Estimation of Maximum Lifting Load Capacities of a Hydraulic Excavator via Multibody Computer Modeling and Simulation

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A three dimensional multibody modeling of a hydraulic excavator is developed to estimate the load capacities via computer simulation. For the modeling of the operating parts, 16 bodies are connected by the several kinematic joints with 4 dof(degrees of freedom). And 5 bodies are connected by joints with 6 dof in the modeling of supporting and carrier parts. There are total 22 bodies in the multibody excavator DADS model including the ground, and the system has 11 dof including the rotation about the swing axis. To model the force interaction between the track and the ground, two experimental results are measured and utilized to estimate the stiffness of the spring. A four-step algorithm is developed to estimate the spring constant combining the force and moment equilibrium equations with the experimental results. Using the estimated spring stiffness, the maximum lifting load capacities of a crawler type excavator in various positions are calculated. The calculated results are in a good agreement to the experimental results before the turnover occurs and are acceptable for the design data.

Key Words: Multibody Modeling, Computer Simulation, Hydraulic excavator, Load Capacity

1. Introduction

In a multibody system, several bodies are connected with each other by kinematic joints. Since the equations of motion of a multibody system are too complicated to solve, a well developed computer program is necessary to analyze multibody dynamic systems. The DADS and the ADAMS (1994) are well known programs for multibody dynamics.

An excavator is a main equipment to dig and smooth the ground in the construction fields. Two different types of excavator, a wheel and a crawler type, are currently used. The wheel type excavator is useful to move the working place with its own mobility, but the machine power and operating capacity are rather small. The crawler type, is becoming widespread because of the large capacity and efficiency of the operation.

Although the ride quality is important to operators, the operational safety is the most critical facter in the design stage because of severe operating circumstances. Among the various safety requirements, rollover due to unexpected forces is crucial to the safety.

The estimation of the maximum lifting load capacity of an excavator is very useful for a designer to calculate the safety factor in the design stage, but the experiment on a critical case is often impossible to implement. Thus the estimation of the critical forces by computer simulation is , if possible, very powerful for this kind of analysis.

In this paper, a three dimensional multibody

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modeling of a hydraulic excavator is developed to carry out dynamic simulations using the DADS program. To model the force interaction between the track and ground, a four-step algorithm is developed to estimate the spring constant from the experimental measurements. The maximum lifting load capacities of a crawler type excavator in various positions are calculated with the estimated spring stiffness.

2. Multibody Modeling of a Crawler Type Excavator

2.1 DADS modeling of an excavator

The configuration of a crawler type excavator is shown in Fig. 1. The model consists of a boom, an arm, a bucket, an arm cylinder, a bucket cylinder , two yokes, two connecting rods, and two boom cylinders. All cylinders are composed of two separate bodies allowing one relative translational degree of freedom between two bodies.

The upper frame containing the engine, the counter weight, the pump, the motor, the valves and accessories is modeled as one body. In the lower frame of the crawler type excavator, two sprockets, two idlers, and two tracks may be modeled as separate bodies for analysis. The hydraulic motor locks the sprockets when the excavator is in operation, however, the lower frame including all the mobility parts can be considered as one body. The lower frame supports the whole weight of the excavator by the forces through the ground. Including the ground, there are 22 bodies in the three dimensional multibody computer model.

The upper frame can rotate about the swing axis named as RJ1 (the first revolute joint) in the Fig. 1. Since each cylinder has one relative translational degree of freedom, four cylinders have four degrees of freedom in the operating part. Including the six degrees of freedom in the lower frame, the system has 11 degrees of freedom.

2.2 Modeling of kinematic joints

In the three dimensional modeling of the excavator, it is somewhat complicated to choose the kinematic joints properly without redundant kinematic constraints. The joints between the upper frame and boom are chosen to make the relative dof(degrees of freedom) zero when two driving constraint equations of the boom are imposed. In the connecting linkages between the bucket and the arm, joints are selected to make the relative dof zero when one driving constraint of the bucket is imposed. The properly chosen kinematic joints are listed in the Fig. 1.

