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Research Article

Modeling and Simulation of Theoretical Digging Force of an Excavator Based on Arbitrary Posture

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Theoretical digging force is an important performance parameter of the hydraulic excavator. Due to the multi-linkage mechanism, the digging posture of an excavator is ever-changing; thus, it is not easy to calculate the theoretical digging force. Traditionally, the theoretical digging force is calculated by selecting a limited number of postures of the excavator based on experience, which cannot reflect the force condition of each posture in the excavation process. In order to calculate the theoretical digging force of any posture in the excavation process, this paper uses the principle of the analytical method to establish a theoretical excavation force mathematical model of bucket excavation and uses Matlab software to solve the theoretical excavation force mathematical models. In order to verify the model's correctness, the experimental method is used to determine the actual maximum excavation force of the excavator. The test results showed that there was little difference between the actual maximum digging force and the theoretical maximum digging force, which verified the correctness of the theoretical digging force mathematical models and provided a theoretical digging force calculation method and reference for the structural design and optimization of the excavator.

1. Introduction

Theoretical digging force is an important index to measure the performance of the hydraulic excavator as well as the basis for calculating the power of the hydraulic system and the power system. Therefore, theoretical digging force is the most important performance parameter concerned by the designer in the design stage of the excavator [1]. In addition, it is also one of the boundary conditions for the structural finite element analysis of the working device of the excavator and other components. Therefore, it is extremely important to obtain the accurate theoretical digging force. There are countless digging postures during excavator operation. The theoretical digging force varies with different digging postures. It is very complicated to calculate the theoretical digging force. It is almost impossible to manually calculate the theoretical digging force corresponding to each digging posture. Therefore, the traditional calculation method of theoretical digging force selects the typical working conditions and postures of the excavator according to experience and then conducts a general survey and calculation with the analytical method [2]. This calculation method is limited by only calculating the digging force of a limited number of digging postures, and the posture of the maximum digging force of the excavator is often difficult to determine accurately. Therefore, the traditional calculation method cannot fully master the stress condition of the excavator [3], and the calculation result may not be the maximum theoretical digging force of the excavator.

Based on the limitations of the traditional calculation method of theoretical digging force, this paper used the principle of the analytical method to establish the theoretical digging force mathematical model of bucket digging and the theoretical digging force mathematical model of bucket rod digging, respectively. The theoretical digging force mathematical models could calculate the theoretical digging force of any posture of the excavator. Matlab software was used to solve the theoretical digging force mathematical models and draw the theoretical digging force map, so as to more intuitively reflect the stress state of the excavator in the whole digging posture. In order to verify the correctness of the theoretical digging force mathematical models, the

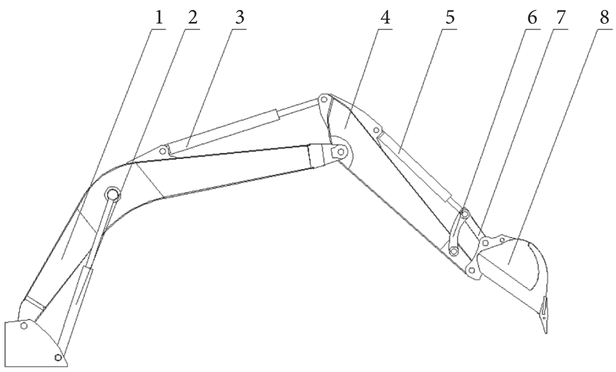

Figure 1: Structure of the working device. (1) bionic boom, (2) hydraulic cylinder of bionic boom, (3) hydraulic cylinder of bucket rod, (4) bucket rod (5) hydraulic cylinder of bucket, (6) swinging rod, (7) linkage, and (8) bucket.

