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Modeling and Analysis of Outrigger Reaction Forces of Hydraulic Mobile Crane

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ABSTRACT

This paper presents an original interactive analysis method consisting of mathematical calculation based on theoretical mechanics and mechanics of materials, and dynamics simulation for quantifying outrigger reaction forces of a kind of hydraulic mobile crane, aiming to avoid the eventualities during normal operation as far as possible, for example, tipping-over. First, a three dimensional dynamic model is established and the statically indeterminate problem of mechanics of materials is employed in the mathematical calculation. Then, the multi body dynamics simulation is investigated and the corresponding force-time curves are generated simultaneously. Finally, the validity of the proposed method is proven by comparing the amplitudes of the two kind of force-time plots upon the model. Thus, the bearing load of the crane can be limited to a feasible range for static stability or avoiding outriggers collapse.

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NOMENCLATURE

M_0	Mass of lifted load (kg)	F	Total equilibrium gravitational force of the lifting system (N)
M_1	Mass of chassis (kg)	M	Equilibrium moment to the rotation center (N·m)
M_2	Mass of counterweight (kg)	M_x	Equilibrium sub moment around X-axis (N·m)
M_3	Mass of boom (kg)	M_y	Equilibrium sub moment around Y-axis (N·m)
L	Length of boom (m)	l	The original length of each outrigger (m)
L_0	The distance between counterweight and working rotation center (m)	Δl	The deformation of the outriggers on vertical direction (m)
α	Lifting angle(°)	Δl_x	Amount of elastic deformation of each outrigger around X-axis (m)
$2a$	The outrigger symmetrical span to Y-axis (m)	Δl_y	Amount of elastic deformation of each outrigger around Y-axis (m)
$2b$	The outrigger symmetrical span to X-axis (m)	θ	The horizontal rotation angle in X-Y plane (°)
β	Rotation angle induced by M_x around X-axis (°)	g	The gravity acceleration (m/s^2)
ϕ	Rotation angle induced by M_y around Y-axis (°)	E	Modulus of elasticity of the outrigger material (N/m^2)
A	The cross-sectional area of the outrigger (m^2)		

1. INTRODUCTION

As a kind of large-tonnage construction machinery, hydraulic mobile cranes have been extensively applied in modern architectural industry. They could be used to help to construct residential buildings, build dykes and dams, erect temples and so on. While to assure the reliability of working, one of the requisites is that the outrigger reaction forces should swing in a moderate range, so that the cranes wouldn't breakdown or fail to operate. Recently, few investigations have focus on quantifying outrigger reaction forces, while other aspects of the manipulator have received considerable attention. In the case of control, a hydraulic forestry

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crane is taken as representative and a nonlinear model predictive control (NMPC) strategy is applied to accomplish the coordinated actions of a boom and a forest machine which are joined in a coordinated manner [1], while in a mobile hydraulic system including bound model uncertainties and external disturbances, a second order sliding mode control, namely a continuous control strategy is applied to achieve good performance and chattering attenuation for tracking problem in practical engineering [2]. In position control about a single-link hydraulic drive, main properties, nonlinearity of a valve and a pressure compensator are taken into account in the control approach, which is a discontinuous control law coupled with a static nonlinearity inversion and a feed-forward term of velocity [3]; in mobile hydraulic velocity control systems, a Time-Varying Gain Differentiator is used to find the first derivative of the position signal in the presence of noise to design better control laws [4].

In terms of dynamic responses, the transverse and longitudinal vibrations of the top beam about a kind of land crane are conducted via finite element and mathematical analytical method [5], and the factors of speed, acceleration, suspension characteristics and structural damping of the moving body are studied in the method. Meanwhile, the heavy load that is suspended by floating crane which works on the seawater is also investigated by means of dynamics analysis method, in which a multibody system consisting of different parts connected phisically by joints and wire ropes is discussed [6, 7]. Besides, the dynamics analysis method is so practical that it has also been used in other fields, such as in treating industrial wastewater in a full scale activated sludge system [8], in evaluating the influence of sudden column loss on the structural response of steel moment frames under blast loading [9] and assessing the liquid sloshing effect on the articulated vehicle under the condition of filling various volumes to eliminate the liquid sloshing effect [10, 11], or to investigate the effects of gas pressure drop on free piston stirling engine by extracting the pistons' dynamic equations and pressure equations to evaluate effects of gas pressure drop in heat exchangers in certain cases [12], to make up for the shortage of experiment due to the absence of experimental installation or testing area under present conditions.

