Structural Optimization of Backhoe Hydraulic Excavator Working Attachment Based on Tested Dangerous Conditions

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***Abstract*—The structural parameter of excavator attachment plays an important role in the structural design, so it is very important to select the most dangerous working condition to improve the structural strength by optimizing the parameters. However, the previous traditional dangerous condition comes from specialized mechanism parameters, which may not be appropriate in the real digging process. Moreover, excavators of same tonnage are quite different in the number and position of inside reinforce plate. In this paper, the actual dangerous condition is concluded from performance testing of a certain backhoe hydraulic excavator. Based on the tested dangerous condition, the best position of the inside reinforce plate is discussed first and then the parameters of the arm are optimized by Genetic Algorithm as an example. The result shows that there is a big difference between the tested dangerous working condition and the traditional condition, and also, the mass of the excavator decreases by 2.38%, the maximum resultant displacement decreases by 1.90% and the average resultant displacement decreases by 2.09% after optimization**

Keywords-excavator; working attachment; dangerous condition; structural optimization; FEA

I. INTRODUCTION

Nowadays backhoe hydraulic excavator plays a more and more important role in mining, construction and forestry. The structural strength design of backhoe hydraulic excavator has become one of the designer's most concerning problems due to the excavator's poor working environment and complex working objects. As a result, a large number of professors and designers make a deep research on this problem. Professor Zhang Weiguo did a test which made the bucket impact the ground and then verified the changing trend of the cylinder working pressure and displacement by ADMS simulation. Then the reliability of the testing stress is verified by transient dynamics simulating test [1]. Prof Wu Shengbin improved the local stress concentration of the arm by trial-and-error method according to the arm FEA results on the bucket digging condition [2]. Prof Long Tian optimized the excavator boom by trial-and-error method on the 4 kind traditional dangerous working conditions of the boom and arm [3].

The researches above are very meaningful. However there are still some problems. First, there is a lack of comparison and verification between the traditional dangerous working condition and the tested condition. Second, the majority of the excavator attachment structure optimization methods are trial-and-error method, which can't get the convergent result. Third, there are many problems about the number and position of inside reinforce plate. This paper shows the differences between the traditional dangerous working condition and the tested dangerous working condition according to the performance testing of a certain backhoe hydraulic excavator, and then uses the tested dangerous working condition as the boundary condition to optimize the number and position of inside reinforce plate by FEM, and finally optimizes the overall structural parameters of the excavator working attachment

II. THE VERIFICATION OF DANGEROUS WORKING CONDITION

The performance testing is carried out by the synchronous test system which tests the digging poses, strain and cylinder pressure so as to get the dynamic testing data of the excavator. The testing system components are shown in figure Ⅰ and there are four dangerous digging working conditions: the working condition-1 is digging by bucket alone, the working condition-2 is digging by arm alone, the working condition-3 is free digging, and the working condition-4 is digging at the maximum digging radius [4].

The hydraulic cylinder pressure and digging poses can be easily obtained from pressure transmitter and angular displacement sensor in the testing system, but the stress of the testing points can only be obtained from three-direction strain. Then the strain of the strain rosette can be transferred into equivalent stress according to the fourth strength theory, given that the material's modulus of elasticity and Poisson ratio μ.

The better digging trajectory then can be selected based on the continuity after the data processing on the testing strain of the boom and arm. The maximum stress of the testing points on the boom and the arm varies with the time, which is shown in figure Ⅱ. Then the limiting value of the maximum stress can be obtained from the figure, which is 158.5Mpa on working condition 4-2 and 110.3Mpa on working condition 2-1. Also the working pose can be easily calculated from the data of the angular displacement sensor. As is known, it is very important to select the most dangerous working condition to optimize the structural parameters. The traditional dangerous working condition is concluded from the structural mechanics. However, the tested dangerous condition is concluded from the performance testing. As is shown in table Ⅰ, we can find that there is a big deviation between the tested dangerous condition and the traditional condition, which reveals that the traditional dangerous working condition can't be used for every excavator [5].