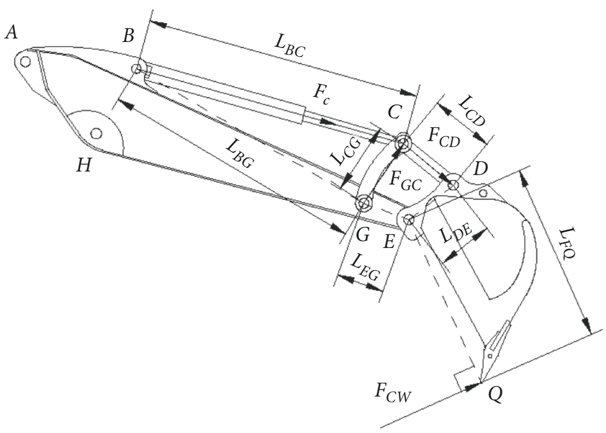

Figure 2: Force analysis of the bucket digging device.

maximum theoretical digging force of the excavator was tested on the spot. The test data showed that there was little difference between the measured maximum digging force and the theoretical maximum digging force, which verified the correctness of the theoretical digging force mathematical models and provided the basis and reference for calculation of the theoretical digging force for the structural design and improvement of the excavator.

2. Establishment of Theoretical Digging Force Mathematical Models

During excavator operation, the bucket teeth cut into the soil and the tips of the bucket teeth are affected by soil resistance, which is called the digging resistance. The digging resistance and the theoretical digging force are in the action-and-reaction relationship, and the theoretical digging force of the excavator is obtained by solving the digging resistance. A digging posture will be formed as long as the hydraulic cylinder moves a unit length during excavator operation. An infinite number of digging postures can be formed within the stroke range of the hydraulic cylinder. When establishing the theoretical digging force mathematical models, an arbitrary digging posture within the stroke range of the hydraulic cylinder was taken as the research object without considering the self-weight of the working device and the weight of the soil in the bucket, and the efficiency of the hydraulic system and linkage mechanism [4], The structure of the working device of the excavator is shown in Figure 1.

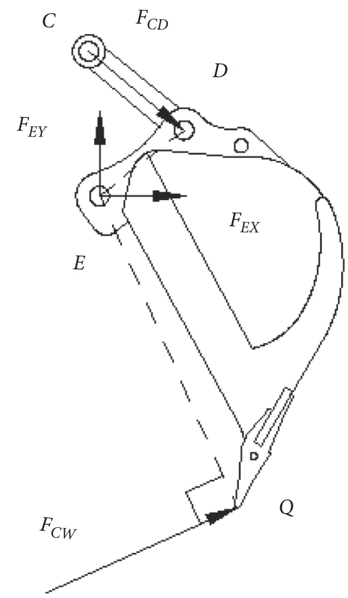

Figure 3: Force analysis of separated linkage and the bucket.

2.1. Establishment of the Theoretical Digging Force Mathematical Model of Bucket Digging. When the excavator operates in the way of bucket digging, the bucket hydraulic cylinder drives the bucket to move, the hydraulic cylinder of the bucket rod and the hydraulic cylinder of the bionic boom are in the locked state, and the bucket teeth tips are affected by the digging resistance F_{CW} and perpendicular to the EQ connecting direction. The stress is shown in Figure 2, wherein, A is the hinge point formed by the hydraulic cylinder of bucket rod and the bucket rod, B is the hinge point formed by the hydraulic cylinder of bucket rod and the bucket rod, C is the hinge point formed by the hydraulic cylinder of the bucket and the swinging rod and linkage, D is the hinge point formed by the linkage and the bucket, E is the hinge point formed by the bionic boom and the bucket, G is the hinge point formed by the bionic boom and the swinging rod, H is the hinge point formed by the bionic boom and the bucket rod, and F_C is the thrust of the hydraulic cylinder of the bucket. The thrust F_C can be divided into two components of F_{CD} and F_{GC}, in which the component F_{CD} is along the hinge points C and D, and the component F_{GC} is along the hinge points G and C, as shown in the figure. Based on the principle of vector decomposition, the following is deduced as

$$\vec{F}_C = \vec{F}_{CD} + \vec{F}_{GC}. \quad (1)$$

The moments of the thrust F_C of the hydraulic cylinder of the bucket before and after decomposition to the hinge point G are the same, as given in the following formula:

$$F_C \cdot L_{BG} \cdot \sin \angle\mathrm{CBG} = F_{C\,D} \cdot L_{CG} \cdot \sin \angle\mathrm{DCG}. \quad (2)$$