In fact, force evaluation is as important as other analysis aspects of a crane. But previous researchers seem inclined to analysis other parts of the crane instead of outrigger force calculation for bracket safety. Savkovic et al. [13] found that the local stress increases at the contact zone between inner and outer segments of the telescopic boom of a truck crane. The earthquake response of a crane bridge was investigated by experimental and numerical studies in another work [14]. The job stress and the effect of operator and workplace characteristics on job stress of electric overhead travelling crane operators are quantified under different factors, such as, role overload for job stress, body weight and body height for studying characteristics of the operators, hours of exposure and cabin feature for considering the workplace characteristics [15]. Several Chinese researchers have used FEA numerical method to study the overall stability of flexible giant crane booms [16], and even the statics and dynamics computational analysis of forest cranes are conducted except for the outrigger reaction forces [17]. So, this indirectly indicates that the study of outrigger reaction forces calculation is few but is necessary to be taken into consideration as job security and veracity are chief issues in actual engineering [18]. Although there is few studies on computing outrigger reaction forces, in a process of force calculation, when a mobile crane keeps level with the supporting of four outriggers, an evaluating method, linear programming is presented, and the minimum/maximum pruning approach is adopted, simultaneously, to increase the computational efficiency [19].

2. MODEL OF A HYDRAULIC MOBILE CRANE

The entity model of a hydraulic mobile crane is shown in Figure 1, and a three dimensional dynamic model for the simulation of boom elementary rotation and force analysis is shown in Figure 2.

The routes of the solution to this problem are listed as follows: first, the forces of each part are moved to the barycentre of this lifting system to get the total equivalent equilibrium gravitational force and total equivalent equilibrium moment; second, the reaction force of each outrigger is obtained via force and moment equilibrium equation sets of theoretical mechanics, and the deformation equations of each outrigger are extracted besed on Hooke's law, when the boom rotates to different positions in horizontal direction as the lifting angle is restricted to the rotation radius in steady operation; third, as this problem is concerned statically indeterminate, thus, a compatibility equation of the deformation about one of the four outriggers is derived to solve the target forces.

Figure 1. Entity model of a hydraulic mobile crane

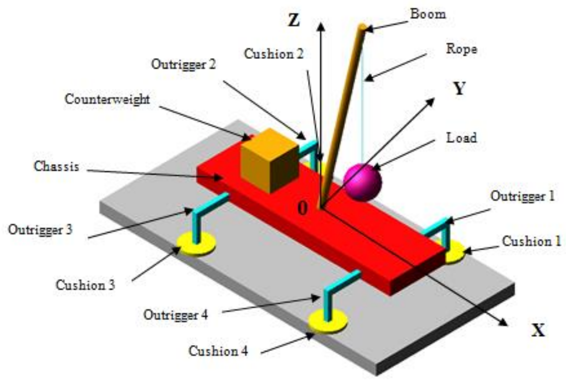

Figure 2. Dynamic model of a hydraulic mobile crane

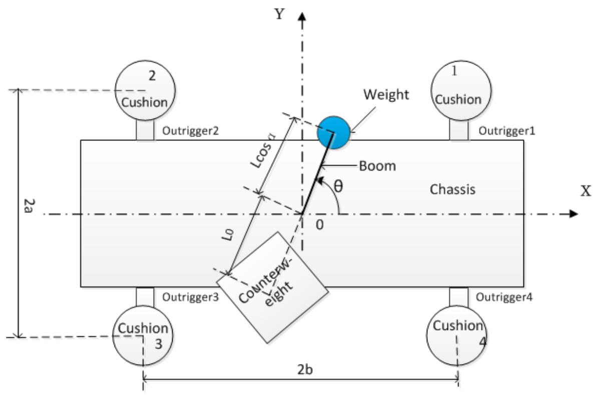

Figure 4. Top view of the dynamic model

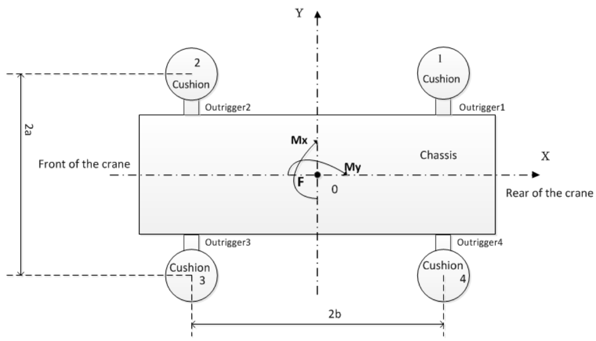

Figure 5. Equivalent resultant force and the sub moment around the X- and Y-axis, respectively