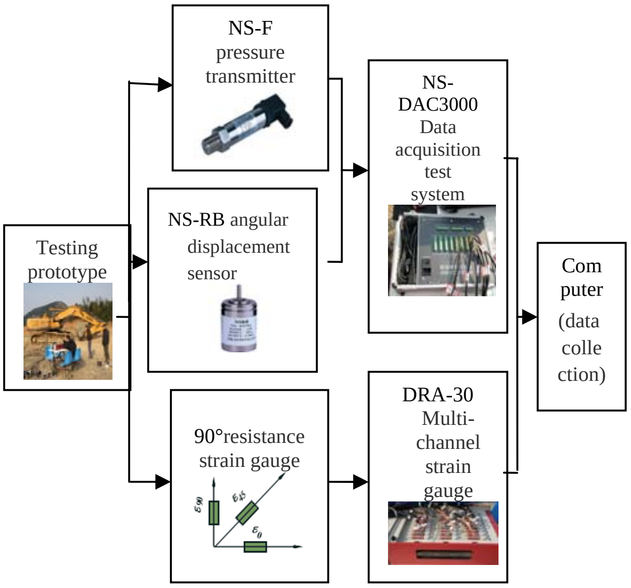


FIGURE Ⅰ. FLOWCHART OF THE SYNCHRONOUS TEST SYSTEM.

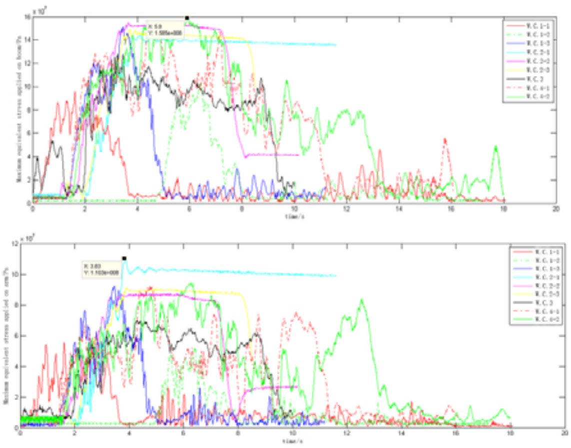


FIGURE Ⅱ. TIME HISTORY OF MAXIMUM STRESS AMONG BOOM AND ARM GAUGE POINTS.

TABLE I. DANGEROUS OCCASIONS OF BOOM AND ARM.

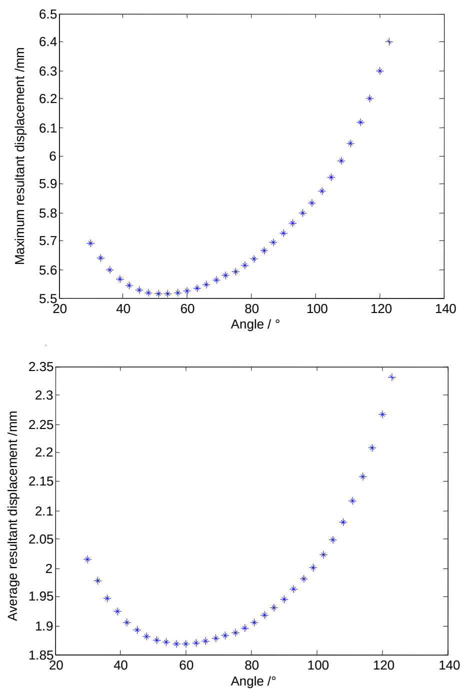
attitude angle	θ_1 /°	θ_2 /°	θ_3 /°
boom in testing	10.5421°	118.5736°	155.7063°
boom in traditional	5.33°	100.36°	155°
Arm in testing	16.4605°	92.6858°	187.2378°
Arm in traditional	5.33°	100.36°	180°

III. THE ARM DESIGNING AND OPTIMIZATION OF THE BACKHOE HYDRAULIC EXCAVATOR

A. *The Arm Designing*

The arm is the key component of the excavator working attachment, but there are a lot of problems about the position of inside reinforce plate of the arm. In order to find the best mounting position, use the enumeration method to optimize the inclination angle of the reinforce plate which varies from 30° to 120° in the global coordinate system. And the accuracy of the FEA mainly depends on the boundary condition whether it is close to the actual condition [6]. So the cosine distributing load is applied on the inner surface of the pin hole according to the theory of Elastic Mechanics. Then select 38 nodes of the inner surface as the assessment nodes to optimize the performance parameters of the arm by assessing the average and the maximum displacement.