The big chamber thrust F_C of the hydraulic cylinder of the bucket is calculated by the following formula:

$$F_C = P_0 \cdot A_1 = \frac{\pi \cdot D_1^2}{4} \cdot P_0. \quad (3)$$

The stress by taking the linkage and the bucket as research objects is shown in Figure 3. For the hinge point E, based on the principle of moment balance, the following is deduced as

$$F_{CW} \cdot L_{EQ} = F_{C\,D} \cdot L_{DE} \cdot \sin \angle\mathrm{CDE}. \quad (4)$$

The following is deduced by substituting formulas (2) and (3) into formula (4), we get

$$F_{CW} = \frac{\pi \cdot D_1^2 \cdot L_{BG} \cdot \sin \angle\mathrm{CBG} \cdot L_{DE} \cdot \sin \angle\mathrm{CDE}}{4 \cdot L_{CG} \cdot \sin \angle\mathrm{DCG} \cdot L_{EQ}} \cdot P_0, \quad (5)$$

where L_{BG} is the the distance between the hinge points B and G; L_{CG} is the the distance between the hinge points C and G; L_{DE} is the the distance between the hinge points D and E; L_{EQ} is the the distance between the hinge points E and Q; P_0 is the rated pressure of the hydraulic system; and D_1 is the inner diameter of the hydraulic cylinder of the bucket.

For formula (5), ∠CBG, ∠CDE, and ∠DCG change with the digging posture, and they are all the functions of the length of the hydraulic cylinder of the bucket. Therefore, the digging posture angle function is established with the length L_{BC} of a hydraulic cylinder as the independent variable. According to the triangle cosine theorem, the following is deduced as

$$\angle\mathrm{CBG} = \mathrm{arc}\,cos\left(\frac{L_{BC}^2 + L_{BG}^2 - L_{CG}^2}{2 \cdot L_{BC} \cdot L_{BG}}\right), \quad (6)$$

$$\angle\mathrm{CDE} = \mathrm{arc}\,cos\left(\frac{L_{C\,D}^2 + L_{DE}^2 - L_{CE}^2}{2 \cdot L_{C\,D} \cdot L_{DE}}\right), \quad (7)$$

$$\angle\mathrm{DCG} = \mathrm{arc}\,cos\left(\frac{L_{C\,D}^2 + L_{CG}^2 - L_{DG}^2}{2 \cdot L_{C\,D} \cdot L_{CG}}\right), \quad (8)$$

$$\angle\mathrm{BGC} = \mathrm{arc}\,cos\left(\frac{L_{BG}^2 + L_{CG}^2 - L_{BC}^2}{2 \cdot L_{BG} \cdot L_{CG}}\right), \quad (9)$$

$$\begin{aligned}\angle\mathrm{DEG} &= \angle\mathrm{CEG} + \angle\mathrm{CED} \\ &= \mathrm{arc}\,cos\left(\frac{L_{CE}^2 + L_{EG}^2 - L_{CG}^2}{2 \cdot L_{CE} \cdot L_{EG}}\right) \\ &\quad + \mathrm{arc}\,cos\left(\frac{L_{CE}^2 + L_{DE}^2 - L_{C\,D}^2}{2 \cdot L_{CE} \cdot L_{DE}}\right),\end{aligned} \quad (10)$$

$$L_{CE} = \sqrt{L_{CG}^2 + L_{EG}^2 - 2 \cdot L_{CG} \cdot L_{EG} \cdot \cos(\angle\mathrm{BGE} - \angle\mathrm{BGC})}, \quad (11)$$

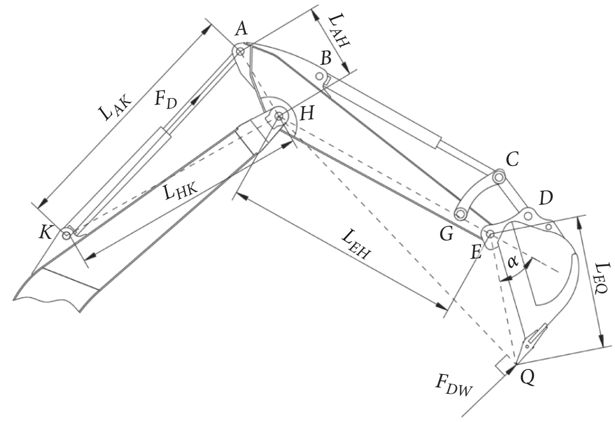

Figure 4: Force analysis of the bucket rod digging device.