2.3 Modeling of under frame

The structure of the under frame is shown in Fig. 2. The under frame consists of main frame, 2

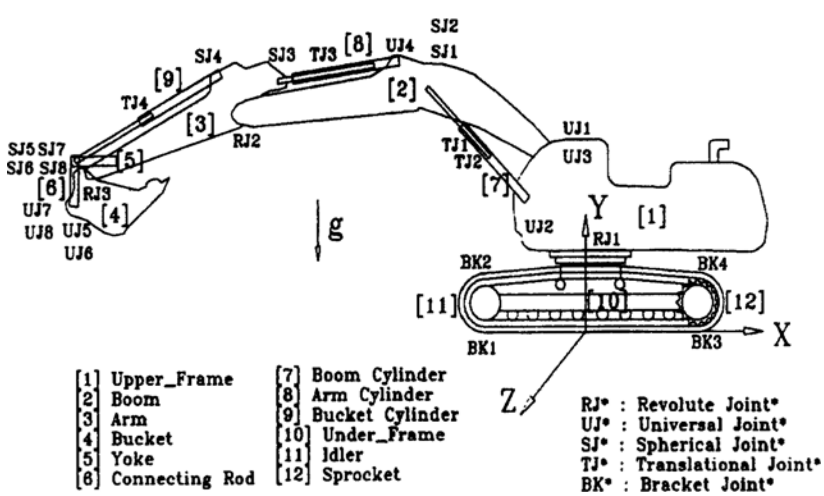


Fig. 1 Multibody modeling of a crawler type excavator.

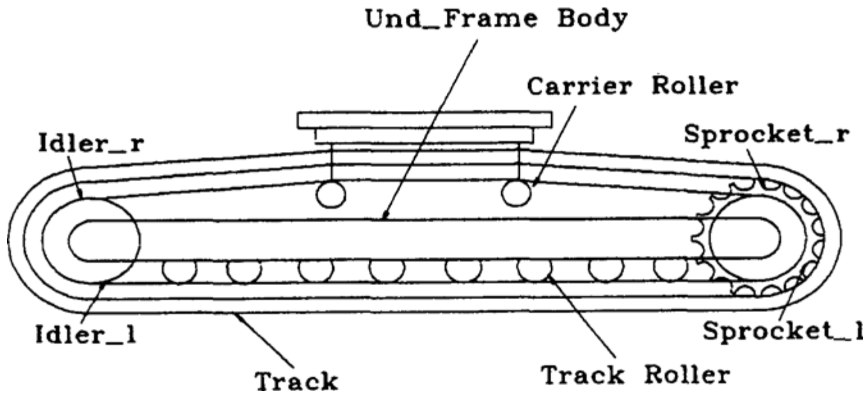


Fig. 2 Structure of the under frame.

sprockets, 2 idlers, 16 track rollers, and 4 carrier rollers. Sprockets and idlers are connected with the main frame by revolute joints, and track rollers are rolling over the track arranged by the track shoes. The ground forces are mainly transmitted to the main frame through these track rollers.

In the DADS modeling, main frame of the under frame, left and right sprockets, left and right idlers are treated as separate bodies, and sprockets and idlers are connected with the main frame by revolute joints. For the stability analysis, carrier roller and track rollers, and track are assumed to be rigidly attached to the main frame and treated as one body.

3. Force Interaction Between the Ground and Track Rollers

3.1 Modeling of contact forces

During the weight lifting, operation, we assume the weight is lifted very slowly. Thus, the state can be treated as a quasi-static, and the transient dynamic effect can be neglected. To represent the force transmission from the ground to under frame, TSDA (Translational Spring Damper and Actuators) elements are used between the ground and under frame. For the stability analysis, 8 TSDA elements are used in each track roller position. Two additional TSDA elements are defined for the sprocket and idler positions, which is shown in Fig. 3.

3.2 Spring stiffness obtained from experimental data

In terramechanics, load-sinkage relationship between the track and ground can be represented by the following formula (Bekker, 1969 ; Wong, 1978).

$$F=\left(\frac{k_e}{b}+k_\varphi\right)z^n \tag{1}$$

where z, b, k_e and k_φ represent ground sinkage, width of the rectangular plate, cohesive modulus of deformation, and frictional modulus of deformation, respectively. At least two experiments should be performed with different width plates to determine k_e, k_φ and n. Moreover, this method is difficult to apply to the excavator operating on concrete ground.

In this paper, the force interaction between the ground and under frame is determined by different experiments, which is quite different from the conventional methods. At first, the initial deformation of the springs are determined by the lifting weight (Wt) and elevation of the track shoes.

From the configuration shown in Fig. 4, the following lifting weight and elevation relationship are obtained. Since the track is linked with several track shoes, the track will deflect due to its own weight when the sprocket is lifted. Therefore, the contact force on the track roller near the idler is still exerting when the sprocket is lifted slightly.

