displacement of the crane body top point:

$$f = \frac{M}{N}(\sec u - 1) \tag{2}$$

where

$$u = kH = \sqrt{\frac{N}{EI}}H \tag{3}$$

where N is all the vertical force above the hinge-connection point of the crane body and the jib under the rated load (including the converted force of the crane body at this place; the conversion method is referred to in attachment G of GB/T 13752 – 1992). M is bending moment caused by the hoisting load, M=QR (where Q is the rated hoisting load, and R is the working amplitude corresponding to Q).

The above equation can be also converted as follows. From the Euler critical load of the pressed column,

$$Ncr = \frac{\pi^2 EI}{(\mu H)^2} \tag{4}$$

For the cantilever pressed column:

$$\mu\text{=2, therefore } u = \frac{\pi}{2}\sqrt{\frac{N}{N_{cr}}} \tag{5}$$

Expand the triangle function sec u into power series

$$\sec u = 1 + \left(\frac{1}{2}\right)u^2 + \left(\frac{5}{24}\right)u^4 + \left(\frac{61}{720}\right)u^6 + \left(\frac{277}{8064}\right)u^8 + \cdots \tag{6}$$

Then Eq. (2) can be simplified into

$$\begin{aligned} f &= \frac{M}{N}[\frac{1}{2}\left(\frac{\pi}{2}\right)^2\frac{N}{N_{cr}} + \frac{5}{24}\left(\frac{\pi}{2}\right)^4\left(\frac{N}{N_{cr}}\right)^2 \\ &\quad + \frac{61}{720}\left(\frac{\pi}{2}\right)^6\left(\frac{N}{N_{cr}}\right)^3 + \frac{277}{8064}\left(\frac{\pi}{2}\right)^8\left(\frac{N}{N_{cr}}\right)^4 + \cdots] \\ &= \frac{MH^2}{2EI}\left(1 + 1.0281\frac{N}{N_{cr}} + 1.0316\left(\frac{N}{N_{cr}}\right)^2 \right. \\ &\quad \left. + 1.032\left(\frac{N}{N_{cr}}\right)^3 + \cdots\right) \end{aligned} \tag{7}$$

Defining the proximity value f as f_1,

$$f_1 \approx \frac{MH^2}{2EI}\left(\frac{1}{1 - N/N_{cr}}\right) = \frac{\Delta_M}{1 - N/N_{cr}} \tag{8}$$

where Δ_M is horizontal displacement of the connection place between the tower body and the jib caused by the bending moment M of the rated hoisting load to the centerline of the tower body

$$\Delta_M = \frac{MH^2}{2EI} \tag{9}$$

and $\frac{1}{1 - \frac{N}{N_{cr}}}$ is deflection amplification factor considering influence of axial force.

4.2 Finite element model

It is possible for the tower crane to be modeled by the finite element method. The finite element model is based on a simplification of the geometry of the tower crane structure. As a numerical method, the result from the finite element method is also approximate. The model of the tower crane is broken into many elements (as shown in Fig. 3). There are three types of elements in this model of tower crane: the beam, bar and beam-spar element. The bow pole is modeled by using beam element. The paunch pole and tensile pole are modeled by using rod element. Steel wire is modeled with the link element. Balance weight is modeled with mass element. The commercial finite element code ANSYS (ANSYS Inc., USA) was used to set up and solve the problem and to analyze the results.

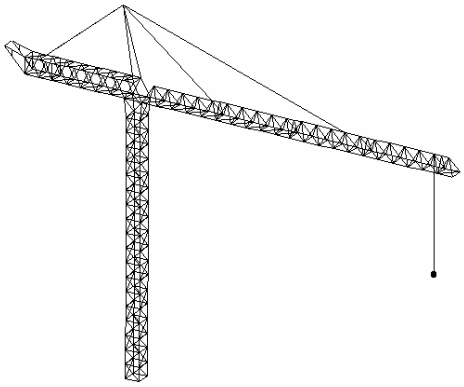

Fig. 3. Finite element model of tower crane.

The material property and load condition is the same as the above section. The dimension of the tower crane is also identical with that in the above formulations.

5. Comparison of various methods for calculation of static displacement with actually measured values

To understand the error value between different calculation methods and the accurate measure, the results of analytical expressions (2) and (8) are compared to the numerical results. Numerical analysis was carried out by software ANSYS. Meanwhile the compared experiment data is the static displacements of the first five types of the tower cranes.

Comparison of the obtained static displacement values of the three calculating methods f_1, f_2, f_3 (calculation values of finite element methods) with the actually measured values is shown in Table 2.

It can be seen from Table 2 that the error of the static displacement calculation values obtained from pressure-bending column mechanics model of the actual body according to Eqs. (2) and (8) is less than 12%. However, the error of finite element methods calculation values is less than 10%. The reason is that the pressure-bending column mechanics model of the continuum mainly considers the stiffness of the chord members and does not consider the web members and its arrangement. Meanwhile, the stiffness of the web members has a great influence on the stiffness of the tower body. There is almost no difference between the proximity calculation value f_1 and the precise value f calculated under a similar mechanics model, while the error does not exceed 1%. Therefore, when calculating the maximum static displacement of the tower body according to the mechanics model, it is reasonable to use Eq. (2) or Eq. (8).