$$L_{DG} = \sqrt{L_{EG}^2 + L_{DE}^2 - 2 \cdot L_{EG} \cdot L_{DE} \cdot \cos \angle\mathrm{DEG}}, \quad (12)$$

where L_{BC} is the the distance between the hinge points B and C; $L_{C\,D}$ is the the distance between the hinge points C and D; L_{CE} is the the distance between the hinge points C and E; L_{EG} is the the distance between the hinge points E and G; L_{DG} is the the distance between the hinge points D and G.

The theoretical digging force mathematical model of bucket digging can be obtained by substituting formulas (6-12) into formula (5). When the hydraulic cylinder of the bucket expands and contracts within its stroke range, the theoretical digging force of any digging posture can be solved by using the theoretical digging force mathematical model, so as to obtain the theoretical digging force of any posture during bucket digging.

2.2. Establishment of the Theoretical Digging Force Mathematical Model of Bucket Rod Digging

For bucket rod digging operation, the theoretical digging force generated by the hydraulic cylinder of the bucket rod is related to the stroke of the hydraulic cylinder of the bucket rod and the rotation angle α, that is, the stroke of the bucket hydraulic cylinder. During bucket rod digging, the hydraulic cylinder of the bucket rod drives the bucket rod to move, and the bucket rod drives the bucket to move to dig. Both the hydraulic cylinder of bionic boom and the hydraulic cylinder of the bucket are locked. The theoretical digging force F_{DW} is equal to the digging resistance of the bucket teeth tips in the opposite direction and is perpendicular to the straight line HQ (the connecting line between the hinge point H and the bucket teeth tips Q). The digging resistance force arm is L_{HQ}, as shown in Figure 4, and K is the hinge point formed by the hydraulic cylinder of the bucket rod and the bionic boom. For the hinge point H, according to the principle of moment balance, the following is deduced as

$$F_D \cdot L_{HK} \cdot \sin \angle\mathrm{AKH} = F_{DW} \cdot L_{HQ}. \quad (13)$$

Then the theoretical digging force during bucket rod digging is

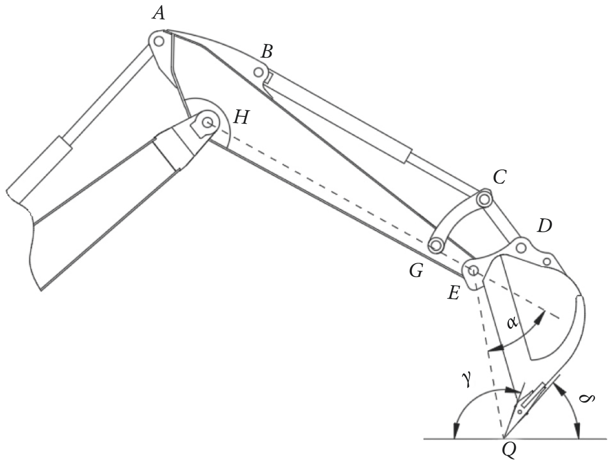

Figure 5: The cutting angle of the front edge of the bucket teeth and the rear cutting angle.

$$F_{DW} = \frac{F_D \cdot L_{HK} \cdot \sin \angle \mathrm{AKH}}{L_{HQ}}. \quad (14)$$

In formula (14), ∠AKH varies with the digging posture and is a function of the length of the hydraulic cylinder of the bucket rod. According to the triangle cosine theorem, the following is deduced as

$$\angle \mathrm{AKH} = \mathrm{arc}\,cos\left(\frac{L_{AK}^2 + L_{HK}^2 - L_{AH}^2}{2 \cdot L_{AK} \cdot L_{HK}}\right), \quad (15)$$

$$L_{HQ} = \sqrt{L_{EH}^2 + L_{EQ}^2 - 2 \cdot L_{EH} \cdot L_{EQ} \cdot \cos(\pi - \alpha)}. \quad (16)$$

