Dynamic Analysis of Working Device of Excavator under Limit Digging Force

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Abstract In order to more accurately analyze the dynamic characteristics of the working device of the hydraulic excavator. The load changes on the two digging trajectories were calculated and analyzed by using the limit digging force model and the theoretical digging force model, respectively. The rigid-flexible coupling model of the working device was established in ADAMS. Taking the limit digging force (LDF) and the theoretical digging force (TDF) as the external load of the working device, the dynamic simulation of the hinge force of the working device in the two trajectories was carried out, and the structural strength analysis of the bucket was carried out by using ANSYS. The results show that the tangential force of the LDF is generally larger than that of the TDF, the hinge point force of the working device changes dynamically with the external load of the tooling, and the influence of the LDF on the hinge point force is greater than that of the TDF. When the LDF is taken as the external load, the structural strength of the bucket meets the operational requirements.

Keywords Hydraulic excavator · Working device · Individual digging trajectory · Rigid-flexible coupling · Hinge point force · Structural strength

Introduction

Hydraulic excavator is one of the most commonly used machines in engineering, and scholars pay close attention to the dynamic performance of its working device. In the previous research [1, 2], the dynamic analysis of tooling based on virtual prototyping technology is one of the research hotspots. For example, Peng et al. [3] compared and analyzed the time-varying curve of excavator tooling in rigid model and rigid-flexible coupling model. Liu et al. [4] take the calculated bucket excavation resistance as the external load of the working device, and analyze the force and dynamic stress distribution of each hinge point of the arm based on the rigid-flexible coupling model. S. Šalinić et al. [5] give the differential equation of motion of hydraulic excavator in the form of Kane equation. Wang et al. [6] use modal function to describe the elastic deformation of working device, and establish the nonlinear dynamic equation of rigid-flexible coupling of working device system. Xiao et al. [7] and Cao et al. [8] simulate the hinge point force and stress under fixed posture based on the excavator virtual prototype model. By comparing the simulation results with the theoretical values, the correctness and validity of the model are verified. Xie et al. [9] use the modal reduction method to flexible the arm and rod, and solve the dynamic stress of the working device and the load of the hydraulic cylinder based on the rigid-flexible coupling model of the excavator. Lv et al. [10] use the Kane-Huston structure to construct the topology of the working device of the hydraulic excavator, and use the fuzzy control method to optimize the bucket tip trajectory. Huang et al. [11] make a transient analysis of the structural strength of the arm and rod based on the rigid-flexible coupling model of the working device considering the dynamic characteristics of the operation. Zhang et al. [12]

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studied the test of load signal and the preparation of load spectrum of hydraulic excavator. Li et al. [13] use an improved parallel particle swarm optimization algorithm to optimize the position of the joint and the length of the connecting rod. Ding et al. [14] based on the theory of graphic modularization and ring algebra, the forward and inverse kinematics and workspace of hydraulic excavator are studied, and the velocity and acceleration are analyzed. Yu et al. [15] through the kinematics and dynamics simulation analysis of the virtual prototype of the working device of the hydraulic excavator, the main parameters of the working range of the excavator and the pressure curve of each hydraulic cylinder point are obtained. Liu et al. [16] take the calculated excavation resistance as a given load, and simulate the driving force curve of the hydraulic cylinder in the excavation process. Yuan et al. [17] proposed a rigid-flexible coupling method to predict the dynamic performance of excavator, such as stress distribution and curve stress. Zou et al. [18] established the limit theory digging force model, which is used to calculate the maximum force and torque that the excavator can exert, an optimal design method of full-parameter working accessories of hydraulic excavator with the goal of maximum stress and minimum stress is put forward. Wang et al. [19] compared the calculated maximum digging radius and other parameters with the ADAMS simulation results. Nabiullin et al. [20] put forward a method to determine the reasonable value of hydraulic mechanism structure and operation parameters of hydraulic excavator lever.

In the above research, scholars have carried out the dynamic analysis of the working device of the excavator and the finite element analysis of the arm and rod, but the dynamic analysis is only based on the transient dynamic analysis of the individual digging point under typical working conditions. In the finite element analysis, the digging resistance calculated by the traditional resistance formula is used as the external load of the working device, at the same time, in the author's previous research [21]. Only the digging trajectory in the limit working condition, the theoretical digging force of the hydraulic cylinder are considered, and the effects of the normal digging trajectory produced by different digging actions and the LDF of the hydraulic cylinder on the overall dynamic response of the working device are ignored. and the key parts under the limit digging load, such as the influence on the structural strength of the bucket.