The variation of the maximum resultant displacement and the average resultant displacement of the single reinforce plate is shown in figure Ⅲ. The figure shows that there is only one extreme point in each curve, and maximum resultant displacement reaches its minimum value 5.515 mm when the reinforce plate locates at 52.5° and average resultant displacement reaches its minimum value 1.863 mm when the reinforce plate locates at 57.5°.In general, the 3 different positions of the reinforce plate are shown in figure IV.



FIGREⅢ. MAXIMUM AND AVERAGE DISPLACEMENTS OF ASSESSING POINTS RESPOND TO PLATE ADJUSTMEN.

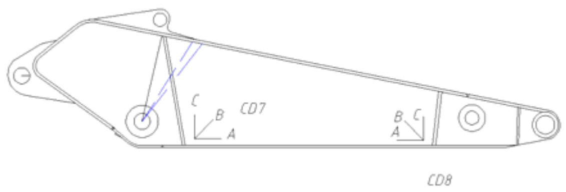


FIGURE IV. THREE DIFFERENT DISTRIBUTING PLAN OF REINFORCING PLATE.

B. Parameters Optimization of the Arm Structure

It is very significant to design a kind of arm which owns less mass and enough strength. The arm is box-section beam structure which is made of side plate, top plate, bottom plate, cranked plate, ear plate, the reinforce plate and the bracing. Then use Genetic Algorithm to optimize the whole arm's parameters because GA is suitable to solve the constrained nonlinear problem which has multivariate, multi-objective and multi-extremum points.

The arm model is built by APDL(ANSYS Parametric Design Language) and its lightweight design is the rational combination of the thickness of different plates. So the design variables are the thickness of different plates, the position of the inside reinforce and other structural parameters, there are 13 design variables in total.

$$\boldsymbol{X}[\boldsymbol{i}] = \left\{ \begin{matrix} N, Th, \ Width, (Theta_1, ..., Theta_N), \\ Tpd, \ Bpd, \ Bspd, \ Mspd, Fspd, \\ Cpd, \ Bthick, \ Uepd, \ Bepd \end{matrix} \right\} = \left\{ \begin{matrix} x_1, \ x_2, \ x_3, \ x_4, \\ x_5, \ x_6, \ x_7, \ x_8, \ x_9, \\ x_{10}, \ x_{11}, \ x_{12}, \ x_{13} \end{matrix} \right\} \tag{1}$$

In the equation:

N is the number of the inside reinforce plates;

Th is the thickness of the inside reinforce plates;

Width is the width of the inside reinforce plates;

Theta is the angle between the reinforce plate and the bottom plate;

Tpd, Bpd are the thickness of the top plate and the bottom plate;

Bspd , Mspd, Fspd are the thickness of the back side

plate, medium side plate and front side plate;

Cpd is the thickness of the cranked plate;

Bthick is the thickness of additional reinforce plate of the bottom plate;

Uepd is the thickness of the ear plate of bucket cylinder;

Bepd is the thickness of the ear plate of arm cylinder.

C. Constraint Conditions of the Working Attachment Structure

In order to realize the lightweight design, the thickness of different plates can be different due to the different strength.