The big chamber thrust F_D of the hydraulic cylinder of the bucket rod is calculated by the following formula:

$$F_D = P_0 \cdot A_2 = \frac{\pi \cdot D_2^2}{4} \cdot P_0. \quad (17)$$

The theoretical digging force mathematical model during bucket rod digging is deduced by substituting formulas (15), (16), and (17) into formula (14):

$$F_{DW} = \frac{\pi \cdot D_2^2 \cdot L_{HK} \cdot \sin \angle \mathrm{AKH}}{4 \cdot \sqrt{L_{EH}^2 + L_{EQ}^2 - 2 \cdot L_{EH} \cdot L_{EQ} \cdot \cos(\pi - \alpha)}} \cdot P_0, \quad (18)$$

where L_{HK} is the the distance between the hinge points H and K; L_{EH} is the the distance between the hinge points E and H; α is the the rotation angle of the bucket relative to the bucket rod; D_2 is the inner diameter of hydraulic cylinder of the bucket rod.

As shown in Figure 5, the included angle formed γ by the front side of the bucket teeth and the horizontal line is called the cutting angle of the front edge of the bucket teeth, and the included angle δ formed by the rear side of the bucket teeth and the horizontal line is called the rear cutting angle. For bucket rod digging, the change of the rotation angle α will change the size of the cutting angle of the front edge of the bucket teeth and the rear cutting angle. From Figure 5, it can be seen that normal digging can be carried out only when the rear cutting angle is greater than 0° in which the bucket teeth tips contact the soil before the bottom of the bucket. When the bucket rotation angle α turns to the position as shown in Figure 6, the bottom of the bucket contacts the soil first, the bucket teeth tips cannot contact the soil, and the bucket rod cannot excavate normally. This posture is called the critical posture of bucket rod excavation, and the rotation angle of the bucket relative to the bucket rod is called the critical rotation angle α_0. When $\alpha < \alpha_0$, that is, the length of the bucket hydraulic cylinder is less than that of the hydraulic cylinder in the critical posture, there is a rear cutting angle of digging, the bucket teeth tips contact the soil first, and the bucket rod can excavate normally. When $\alpha \geq \alpha_0$, that is, the length of the hydraulic cylinder of bucket is greater than or equal to the that of the hydraulic cylinder in the critical posture, the rear cutting angle is less than or equal to 0, so the bucket rod cannot dig normally.

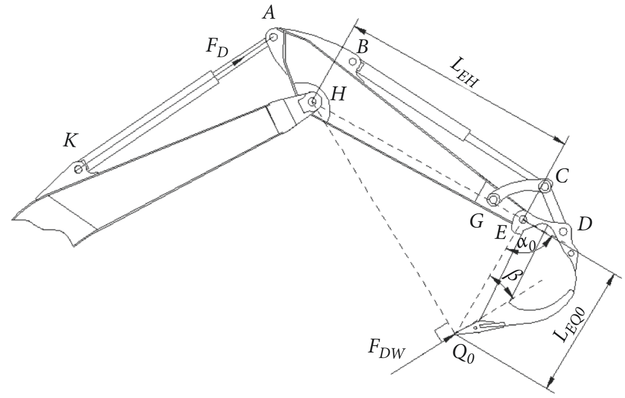

Figure 6: Critical posture of bucket rod digging.

The following is deduced in the critical posture as

$$\alpha_0 = \pi - \angle \mathrm{HEQ}_0, \quad (19)$$

$$\angle \mathrm{HEQ}_0 = \mathrm{arc}\,cos\frac{L_{EH}^2 + L_{EQ_0}^2 - L_{HQ_0}^2}{2 \cdot L_{EH} \cdot L_{EQ_0}}, \quad (20)$$

$$L_{HQ_0} = L_{EQ_0} \cdot \cos\left(\frac{\pi}{2} - \beta\right) + \sqrt{L_{EH}^2 - \left[L_{EQ_0} \cdot \sin\left(\frac{\pi}{2} - \beta\right)\right]^2}, \quad (21)$$

where α_0 is the critical rotation angle of bucket and β is the included angle between the EQ_0 connecting line and the bucket teeth.