3. MATHEMATICAL CALCULATION OF THE OUTRIGGER REACTION FORCES

Assuming the crane is set horizontally on plate ground surface, it is completely axisymmetric in this paper. A space rectangular coordinate with X-, Y- and Z-axis is setup at the intersection with a rotation center O as shown in Figure 2. When the crane works, the four outriggers should stretch to the ground to prop up the whole crane so that all the tires are suspended, and the entire forces of the lifting system are completely distributed to the four outriggers. To ensure normal operation and aviod collapse of the outriggers and instability of the crane, the four outriggers should be in elasticity deformation when the weight is loaded to the rope, so the deformation equation of each outrigger follows Hooke's law. In order to assist the mathematical calculation process, a group of simplified two dimensional models in different views and conditions are built up as shown below in Figures 3 –9.

According to Figures 3-5, the working balance state can be established on force and moment equivalent equilibrium equation sets by knowledge of theoretical mechanics:

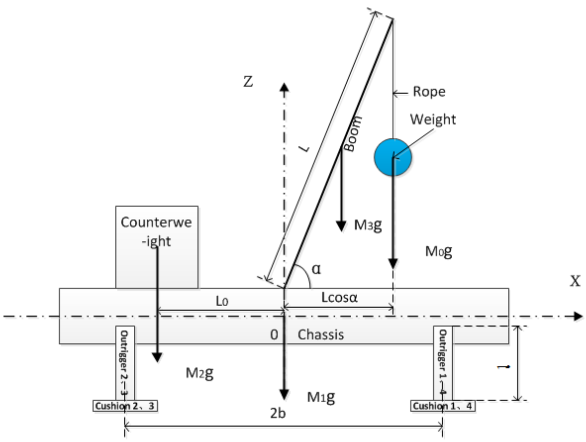

Figure 3. Main view of the dynamic model

$$\begin{bmatrix} F \\ M \end{bmatrix} = g \begin{bmatrix} 1 & 1 & 1 & 1 \\ L\cos\alpha & 0 & -L_0 & \frac{1}{2}L\cos\alpha \end{bmatrix} \begin{bmatrix} M_0 \\ M_1 \\ M_2 \\ M_3 \end{bmatrix} \tag{1}$$

while in this situation, the rotation radius is $L \cdot \cos\alpha = 3$ m.

Then seeing from Figures 4 and 5, the sub moments can be expressed as:

$$\begin{bmatrix} M_x \\ M_y \end{bmatrix} = M \begin{bmatrix} \sin\theta \\ \cos\theta \end{bmatrix} \tag{2}$$

where $\theta = (\pi/6)\cdot t$ is the horizontal rotation angle of the boom with the same initial direction of X-axis.

The following deformation calculation of the outriggers are based on the continuity hypothesis, homogeneity assumption and isotropy assumption of mechanics of materials. And the outrigger reaction forces should be solved with supplementation of deformation compatibility equation about one of the outriggers as this is a statically indeterminate problem [19, 20].

When the total equivalent equilibrium gravitational force is imposed to the barycentre of the crane, the four outriggers will be compressed simultaneously, that is to say, the deformation quantities of each outrigger are the same.Then Δl of the outriggers' deformation on vertical direction caused by F, as shown in Figure 6, is:

$$\Delta l = \frac{1}{4} \cdot \frac{F \cdot l}{AE} \tag{3}$$

As all the forces are bore by the four outriggers, the chassis is assumed to be no bending and no twisting deformation, so the tiny rotational angle β around X-axis related to each outrigger's elastic deformation Δl_x induced by M_x as shown in Figure 7 can be derived as:

$$\begin{cases} \Delta l_x = \beta a \\ \beta a = \dfrac{\frac{M_x}{4a} \cdot l}{AE} \end{cases} \tag{4}$$

while in this situation, two outriggers in the left are stretched and the others are compressed, and the deformations in each side are the same, so there are four identical deformations to resist M_x.

