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Research Article

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Simulation and optimization of hydraulic excavator's working device based on MATLAB

[1,2]Gui Ju-Zhang, [2]Cai Yuan-Xiao*, [1]Qing-Tan and [3]You Yu-Mo

[1]College of Mechanical and Electrical Engineering, Central South University, Changsha, Hunan, China
[2]Department of Mechanical and Energy Engineering, Shaoyang University, Shaoyang, Hunan, China
[3]Hydraulic Technology Institute of Guangxi Yuchai Heavy Industry Co., LTD, Yulin, Guangxi, China

ABSTRACT

The kinematic and dynamic analysis of hydraulic excavator's working device was carried out in this paper by using the De-navit-Hartenberg homogeneous transformed matrix. And then we worked out the optimization results of comprehensive characteristics for kinematic and dynamics based on using the max digging power as the aim of optimization. It established the theoretic foundation for further study in order to realize the hydraulic excavator's automatic control. Finally take the type of YC225LC-8 hydraulic backhoe excavator for example, simulation and optimization analysis of it's comprehensive characteristics. The research results showed that the method of C + + Builder and MATLAB mixed programming is make full use of MATLAB powerful scientific computing, as well as C + + Builder powerful interface development function. And the program development process is simple, high process efficiency and has reliable optimization results. It can find solid theoretical calculation foundation for further research on mining automatic. And it own the value of engineering application.

Keywords: hydraulic excavator; working device; boom; MATLAB

INTRODUCTION

For its high efficiency and multifunction, hydraulic excavator is widely used in mines, road and railway building, water conservancy, civil and military construction and hazardous waste cleanup areas． In the design process of hydraulic excavator, the working device's design is one of the most important contexts. Especially, the boom is the main load-bearing component in an excavator, its stiffness directly influence the working efficiency and service life of an excavator. [1]

In the traditional strength calculation of hydraulic excavator's boom, we usually use the material mechanics method, the boom is assumed to be a beam, and then calculate the bending strength of various cross sections. However, because the actual boom structure is far different from the ideal beam structure and stress is very complex, so that the errors will be apparentlylargeaccording to beam assumption and can not reflect the deformation and stress of the whole structuredistribution.[2] In practice, the excavator produced by traditional design method is often failurewhen in use.

Thus, it is necessary to analyze the kinematic and dynamic characteristics for hydraulic excavator's boom. In this paper, we have simulated and optimized the boom structure by using C + + Builder and MATLAB software. From the view of De-navit-Hartenberghomogeneous transformed matrix, we established the kinematic and dynamic function. We also build the 3D model of boom by UG, and then successfullyimported it into simulating software MATLAB to find out whether the boom structure is reasonable.

THE KINEMATIC AND DYNAMICANALYSIS OF HYDRAULIC EXCAVATOR'S WORKING DEVICE.

The kinematic analysis of robotized motion for hydraulic excavator: As shown in Fig.1. The operation of the hydraulic excavator's working equipment is very similar to the stock-taking robot [3]. It's a kind of multi-rod system with four degrees of freedomrespectively as:the revolute pair of rotary device around substrate base, the revolute pair of boom relative to rotarydevice, therevolute pair of bucket rod around the end of the boom and the revolute pair of bucket around the end of bucket rod.

For hydraulic excavator robot,given the base coordinate system $L_0(x_0, y_0, z_0)$ and rotating coordinate system $L_i(x_i, y_i, z_i)$ (i = 1, 2, 3), it uses theDenavit-Hartenberghomogeneous.

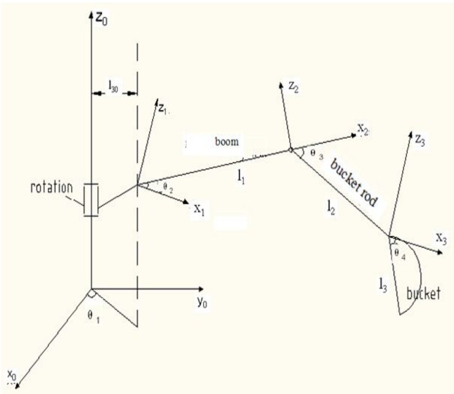

Fig.1: The coordinate system of working equipment robotics

homogeneous transformation matrix to carry out kinematic analysis for excavator . The bars l_i and brackets L_i can be considered as firstly rotate degrees α_{i-1} around X_{i-1} axis relative to the L_{i-1} denoted as the Rot (X_{i-1} , α_{i-1}); then translate a_{i-1} along X_{i-1} axis denoted as Trans (X_{i-1}, a_{i-1}); and then translate d_i along Z_i axis denoted by Trans (Z_i , d_i); and finally rotate degrees θ_i around Z_i axis denoted as the Rot (Z_i , θ_i); Thus the homogeneous transformation L_i relative to L_{i-1} can be considered as: rotation (α_{i-1}) — translation(a_{i-1})— translation (d_i) — rotation (θ_i), whose transformation matrix is:

$$A_i^{i-1} = \mathrm{Rot}(X_{i-1}, \alpha_{i-1})\mathrm{Trans}(X_{i-1}, a_{i-1})\mathrm{Trans}(Z_i, d_i)\mathrm{Rot}(Z_i, \theta_i) = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i \sin\theta_i & \sin\alpha_i \sin\theta_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\alpha_i \cos\theta_i & -\sin\alpha_i \cos\theta_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Where, the four scalars α_i a_i d_i and θ_i are the parameters of i-th link. For rotating joints, θ_i is corresponding to the joint variables α_i , and for moving the joint, d_i is alignment at the joint variable θ_i .