Therefore, in this study, two individual digging trajectories are selected based on the working characteristics of the excavator, the external load of the working device is calculated by using the LDF model and the TDF model, and the rigid-flexible coupling model of the tooling is established. The hinge force of the working device and the structural strength of the bucket are simulated and analyzed.

Load Calculation considering individual Digging Trajectory

For the construction machinery such as excavator, which has different motion states and complex working objects, it bears the joint action of various loads such as tension, compression, impact and torsion in the process of operation, and the digging resistance is complex and changeable, so it is difficult to get accurate results. Different digging movements of the excavator produce different digging trajectories, and also put forward higher requirements for the accuracy of the solution of digging resistance.

The traditional theoretical digging force (TDF) only considers the tangential force and normal force in a fixed digging point, and treats them as a simple proportional relationship, but in the actual test, it is found that the combination of many discrete digging points forms the digging trajectory, and the digging force also changes with the change of digging activity. The digging force calculated by the traditional TDF model has the phenomenon of instability in the test. It does not represent the true digging ability of the excavator.

As shown in Fig. 1, taking the working device of the excavator and the hinge point of the car body as the origin, the front of the working device as the Y axis and the upper part of the working device as the Z axis. The vertical direction with the whole working device as the X axis, the X axis is perpendicular to the YZ plane and oriented toward the picture.

The initial angle and termination angle of the arm relative to the rod and the angle between the rod and the bucket can be taken according to the actual digging needs, and the desired digging trajectory can be obtained by changing the

Fig. 1 Trajectory of working device

relative angle. In the DD_1 trajectory, the angle between the moving arm OB and the horizontal plane θ_1 remains unchanged, the angle between the rod BC and the arm OB remains unchanged, the bucket hydraulic cylinder protrudes, the bucket CD begins to move, the angle between the bucket and the rod θ_3 changes from 180° to 140° , and the bucket tooth tip moves from D point to D_1 point, forming a DD_1 trajectory. Similarly, the angle between the bucket rod BC and the moving arm OB is changed from 140° to 100° , and the DD_2 trajectory is obtained.

The hydraulic excavator has the maximum digging resistance in the actual digging operation, that is, the maximum digging force exerted by the excavator in the actual digging process. The maximum digging resistance is calculated, that is, the maximum digging force of the excavator is calculated. The traditional calculation method is that the TDF is composed of tangential force and normal force. As shown in Fig. 2, the tangential force is perpendicular to the connection line between the hinge point C and the bucket tooth tip D at D point (that is, the bucket cutting radius CD), direction of the bucket is opposite to the bucket digging direction, the normal force is perpendicular to the tangential force at D point, and the direction points to the hinge point C along the cutting radius CD. However, TDF obviously ignores the important factor of resistance moment.

In the actual excavation process, the bucket bears a complex force system which changes at any time. When the lateral force is not considered, the complex force system can be regarded as a plane force system because of the symmetry of the working device. The tangential force F_t , the normal force F_n and the resistance moment T_r , acting on the D point in the middle position of the bucket cutting edge are called the limit digging force (LDF). LDF is a plane force system, and the digging trajectory is also a two-dimensional trajectory, so only studies it in the YZ plane.

Fig. 2 Bucket load

Although the LDF model adopted as per the researches [22], also takes tangential force as independent variable, the normal force F_n and resistance moment T_r change the coefficient of tangential force F_t in a certain range. By setting the principal value interval of resistance coefficient ε and resistance moment coefficient δ , the range of ε is $-0.4 \sim 0.5$, and that of δ is $-0.4 \sim 0.2$. And constantly changing the values of the two coefficients according to a certain step, a more comprehensive force balance equation is solved. Finally, the maximum TDF is selected as the final digging force, that is, the LDF. Therefore, the selection of the LDF as the external load of the bucket is closer to the real situation than the TDF.

As shown in Fig. 3a, b are the changes of the digging force of the bucket and rod hydraulic cylinder with the angle.

(a) DD_1 trajectory

(b) DD_2 trajectory

Fig. 3 Continuous digging load

Table 1 Working device constraints

Component 1	Component 2	Restraint pair
Body	Arm	Rotating pair
Body	Block of arm hydraulic cylinder	Cylindrical pair
Arm	Piston of arm hydraulic cylinder	Cylindrical pair
Arm	Block of rod hydraulic cylinder	Cylindrical pair
Rod	Piston of rod hydraulic cylinder	Cylindrical pair
Arm	Rod	Rotating pair
Rod	Block of bucket hydraulic cylinder	Cylindrical pair
Pendulum bar	Piston of bucket hydraulic cylinder	Cylindrical pair
Rod	Pendulum bar	Rotating pair
Bucket	Pendulum bar	Rotating pair
Rod	Connecting rod	Rotating pair
Bucket	Connecting rod	Rotating pair
Pendulum bar	Connecting rod	Cylindrical pair
Rod	Bucket	Rotating pair
Piston of arm hydraulic cylinder	Block of arm hydraulic cylinder	Moving pair
Piston of rod hydraulic cylinder	Block of rod hydraulic cylinder	Moving pair
Piston of bucket hydraulic cylinder	Block of bucket hydraulic cylinder	Moving pair