The critical rotation angle α_0 of the bucket under the critical posture can be solved by substituting formulas (20) and (21) into formula (19). When $\alpha < \alpha_0$ and $L_{HQ} > L_{HQ_0}$, there is a rear cutting angle of digging. At this time, the bucket rod can dig normally, that is, once the hydraulic cylinder of the bucket changes one unit length every time within the range of critical rotation angle α_0, the hydraulic cylinder of the bucket rod expands and contracts within its stroke range for digging. In bucket rod digging, the

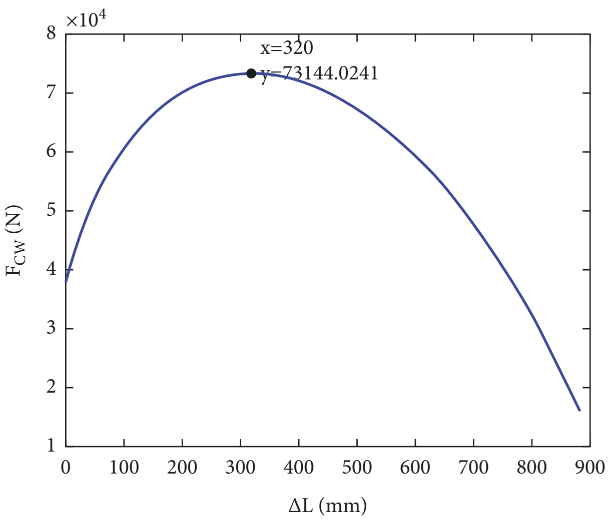

Figure 7: Relationship between theoretical digging force of bucket digging and stroke of the hydraulic cylinder of the bucket.

theoretical digging force of any posture within the range of the critical rotation angle can be obtained with formula (18).

2.3. Solution of the Theoretical Digging Force Mathematical Model. In order to accurately and quickly solve the theoretical digging force, the powerful computing function and the convenient programming method of Matlab numerical calculation software were used to transform the theoretical digging force mathematical model into the Matlab programming language and then realize the programming and automatic solution of the theoretical digging force, and the theoretical digging force was drawn into intuitive map output.

2.4. Solution of Theoretical Digging Force of Bucket Digging. The installation distance of the hydraulic cylinder of the bucket was 1378 mm and the stroke was 885 mm, i.e., $L_{BC} = [1378 \sim 2263]$. The other information were as follows: inner cylinder diameter: $D_1 = 90$ mm; rated pressure of hydraulic system: $P_0 = 34.3$ MPa; $L_{BG} = 1834.6$ mm; $L_{CG} = 495$ mm; $L_{DE} = 390$ mm; $L_{EQ} = 1239$ mm; $L_{CD} = 450$ mm; $L_{EG} = 332$ mm; $\angle BGE = 169°$. The Matlab program was compiled and solved according to the theoretical digging force mathematical model of the bucket, and the relevant data and initial values were substituted into the program for automatic solution, so as to obtain the theoretical digging force of any posture during bucket digging, as shown in Figure 7. It can be seen from the figure that when the bucket hydraulic cylinder stroke is 320 mm (i.e., the length of the hydraulic cylinder of the bucket is 1698 mm), the theoretical digging force of the hydraulic cylinder of the bucket reaches the maximum value of 73.144 KN.