The kinematic equations of mechanism are described by the transform matrix A_i^0 . In order to easily control the parameters as position, velocity and acceleration for boom, bucket rod as well as bucket. A_i^0 can be represented as the function which only conclude variables of θ_1 , θ_2 , θ_3 and θ_4 :

$$A_i^0(\theta_1, \theta_2, \cdots, \theta_i) = A_1^0(\theta_1) A_2^1(\theta_2) \cdots A_i^{i-1}(\theta_i)$$
$$(i = 1, 2, 3, 4) \quad (2)$$

P is in a certain position of component i, which is described as p^i in rotating coordinate system L_i (i = 1, 2, 3, 4) and as p^0 in base coordinate system L_0. Both of them are linked by the transformation matrix, i.e. $p^0 = A_i^0 p^i (i = 1,2,3,4)$. In this case, the velocity of the point is:

$$\frac{d_{p^0}}{d_t} = \left(\sum_{j=1}^{i} \frac{\partial A_i^0}{\partial \theta_j} \theta_j \right) p^i$$

$(i=1, 2, 3, 4)$ (3)

Acceleration is:

$$\frac{d^2 p^0}{{d_t}^2} = \left(\sum_{j=1}^{i} \frac{\partial^2 A_i^0}{\partial \theta_j^2} \theta_j \right) p^i$$

$(i=1, 2, 3, 4)$ (4)

The calculation of digging force (driving force) : The digging force d_m of a tiny mass concentrated on a point for mechanism is:

$$dF_i = \frac{d^2 p^0}{{d_t}^2} d_m = \left(\sum_{j=1}^{i} \frac{\partial^2 A_i^0}{\partial \theta_j^2} \theta_j \right) p^i d_m$$

$(i=1, 2, 3, 4)$ (5)

Digging force F_i of the entire mechanism i is the integration to tiny mass digging force d_{F_i} :

$$F_i = \int dF_i = \int \frac{d^2 p^0}{{d_t}^2} d_m = \int \left(\sum_{j=1}^{i} \frac{\partial^2 A_i^0}{\partial \theta_j^2} \theta_j \right) p^i d_m \quad (i=1, 2, 3, 4) \tag{6}$$

Digging force is one of the important indicators to measure the performance of the hydraulic excavator. When design digging force, the working equipment should ensure structural optimization and meet strength requirement under the specified rated load [4], at the same time, it also must be ensure the other two cylinders can be interlocked when independently operated any hydraulic cylinder and developed a maximum thrust forceunder the setting pressure of system, thereby it can achieve maximum digging force and avoid slipping of machine topples [5]. The whole machine digging force can be calculated and measured by bucket hydraulic cylinder and hydraulic cylinders.And the theoretical maximum digging force can be obtained by optimization method.

The maximum digging force of bucket hydraulic cylinder is:

$$\begin{aligned} MaxF\ (\theta_4) &= m_3 a_4 = m_3 \frac{d^2 p^0}{{d_t}^2} \\ &= m_3 \frac{\partial^2 A_4^0}{\partial \theta_4^2} \theta_4 = m_3 l_3 \sqrt{{a_3}^4 + {\varepsilon_3}^2} A_4^3 \end{aligned} \tag{7}$$

The maximum digging force of bucket rod hydraulic cylinder is:

$$\begin{aligned} MaxF(\theta_3, \theta_4) &= m_2 a_3 A_4^3 = m_2 \frac{d^2 p^0}{{d_t}^2} A_4^3 \\ &= m_2 \frac{\partial^2 A_3^0}{\partial \theta_3^2} \theta_3 A_4^3 = m_2 l_2 \sqrt{{a_2}^4 + {\varepsilon_2}^2} A_4^3 \end{aligned} \tag{8}$$

When using the bucket cylinder or the bucket rod cylinder digging, the machine's theoretical maximum digging force is influenced by several forces, such as the interlocking force W_1 of boom cylinder, the interlocking force $W_2$of bucket rod hydraulic cylinder, the interlocking force $W_3$of bucket cylinder,the maximum digging force W_4overcomed by ground condition's attached limitations, and the maximum digging force W_5overcomed by the whole machine's steady state. The actual digging force of which is the smallest one from W_1, W_2, W_3, W_4, W_5 , whose value can be used as a known quantity[6].