As shown in Fig. 3, due to the existence of resistance coefficient ε and resistance moment coefficient δ , each excavation point corresponds to different normal force F_n and resistance moment T_r . Due to the existence of negative coefficient, continuous load and resistance moment have negative value. The frequent change of resistance coefficient ε leads to the change of normal force F_n in Fig. 3b. The change law of tangential force F_t is basically the same as that of normal force F_n and resistance moment T_r . When the trajectory is completed, the loading state of the bucket changes from no load to full load, and the operating object of the excavator is grade III soil. When the bucket is fully loaded, the formula for calculating the gravity of the material in the bucket is as follows.

$$G = \rho \cdot v \cdot g$$

If the earthwork excavated is standard bucket volume von 0.9m^3 , and the density of grade III soil is $\rho=1.8 \times 10^3 \text{ kg/m}^3$, the gravity of the bucket is $15\,876 \text{ N}$ when the bucket is full of materials.

Dynamic Modeling based on Rigid-Flexible Coupling

The rigid-flexible coupling multibody model of the working device is established in the dynamic simulation software ADAMS. In order to reduce the simulation time and not affect the simulation results, the working device is simplified in the modeling process, and the bucket is

treated as a flexible body, while the arm, bucket rod, connecting rod and other parts are still rigid bodies. The established model needs to add corresponding constraints to each component at the marker point, and the working device constraints are shown in Table 1

Dynamic Analysis of Working Device

During the simulation, the STEP function is used to control the telescopic stroke of the hydraulic cylinder and the loading of the dynamic load, and the marker point of the load is established at the tip of the bucket tooth. In this paper, 0.1° as the step, $0 \sim 2 \text{ s}$ as the preparation stage, the working device moves from the original position to the OBCD, and the $2 \sim 22 \text{ s}$ is the movement stage, and the working device movement forms two tracks, respectively. The STEP function of the working device is shown in Table 2.

The simulated forces at each hinge point of the arm, the rod and the bucket are shown in Fig. 4.

In the bucket digging trajectory and rod digging trajectory, the Y and Z hinge point forces of the three hinge points of the working device also increase with the change of time. The increasing trend of hinge force in Y and Z direction is basically the same under different loads. The hinge point of the arm is far away from the bucket tooth tip of the load, and at the same time, the arm does not move in the trajectory, so the hinge point of the arm is less affected by the external load, and the change of the hinge point

Table 2 STEP function of working device

STEP function	TDF		
	LDF	DD ₂ trajectory	DD ₁ D ₂ trajectory
Arm	DD ₁ trajectory	DD ₂ trajectory	DD ₁ D ₂ trajectory
hydraulic cylinder	STEP(time,0,0,2,-100)	STEP(time,0,0,2,-100)	STEP(time,0,0,2,-100)
Rod	STEP(time,0,0,2,-200)	STEP(time,0,0,2,-200)	STEP(time,0,0,2,-200)
hydraulic cylinder	STEP(time,0,0,2,-300)	STEP(time,0,0,2,-300)	STEP(time,0,0,2,-300)
Bucket	+ STEP(time,2,0,22,600)	+ STEP(time,2,0,22,600)	+ STEP(time,2,0,22,600)
hydraulic cylinder	STEP(time,2,73,425,22,106,521)	STEP(time,2,73,425,22,106,521)	STEP(time,2,44,035,22,70,607)
Tangential force	STEP(time,2,-29,370,12,-40,620) + STEP(time,12,-40,620,22,-21,304)	STEP(time,2,-29,370,12,-40,620) + STEP(time,12,-40,620,22,-21,304)	STEP(time,2,48,294,22,92,721)
Normal force	STEP(time,2,-29,370,22,-51,501)	STEP(time,2,-29,370,22,-51,501)	
Resistance moment	STEP(time,2,-29,370,22,-51,501)	STEP(time,2,-29,370,22,-51,501)	
Material gravity	STEP(time,2,0,22,15,876)	STEP(time,2,0,22,15,876)	STEP(time,2,0,22,15,876)

(a) condition 1 **(b) condition 2****Fig. 4** Strength analysis of bucket

force is relatively stable; the peak forces of the Y and Z hinge points of the three hinge points are consistent with the occurrence time of the maximum LDF in the trajectory.