Again, the tiny rotational angle ϕ around Y-axis coincided with Δl_y caused by My as shown in Figure 8 is:

$$\begin{cases} \Delta l_y = \phi b \\ \phi b = \dfrac{\frac{M_y}{4b} \cdot l}{AE} \end{cases} \tag{5}$$

Taking F_1, F_2, F_3, F_4 as representative of the reaction forces of outrigger 1, 2, 3, 4, respectively.

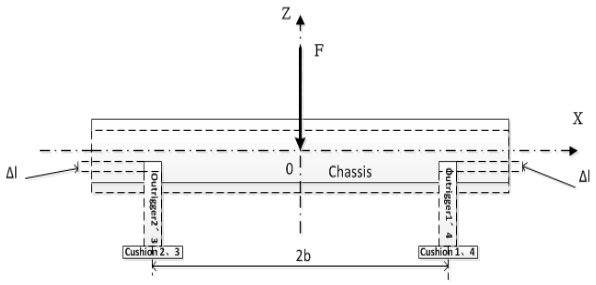

Figure 6. Outrigger deformation caused by F

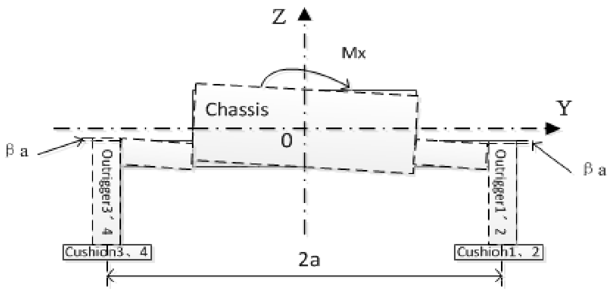

Figure 7. Outrigger deformation caused by M_x

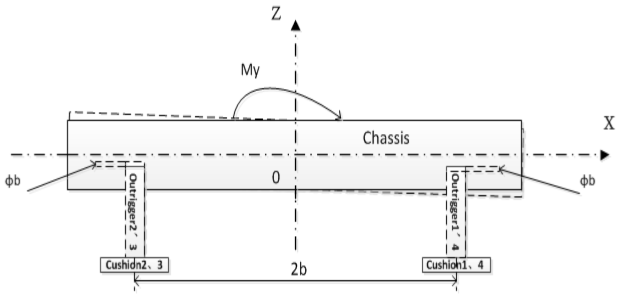

Figure 8. Outrigger deformation caused by M_y

Taking into consideration of force and moment balance of the hoisting system, the equivalent force and moment equilibrium equation sets are:

$$\begin{bmatrix} F \\ M_x \\ M_y \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ a & a & -a & -a \\ b & -b & -b & b \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} \tag{6}$$

Taking outrigger 1 into concrete analysis, the total equivalent equilibrium deformation can be indicated in Figure 9, and the deformation compatibility equation in this statically indeterminate problem is:

$$\Delta l_1 = \Delta l + \Delta l_x + \Delta l_y \tag{7}$$

while Δl_1 is the eventual deformation of outrigger 1 resulted from vertical downward force and the reaction force F_1. Then:

$$\Delta l_1 = \frac{F_1 \cdot l}{AE} \tag{8}$$

Incorporating Equation (3)-(5) with Equation (7), (8) into the following equivalent form:

$$\frac{F_1 \cdot l}{AE} = \frac{1}{4} \cdot \frac{F \cdot l}{AE} + \frac{M_x \cdot l}{4a \cdot AE} + \frac{M_y \cdot l}{4b \cdot AE} \tag{9}$$

This equation can be rewritten as:

$$F_1 = \frac{F}{4} + \frac{M_x}{4a} + \frac{M_y}{4b} \tag{10}$$

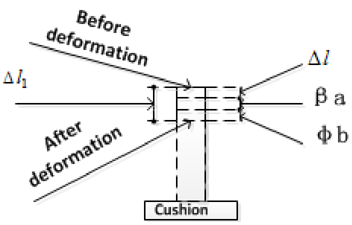

Figure 9. Equivalent equilibrium deformation about outrigger 1

Combining Equation (10) with Equation set (6), the four outrigger reaction forces can be extracted as :

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} = \frac{1}{4} \cdot \begin{bmatrix} 1 & \frac{1}{a} & \frac{1}{b} \\ 1 & \frac{1}{a} & -\frac{1}{b} \\ 1 & -\frac{1}{a} & -\frac{1}{b} \\ 1 & -\frac{1}{a} & \frac{1}{b} \end{bmatrix} \begin{bmatrix} F \\ M_x \\ M_y \end{bmatrix} \tag{11}$$

So the calculation force-time curves can be extracted using Equations (1), (2), and (11) with canditate parameters in Table 1 as shown in Figure 8.