(1) When the lifting weight W_t becomes 3.38 tons, the track shoe just below the sprocket starts to lift the ground.

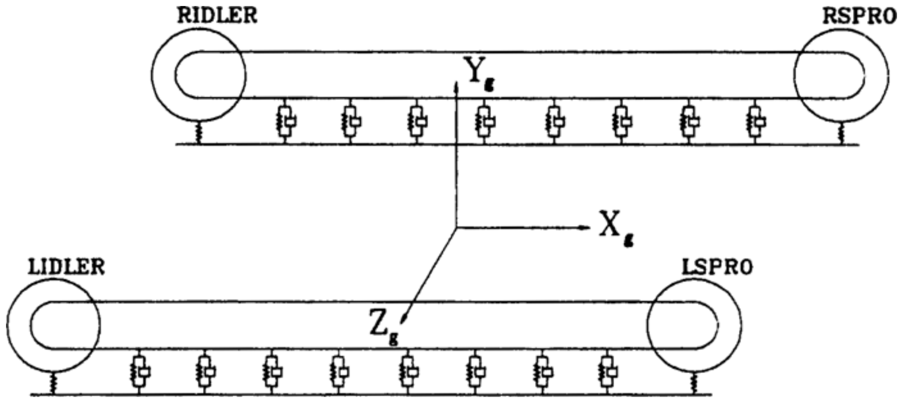


Fig. 3 TSDA modeling between the under frame and ground.

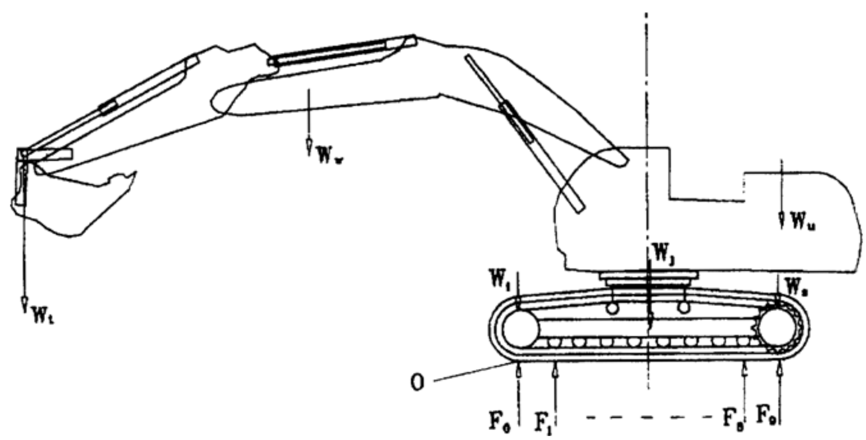


Fig. 4 Configuration of the front job full-reach position.

(2) When the lifting weight W_t becomes 5.70 tons, the track shoe just below the sprocket is lifted 70mm from the ground.

With the above two results, the spring stiffness k and the exponent n in the equation $F=kz^n$ are calculated with the following four step algorithm.

Step 1 : Formulate the equilibrium equations for vertical direction force and moment

$$F_0+F_1+F_2+\cdots+F_9 = W_t+W_W+W_u+W_l+W_s+W_i \quad (2)$$

where W_t, W_W, W_u, W_l, W_S, and W_i represent the lifting weight, the weight of the working part, the weight of the upper frame, the weight of the lower frame, the weight of the sprocket, the weight of the idler respectively. The forces F_1, $\cdots$, F_8 represent forces acting on the track rollers, and F_0 and F_9 represent forces acting on the idler and sprocket.

The equation of moment about the point O (center of the idler) becomes

$$F_1l_1+\cdots+F_9l_9 = W_tl_t+W_Wl_W+W_ul_u+W_ll_l+W_sl_s \quad (3)$$

where l_t, l_W, l_u, l_l, l_S, l_i represent the moment arm of the weight measured from the point O, and l_1, l_2, $\cdots$, l_8 represent the distance to the each track roller measured from the point O, and l_9 is the distance to the sprocket.

Step 2 : Assume force distributions

Since we just have 2 equations to determine 10 unknowns(F_0, $\cdots$, F_9) in the Eqs. (2) and (3), 10 unknown forces can not be determined directly.