And it can be seen from the Fig. 5 that the component of some hinge force is negative, or there is a change from positive to negative, the positive and negative sign only represents the direction of the force, and the force has a negative value or a positive or negative sign. It shows that the direction of the force component of the hinge point has changed in the coordinate system set up in Sect. 2. Compared with the dynamic analysis results in reference [21], the LDF is closer to the real situation, and the influence of

(c) condition 3

(d) condition 4

Fig. 4 continued

the LDF on the hinge force of the working device is obviously greater than that of the TDF.

Strength Analysis of Bucket

As the task execution terminal of the hydraulic excavator, the bucket is in direct contact with the material, and its structural characteristics have a great influence on the overall performance of the tooling. Therefore, it is necessary to take the LDF as the external load, combined with ANSYS to analyze the transient dynamics of the bucket. When the bucket material is E355DD, the stress and

Fig. 5 Stress and deformation of bucket in trajectory

(a) stress

(b) deformation

Fig. 6 Maximum stress and deformation of bucket

deformation results of the bucket are shown in Fig. 5; the maximum stress and deformation of the bucket in the DD₁ trajectory are shown in Fig. 6.

In the DD₁ trajectory, the maximum stress value of the bucket is 327.43 MPa, the maximum deformation is 6.041 mm; DD₂, and the maximum stress value is 253.66 MPa, the maximum deformation is 4.442 mm. In the two trajectories, the larger stress and deformation part of the bucket are the same, and the larger stress area is mainly distributed in the welding place of the bucket back plate, ear plate and rear wall plate, and the largest deformation is at the tip of the middle bucket tooth. The results of strength analysis show that in the two trajectories, the maximum stress of the bucket is less than the yield strength of the bucket material, so the bucket meets the operational requirements.

Conclusion

- (1) According to different digging force calculation models, the variation of digging force with the angle between two individual digging trajectories is obtained. The tangential force of LDF is generally larger than that of TDF, and the growth law is the same.
- (2) In the hinge point force simulation, due to the difference of the external load of the working device, the hinge point force of the three hinge points varies with the change of the external load. The variation law of hinge point force under the same hinge point and different load is basically the same. The influence of the limit digging load on the dynamic response of the working device is obviously greater than that of the theoretical digging load.
- (3) Under the LDF load, the maximum stress of the bucket in the two individual digging trajectories is less than the yield stress of the bucket material, which meets the design requirements. On this basis, the overall strength analysis and fatigue life evaluation of the working device can be carried out, so as to evaluate the fatigue life of the working device in the structural design stage.

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Declaration

Conflict of interest The authors have no conflict of interest.