So, the thickness of the medium side plate is less than that of the front side plate:

$$Mspd \le Fspd \tag{2}$$

The thickness of the medium side plate is less than that of the back side plate:

$$Mspd \le Bspd \tag{3}$$

The stress of the cranked plate is complex due to the compression-extrusion of the arm cylinder and the bending and torsion deformation of the arm root pivot, so:

$$Cpd \ge Tpd \tag{4}$$

The arm root pivot is easy to occur stress concentration, and that position often cause crack in the real digging operation. So based on the quasi-equal strength criterion:

$$Cpd = Bpd \tag{5}$$

D. Objective Function

The arm structural optimization based on the testing dangerous condition demands that the arm should have less mass, longer service life and proper manufacturing technique. The optimization object is the plate, whose mass is proportional to the volume. So the objective function is as follows:

$$f(x) = X_1 \times \lambda_1 + X_2 \times \lambda_2 + X_3 \times \lambda_3 \tag{6}$$

In the equation,

X_1—the maximum displacement of the assessment points,

X_2—the average displacement of the assessment points,

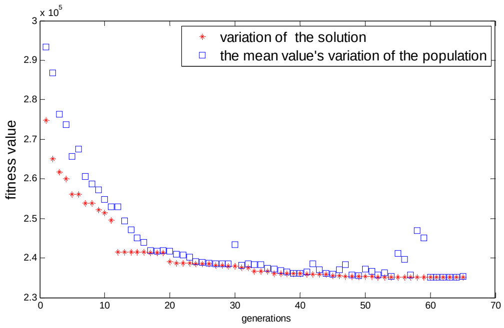
X_3— The volume of the model.

λ_1, λ_2, λ_3—the weight coefficients of the sub-objective functions and $\lambda_1 + \lambda_2 + \lambda_3 = 1$

The values of the sub-objective functions need to do the normalized processing due to the big difference of the values, which can avoid the small value of the sub-objective functions lose its effect.

E. Optimization Example

Use the genetic algorithm (GA) to optimize the arm of the testing prototype. GA starts from the population, then crossover mutating and ends in getting the best population. The population size is 20, the Iterative algebra is 65 and the generation gap is 0.9 in the optimization processing. The convergence process of the testing prototype is shown in the figure Ⅴ.



FIGUREⅤ. CONVERGENCE PROCESS OF OPTIMIZATION ALGORITHM.

After adjusting the weight coefficients of the sub-objective functions continuously, the program can converge fast and the optimization result is more close to the reality when the weight coefficient w1=0.24, w2=0.12, w3=0.64. The comparison between the parameters before optimization and the ones after optimization is shown in the table Ⅱ. The table shows that the thickness of the top plate, back side plate and front side plate decreases but the thickness of the bottom plate and medium side plate increases. Also the thickness of the bottom reinforce plate increases a little in order to strengthen the torsion.

TABLE II. ARM PARAMETER BEFORE AND AFTER OPTIMIZATION.

Parameters	**N**	**Thick**	**Width**	**Theta**	**Tpd**	**Bpd**	**Bspd**
Before optimization	1	12	244	75	16	20	22
after optimization	1	13.5	242.6	59.7	15	20.9	19.7

Parameter	**Mspd**	**Fspd**	**Cpd**	**Bthick**	**Uepd**	**Bepd**	
Before optimization	14	22	20	10	36	45	
after optimization	14.1	19.5	18.8	11.4	34.2	44	

Whether the arm's performance is improved can be assessed by comparing the volume of the model, the maximum and the average displacement of the assessment points. The result in table III shows that the volume decreases by 2.38%, the maximum displacement decreases by 1.90% and the average displacement decreases by 2.09%. The decrease of the volume, maximum and average displacement shows that the arm after optimization has less mass but better stiffness and strength. So it has significant meaning in the primary design of the working attachment as a new kind of optimization method.

TABLE III. ARM PERFORMANCE BEFORE AND AFTER OPTIMIZATION.

	volume/mm^3	**Maximum displacement/mm**	**Average displacement/mm**
Before optimization	160514757.4	81248.35	31411.86
After optimization	156692758.0	79702.85	30755.66

IV. CONCLUSIONS

This paper shows that there is a big difference between the tested dangerous condition and the traditional condition, and the former is more suitable for optimizing the working attachment as the dangerous condition. Based on the tested dangerous condition, the best position and number of the inside reinforce plate is solved first and then the parameters of the arm are optimized by GA. The result shows that the volume decreases by 2.38%, the maximum displacement decreases by 1.90% and the average displacement decreases by 2.09%. It can bring great benefits for the enterprise when this method is used into the design process.

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