Thus, the force-deflection relationship is assumed to be $F=kz^n$. In addition, the under frame is so stiff that the spring deformations (z_0, $\cdots$, z_9) attached to the track roller are assumed to be linear ($n=1$). Then, the RHS terms with zero lifting weight ($W_t=0$) are calculated as ;

$$F_0+F_1+F_2+\cdots+F_9=31936 \quad (4)$$

$$F_1 l_1+\cdots+F_9 l_9=56031 \quad (5)$$

From the assumption that the force distribution is linear, forces F_1, $\cdots$, F_8 can be represented with F_0 and F_9.

$$F_i=F_0-\frac{l_i}{l_9}(F_0-F_9)=K_{1i}F_0+K_{2i}F_9,$$

$$i=1, 2, \cdots, 8 \quad (6)$$

Values of K_{1i} and K_{2i} are given in Table 1.

Table 1 Values of K_{1i} and K_{2i}.

i \ K_i	K_{1i}	K_{2i}
1	0.8806	0.1194
2	0.7761	0.2239
3	0.6704	0.3296
4	0.5622	0.4378
5	0.4527	0.5473
6	0.3445	0.6555
7	0.2388	0.7612
8	0.1343	0.8657

Substituting Eq. (6) into the Eqs. (4) and (5), forces F_0, $\cdots$, F_9 are calculated. At this point, the calculated forces satisfy the equilibrium equations.

Step 3 : Apply the first weight-elevation relation

Check the first weight-elevation relationship between the calculated forces. The first relationship says that the sprocket is just lifted when the lifting weight is 3. 38 tons. Assigning the force F_9 and the lifting weight W_t to be zero and 3.38 tons respectively, calculate the RHS of the Eqs. (2) and (3).

$$F_0+F_1+F_2+\cdots+F_8=35316 \quad (7)$$

$$F_1 l_1+\cdots+F_8 l_8=31391 \quad (8)$$

Assuming the force relation to be linear, forces F_1, $\cdots$, F_8 can be represented with F_0.

$$P_i=F_0\left(1-\frac{l_i}{l_9}\right)=K_{1i}F_0,\ i=1, 2, \cdots, 1, 2 \quad (9)$$

Value of K_{1i} is given in Table 1.

If the calculated forces satisfy the first lifting weight-elevation condition, then move to the step 4. If the calculated forces do not satisfy the first lifting weight-elevation condition, the assumption that force distribution is linear is not correct. Thus, move to the step 2 and try again with another force relation, i.e., quadratic ($n=2$). When the forces with $n=2$ do not satisfy the first lifting weight-elevation condition, try with other value for n, i. e., $n=3$ or $n=0.5$. With a trial and error method, select an exponent satisfying both the equilibrium equation and the first force-elevation relation.

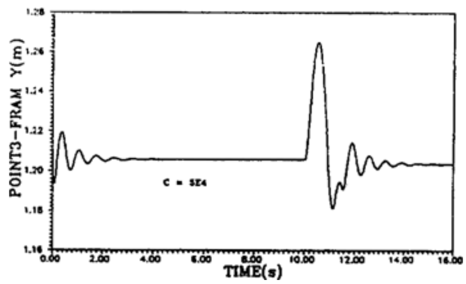
Step 4 : Apply the second weight-elevation relation

Apply the second weight-elevation relation, which tells that the sprocket is lifted 70mm when the lifting weight reaches 5.70 tons. With this condition, it is possible to determine the number of track rollers which are off the ground. With the exponent n value determined in step 3, check the relation assigning the force F_8 to zero. If it is not satisfied, then try with $F_9=F_8=F_7=0$. Proceed this process until the second force-elevation relation is satisfied.

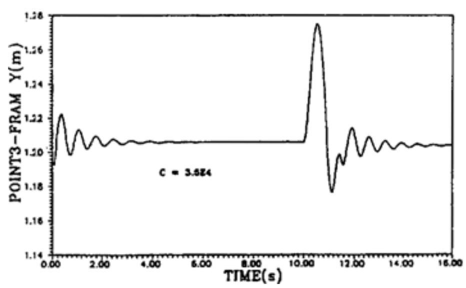
When the fourth step is completed, selected stiffness k and exponent n satisfy the equilibrium equations and two weight-elevation results. The final values obtained from the final step are as follows: the stiffness $k=737145$ N/m, and the exponent $n=0.92$. Using this force-deflection relation to TSDA, the multibody DADS modeling of the excavator is generated.

3.2 Damping coefficient from dynamic response

The damping coefficient c of the TSDA element between the ground and track roller is also deter-



(a) $c=5.0\times10^4$



(b) $c=3.5\times10^4$

Fig. 5 Dynamic responses from DADS simulation with different damping coefficients.

mined by utilizing the experimental result. The test is carried out for the excavator to move abruptly from the horizontal position to the maximum height position within 1.5 seconds. The number of piching oscillation measured at the bottom point of the counterweight is 9 and it lasts about 6 seconds, and the maximum amount of the pitching is up to 50 mm.