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References

1. Y. Li, Q. Qiu, P. Feng, Dynamic analysis of time-varying structure based on rigid-flexible hybrid modelling [J]. J. Zhejiang Univ. Eng. Sci. **02**(311), 314 (2007). <https://doi.org/10.3785/j.issn.1008-973X.2007.02.026> (inChinese)
2. S. Frimpong, H. Yafei, H. Inyang, Dynamic modeling of hydraulic shovel excavators for geomaterials[J]. Int. J. Geomech. **8**(1), 20 (2008). [https://doi.org/10.1061/\(ASCE\)1532-3641\(2008\)8:1\(20\)](https://doi.org/10.1061/(ASCE)1532-3641(2008)8:1(20))
3. J. Peng, L. He, K. Liang et al., Dynamic analysis and research on hydraulic excavator based on rigid-flexible coupled modeling[J]. J. Mach. Des. **29**(04), 38–43 (2012). <https://doi.org/10.3969/j.issn.1001-2354.2012.04.009> (inChinese)
4. Z. Liu, B. Sun, J. Zhang, Rigid-flexible coupling simulation and analysis of crawler excavator working device [J]. J. Vib. Meas. Diagn. **33**(S1), 37–40+217 (2013). <https://doi.org/10.3969/j.issn.1004-6801.2013.z1.009> (in Chinese)
5. S. Salinic, G. Boskovic, M. Nikolic, Dynamic modelling of hydraulic excavator motion using Kane's equations[J]. Autom. Constr. **44**(8), 56–62 (2014). <https://doi.org/10.1016/j.autcon.2014.03.024>
6. X. Wang, S. Tong, Nonlinear dynamics behavior analysis on rigid-flexible coupling mechanical arm of hydraulic excavator[J]. J. Vib. Shock **33**(01), 63–70 (2014). <https://doi.org/10.3969/j.issn.1000-3835.2014.01.011> (inChinese)
7. C. Xiao, G. Zhang, Dynamic simulation analysis of working device for hydraulic excavator based on ADAMS[J]. Telkomnika **14**(3), 194–201 (2016). <https://doi.org/10.12928/TELKOMNIKA.v14i3A.4430>
8. L. Cao, Q. Wang, L. Cao, et al., Dynamics simulation of hydraulic excavator working device based on ADAMS[C]. in *International Conference on Mechanical Design* (Springer, Singapore, 2018). https://doi.org/10.1007/978-981-10-6553-8_60
9. Q. Xie, Wu. Yunxin, Rigid-flexible coupling dynamics analysis of hydraulic excavator[J]. J. Mecha. Transm. **40**(05), 101–104 (2016). <https://doi.org/10.16578/j.issn.1004.2539.2016.05.024> (inChinese)
10. G. Lv, G. Xu, S. Xie, Dynamics analysis and fuzzy control for the working device of hydraulic excavator[J]. in *International Conference on Oriental Thinking and Fuzzy Logic*, pp. 151–160 (2016). https://doi.org/10.1007/978-3-319-30874-6_16
11. H.Y. Yu, M.H. Yuan, K. Deng, et al., Kinematic and dynamic simulation analysis of hydraulic excavator's working equipment based on ADAMS[J]. MATEC Web Conf. **63**, 02020 (2016). <https://doi.org/10.1051/mateconf/20166302020>
12. M. Huang, G. Huang, Z. Sun et al., Structure strength analysis of working device of hydraulic excavator considering dynamic working characteristics[J]. Chin. J. Construct. Mach. **15**(05), 426–429 (2017). <https://doi.org/10.15999/j.cnki.311926.2017.05.010> (inChinese)
13. H. Zhang, G. Feng, H. Zhang, et al., Study on test and preparation of load spectrum of hydraulic excavator[C]. in *Seventh International Conference on Electronics and Information Engineering* (International Society for Optics and Photonics, 2017). <https://doi.org/10.1117/12.2266910>

14. X. Li, G. Wang, S. Miao et al., Optimal design of a hydraulic excavator working device based on parallel particle swarm optimization[J]. *J. Braz. Soc. Mech. Sci. Eng.* **39**(10), 3793–3805 (2017). <https://doi.org/10.1007/s40430-017-0798-5>
15. H. Ding, L. Han, W. Yang et al., Kinematics and dynamics analyses of a new type face-shovel hydraulic excavator[J]. *Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci.* **231**(5), 909–924 (2017). <https://doi.org/10.1177/0954406215625675>
16. B. Liu, Z. Feng, S. Mo, Dynamics analysis and simulation on the working device of face-shovel hydraulic excavator[J]. *J. Mech. Transm.* **42**(06), 115–119 (2018). <https://doi.org/10.16578/j.issn.1004.2539.2018.06.024> (inChinese)
17. Y. Yuan, M. Mostafa, Rigid-flexible coupling analysis of backhoe hydraulic excavator working device[J]. *E3S Web Conf.* **38** (2018). <https://doi.org/10.1051/e3sconf/20183802020>
18. Z. Zou, J. Chen, X. Pang, Lightweight and high-strength optimization design for a fully parametric working attachment of a hydraulic excavator based on limiting theoretical digging capability model[J]. *Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci.* **233**(14), 4819–4835 (2019). <https://doi.org/10.1177/0954406219840671>
19. J. Wang, H. Wang, Motion simulation of 8t hydraulic excavator working device[J]. *J. Guangxi Univ. Sci. Technol.* **30**(01), 90–95 (2019). <https://doi.org/10.16375/j.cnki.cn45-1395/t.2019.01.014> (inChinese)
20. R. Nabiullin, A. Komissarov, V. Shestakov, Development of a digital model of the working process of a hydraulic excavator[J]. *E3S Web Conf.* **177**(2), 03012 (2020). <https://doi.org/10.1051/e3sconf/202017703012S>
21. H. Sun, Z. Ren, J. Wang, et al., Dynamic analysis of working device of excavator based on limit trajectories[J]. *J. Mech. Electr. Eng.* **37**(09), 1075–1079 (2020). <https://doi.org/10.3969/j.issn.1001-4551.2020.09.014> (inChinese)
22. Z.G. Ren, J.L. Wang, Z.H. Zou et al., Modeling of the limiting digging force of hydraulic excavator based on resistance characteristics[J]. *Mechanika* **25**(5), 357–362 (2019). <https://doi.org/10.5755/j01.mech.25.5.22805>

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