The calculation method of the maximum horizontal static displacement value of the relative theoretic centerline of the tower body in actual work is referred to [12]. Besides vertical load, it is necessary to consider the bending moment caused by the self-weight and the lifting load. The wind load is distributed along the tower body, because the wind force, changing amplitude and rotation plays the role of brake, and the rotating centrifugal force causes concentrated horizontal force on the end part of the tower body.

Table 2. Comparison of maximum static displacement of the tower body f_1, f_2, f_3 and the actually measured values.

No.	Actually measured value $\triangle x$(mm)	f (mm)	$\lvert f-\triangle x\rvert /\triangle x$ (%)	f_1 (mm)	$\lvert f_1-\triangle x\rvert /\triangle x$ (%)	f_2 (mm)	$\lvert f_2-\triangle x\rvert /\triangle x$ (%)	$f\text{-}f_1/f$ (%)
1	655	724	10.5	720	9.9	691	5.5	0.55
2	768	811	5.6	807	5.1	741	3.5	0.49
3	962	1028	6.9	1022	6.2	927	3.6	0.58
4	1092	1026	6.0	1021	6.5	985	9.8	0.49
5	382	428	12.0	426	11.5	410	7.3	0.47

6. Conclusions

Based on the analysis of the static stiffness filed data collected from many tower cranes which are in good working condition, if the static stiffness control value is specified to be H/100 (as required in GB 3811-1983 “Design rules for cranes” and GB/T 13752–1992 “Design rules for tower cranes”) only 5% of the investigated tower cranes can meet this requirement. If the control value of $1.34H/100$ as suggested in this paper is used, 75% of the investigated tower cranes can meet this requirement.

The simplified formula proposed in this paper and the Finite Element method are used to calculate the static stiffness of several types of tower cranes. The results show that the finite element method is more accurate. However, the simplified formulas in Eq. (2) or Eq. (8) provide a simpler and easier approach. Future work is necessary to study the dynamic response of tower cranes induced by different kinds of payloads, such as the job of Ju [13] and Chin [14].

References

[1] A. Sagirli, M. E. Bococlu and V. E. Omurlu, Modeling the dynamics and kinematics of a telescopic rotary crane by the bond graph method: Part II, *Nonlinear Dynamics,* 33 (4) (2003) 353-367.

[2] D. A. Barrett and T. M. Hrudey, Investigation of hoist-induced dynamic loads on bridge crane structures, *Canadian Journal of Civil Engineering,* 23 (4) (1996) 926-939.

[3] D. E. Grierson, Optimal design of structural steel frameworks, *Computing Systems in Engineering,* 2 (4) (1991) 409-420.

[4] H. Z. Huang, W. D. Wu and C. S. Liu, A coordination method for fuzzy multi-objective optimization of system reliability, *Journal of Intelligent and Fuzzy Systems,* 16 (3) (2005) 213-220.

[5] H. Z. Huang, Z. G. Tian and M. J. Zuo, Intelligent interactive multiobjective optimization method and its application to reliability optimization, *IIE Transactions,* 37 (11) (2005) 983-993.

[6] H. Z. Huang, Z. G. Tian and M. J. Zuo, Multiobjective optimization of three-stage spur gear reduction units using interactive physical programming, *Journal of Mechanical Science and Technology,* 19 (5) (2005) 1080-1086.

[7] H. Z. Huang and H. B. Li, Perturbation fuzzy element of structural analysis based on variational principle, *Engineering Applications of Artificial Intelligence,* 18 (1) (2005) 83-91.

[8] H. Z. Huang, Y. H. Li and L. H. Xue, A comprehensive evaluation model for assessments of grinding machining quality, *Key Engineering Materials,* 291-292 (2005) 157-162.

[9] H. Z. Huang, Y. K. Gu and X. Du, An interactive fuzzy multi-objective optimization method for engineering design, *Engineering Applications of Artificial Intelligence,* 19 (5) (2006) 451-460.

[10] H. Z. Huang, P. Wang, M. J. Zuo, W. Wu and C. Liu, A fuzzy set based solution method for multiobjective optimal design problem of mechanical and structural systems using functional-link net, *Neural Computing & Applications,* 15 (3-4) (2006) 239-244.

[11] H. Z. Huang, Z. J. Liu and D. N. P. Murthy, Optimal reliability, warranty and price for new products, *IIE Transactions,* 39 (8) (2007) 819-827.

[12] L. Yu, J. Wang, J. Zheng and X. Wang, On the control to static stiffness of tower in tower crane, *Hoisting & Conveying Machinery,* 7 (2004) 1-4.

[13] F. Ju, Y. S. Choo and F. S. Cui, Dynamic response of tower crane induced by the pendulum motion of the payload, *International Journal of Solids and Structures,* 43 (3) (2006) 376-389.

[14] C. Chin, A. H. Nayfeh and E. Abdel-Rahman, Nonlinear dynamics on a boom crane, *Journal of Vibration and Control,* 7 (2) (2001) 199-220.