The damping coefficient data is obtained from the computer simulation which gives the same dynamic response from the experiment. Several simulations using the spring stiffness obtained at the previous section are carried out to get a proper damping coefficient which shows the similar pitching motion to the identical dynamic test. In Fig. 5, two typical responses obtained from the DADS simulation with different damping coefficients are shown. Since the response with damping coefficient $c=3.5\times10^4$ is well matched to the experimental result, that value is chosen as the damping coefficient.

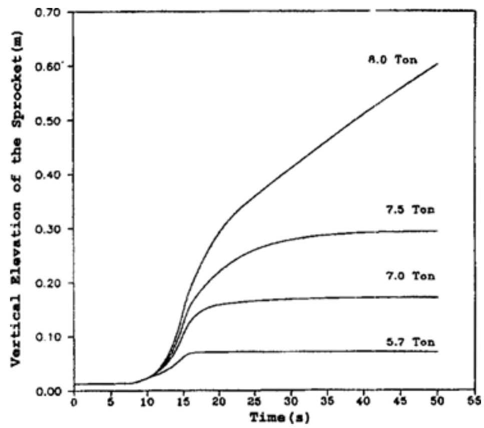


Fig. 6 Maximum lifting force in full-reach position (front job).

4. Estimation of Maximum Lifting Forces

With the developed DADS modeling of the crawler-type excavator, two simulations are carried out to estimate the maximum lifting forces in the front job position.

4.1 Front job full-reach position

To measure the maximum lifting forces in the full-reach position, which is shown in the Fig. 2, the lifting weight is increased from the 5. 70 tons. As the lifting weight increases, the elevation of the sprocket obtained from the DADS simulation is represented in the Fig. 6. As shown in the Figure, the sprocket elevates 170mm above the ground with 7.00 ton of lifting weight, and 300mm elevation with 7.50 ton of lifting weight. However, the lifting weight 8.00 tons may cause the excavator to roll over the ground.

4.2 Front job medium-reach position

To measure the maximum lifting forces in the medium-reach position which the distance between the swing center and the lifting weight is 4940mm, the lifting weight is increased from the 5. 70 tons. As the lifting weight increases, the elevation of the sprocket obtained from the DADS simulation is shown in the Fig. 7. As shown in the Figure, the sprocket elevates 18mm above the ground with 8.00 ton of lifting weight, and

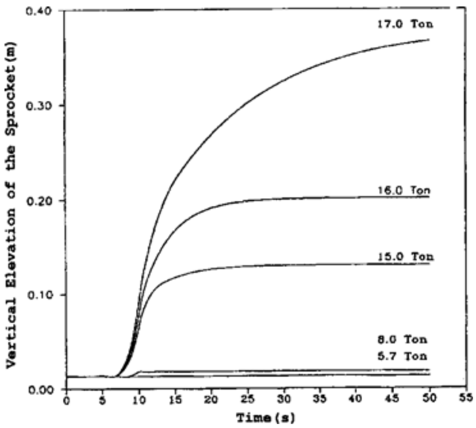


Fig. 7 Maximum lifting force in medium-reach position (front job).

130mm elevation with 15.00 tons of lifting weight. These results are compared with those of the experiments, and they are in a good agreement.

However, the lifting weight above the 15.00 tons was not implemented for the safety of the operator. Simulations over the 15.00 tons of lifting weight were carried out to estimate the maximum lifting force maintaining the stable position. As shown in the Fig. 7, the sprocket elevates 200mm above the ground with 16.00 ton of lifting weight, and 17.00 tons may cause the excavator to roll over the ground.

5. Conclusions

The estimation of the maximum lifting load capacity of an excavator is suggested from the computer simulation. To obtain the computational results, a three dimensional multibody modeling of a hydraulic excavator is developed. The model consisting of 22 bodies with 11 degrees of freedom is developed.

To model the force interaction between the under frame and ground, two experimental results are measured and utilized to estimate the stiffness of the spring. Then, a four-step algorithm, which combines the force and moment equilibrium equations with the experimental results, is developed to estimate the spring constant.

Using the calculated spring constant, the maximum lifting load capacities of a crawler type excavator in various positions are calculated. The calculated results are in a good agreement with the experimental ones and are useful for the design purposes.

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