INTEGRATED OPTIMIZATION OF MOTION AND POWER

Establish the mathematical modelof the performance parameters: For the optimization problem of the hydraulic excavator's working equipment, they often want to havemaximum digging force of the bucket cylinder, maximum digging force of bucket rod cylinder and other indicators which can reach the optimal value. They have more than one objective functions, and this problem is known as a multi-objective optimization problem.

Design variables: $x = x(l_{30}, Z_C, l_1, l_2, l_3, \theta_2, \theta_3, \theta_4)$ (9)

which Z_C is the z-axis coordinate of movable .

Mathematical model of optimization problems：

$$\min F(x) = \sum_{i=1}^{n} (F_i(x) \bullet ZG_i) \ x \in R^n$$
$$G_i(x) = 0 \ i = 1, \cdots, m_e$$
$$G_i(x) \le 0 \ i = m_e + 1, \cdots, m, \qquad x_i \le x \le x_n \tag{10}$$

In the formula, $F(x)$ is the objective function vector, $F_i(x)$ are sub-objective functions, ZG_i and are sub-objective weighted coefficients.

There are many solutions of multi-objective planning problems: weight-sum method, ε constraint method, goal attainment method and so on.

The performance parameters of movement and power integrated optimization methods and proceduresUsing C++ Builder to develop the interface of application program and using MATLAB to write optimization model for solving subroutine, then achieving mixed programming of MATLAB engine and C++ Builder by invoking MATLAB engine functions. On the basis of the established specific optimization model, they regard optimization toolbox function as a "black box" [7]. According to the requirements of the chosen optimization tool function, they analyze the constraints, list the files and corresponding constraints of system matrix, call optimization toolbox, then they can get reliable optimization results simply and rapidly. Look YC225-LC-8 hydraulic excavator as an example, part of the optimization program is as follows:

%flopt0.1m
Function f=flopt01 (x)
$f = -(-500 * X\hat{}3 - 8957 * X\hat{}2 - 11283 * X + 14000);$[X, fval] =fminbnd (‘flopt01’, -2.2959, 0.5381)
The results：
X=
－0.6671
fval=
－1.78009e+005

The results showed that, when $\theta_4 = -0.6671$, the maximum digging force is 17800kN.

And also, it can calculate the maximum digging force of the bucket rod hydraulic cylinder and bucket rod together while it have maximum digging force. The result is shown in Fig. 2 and table 1.

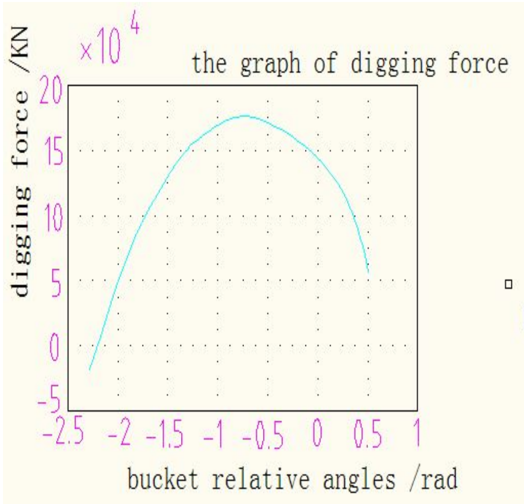

Fig.2: Excavator digging force curves before and after optimization

Table 1: Optimization of parameters before and after contrast table

	working condition	θ 2	θ 3	θ 4	maximum digging force/KN	note
before the optimization	bucket hydraulic cylinder motion	arbitrary	arbitrary	-0.6671	178010	with the design parameters
	bucket rod hydraulic cylinder motion	arbitrary	-0.527	0.5381 (transformation)	186410	θ 4 where nonsense
the optimized	Bucket hydraulic cylinder motion	arbitrary	arbitrary	-0.567	191010	Increased by 7.5%
	Bucket rod hydraulic cylinder motion	arbitrary	-0.563	0.5381 (transformation)	196710	θ 4 where nonsense

CONCLUSION

According to the results of the YC225LC-8 hydraulic excavator optimization analysis, its original design parameters need to further improve. The optimization results show that compared with foreign advanced models, the main design of the excavator working device amended as follows: using a long boom, boom hinge point distance of 5700mm; boom bending angle of 112.5^0 (the original is 131^0). The aim is to expand the job range of the excavator above ground; using standard stick to expand the operating range following the excavator ground; doing research and analysis on wording condition on the basis of ensuring the carrying capacity of the institution of a variety of conditions to reduce the geometry of the plateand reinforce sectional view of the main force, thereby reduce the weight of the work apparatus. After calculated, the working device is lighter than the original model by 11.7%; it can increase the size of the apparatus on the basis of the same machine heavy grade to expand the scope of the job.

The method of C + + Builder and MATLAB mixed programming is make full use of MATLAB powerful scientific computing, as well as C + + Builder powerful interface development function. And the program development process is simple, high process efficiency and has reliable optimization results. It can find solid theoretical calculation foundation for further research on mining automatic. And it has the value of engineering application.

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