4. DYNAMICS SIMULATION AND RESULTS COMPARISON

In this method, mutual authentication is provided between ADAMS dynamics calculation and the mathematicals of the outrigger reaction forces. As ADAMS is a kind of poweful software in the field of mechanical engineering, it could be used to simulate vehicle ride and handing performance [21], to study the adaptive navigation behaviour about a multiple degree of freedom biomorphic machine driven by an analogue neuronal network [22], and to define the generalized coordinates and loads in the parallel kinematic structure for envelope convex surface in designing parallel kinematic systems [23]. Besides, it also can be applied in automotive industry. For example, it could be adopted to construct and simulate a tracked vehicle model parametrized and performing other subsequent relevant analysis [24].

The 3D dynamic model shown in Figure 2 is established in ADAMS with relevant parameters as shown in Table 1. The simulation is conducted with proper constraints. In the simulation, rotation speed of the boom is set as π/6 rad/s, while the execution time is set as 12 seconds. The simulation results are represented with different force-time curves [25].

Considering the calculation results and the simulations comprehensively, the contrast curves of the two kinds of results are shown in Figure 10. The horizontal ordinate represents execution time (s), while the vertical ordinate expresses numerical value of the reaction forces (N). The simulation curves are marked by different Arabic numerals while the calculation curves are signed with different colors. Seeing from the contrast curves, the mathematical results are in coincident with the simulation results.

TABLE 1. Candidate parameters of a crane

Parameter	Value	Unit
2a	8.50	m
2b	9.50	m
L	13.5	m
L_0	3.75	m
M_0	158	t
M_1	42	t
M_2	72	t
M_3	17	t

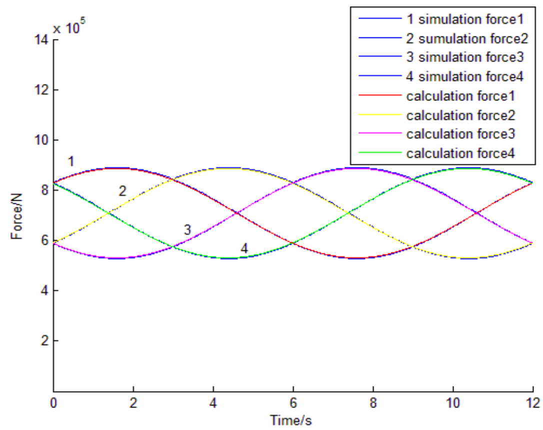

Figure 10. Comparison of mathematical calculation results and dynamics simulations

5. CONCLUSIONS

In this paper, a method which combines mathematical calculation and dynamics simulation is investigated to assess the outrigger reaction forces of a hydraulic mobile crane. A serial two dimensional physical model in different views is established to assist calculating the outrigger reaction forces while a three dimensional dynamic model is put forward for dynamics simulation. The principles of force equivalent equilibrium and compatibility of deformation are employed in this work. The good coincidence of the calculation force-time curves and the simulations proves that this method is theoretically reasonable and could provide referential significance in experiment and actual engineering to prevent the crane from lifting overweight.

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چکیده

این مقاله یک روش تحلیلی تعاملی ارائه می دهد که متشکل از محاسبه ریاضی بر اساس مکانیک نظری و مکانیک مواد و شبیه سازی دینامیک برای اندازه گیری نیروهای واکنش بیرونی نوعی جرثقیل هیدرولیک متحرک است که هدف آن اجتناب از احتمالات در عملیات عادی است. اول، یک مدل پویای سه بعدی ایجاد شده است و سپس یک مساله نامعلوم مکانیک مواد در محاسبه ریاضی استفاده می شود. سپس، شبیه سازی دینامیک چند جسم مورد بررسی قرار می گیرد و منحنی های نیروی زمان مربوطه به طور همزمان تولید می شوند. در نهایت، اعتبار روش پیشنهادی با مقایسه دامنه های دو نوع نمودار توزیع نیرو- زمان، اثبات شده است. بنابراین، بار جرثقیل می تواند به یک محدوده قابل اجرا برای ثبات استاتیک محدود شود یا از سقوط بار جلوگیری شود.

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