2.5. Solving of Theoretical Digging Force of Bucket Rod Digging. The installation distance of the hydraulic cylinder of the bucket rod was 1700 mm and the stroke was 1175 mm, i.e.,

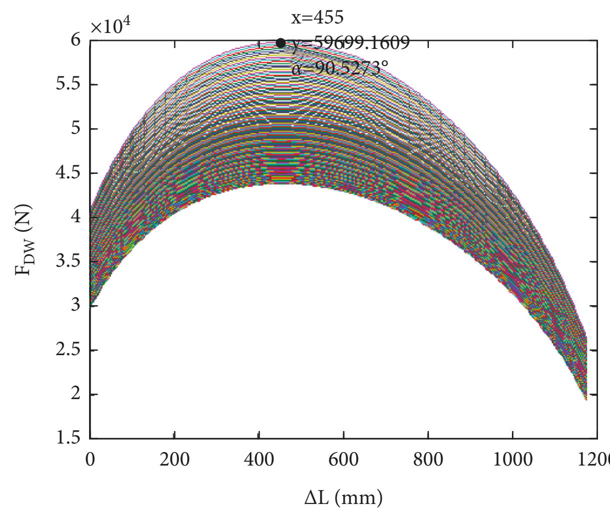

Figure 8: Relationship between theoretical digging force of bucket rod digging and stroke of the hydraulic cylinder of the bucket rod.

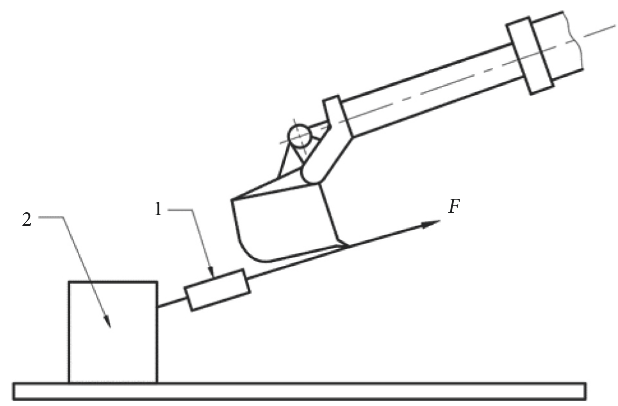

Figure 9: Principle of the maximum theoretical digging force test.

Figure 10: Test of maximum theoretical digging force.

$L_{AK} = [1700 \sim 2875]$. The other information were as follows: inner cylinder diameter: $D_2 = 90$ mm; rated pressure of hydraulic system: $P_0 = 34.3$ MPa; $L_{HK} = 2267$ mm; $L_{AH} = 700$ mm; $L_{EH} = 2250$ mm; $L_{EQ} = 1239$ mm. The Matlab solution program was compiled according to the theoretical digging force mathematical model of the bucket rod, and the relevant data and initial values were substituted into the program for solution, so as to obtain the theoretical digging force of any posture during bucket rod digging, as

Table 1: Comparison between measured values and theoretical values of maximum theoretical digging force.

Maximum digging force	Engine rotation speed/rpm	Length of hydraulic cylinder of bucket/mm	Length of hydraulic cylinder of bucket rod/mm	1st test value/KN	2nd test value/KN	3rd test value/KN	Average/KN	Calculate value/KN	Error rate (%)
Maximum digging force of bucket	2060	1698	--	68.5	68.2	69.1	68.6	73.144	6.60
Maximum digging force of bucket rod	2060	2155	2132	56.1	56.6	56.4	55.2	59.699	8.20

Note: error rate = calculated value of maximum theoretical digging force − tested value of maximum theoretical digging force/tested value of maximum theoretical digging force.

shown in Figure 8. It can be seen from the figure that when the stroke of the hydraulic cylinder of the bucket rod is 455 mm (the length of the hydraulic cylinder of the bucket rod is 2155 mm) and the rotation angle of the bucket is 90.5°, the theoretical digging force of the hydraulic cylinder of the bucket rod reaches the maximum value of 59.699 KN.

3. Test of Maximum Theoretical Digging Force

In order to verify the correctness of the theoretical digging force mathematical model, the test method is used to test the maximum theoretical digging force of the excavator. The test value and the calculated value of the maximum theoretical digging force are analyzed and compared to verify the correctness of the theoretical digging force mathematical models. The mathematical models are wrong when the error rate of the calculated value exceeds 10%, or else, they are correct. The principle of maximum theoretical digging force test is shown in Figure 9. The mechanical sensor dynamometer is used for testing. The excavator model is completely consistent with the excavator model used to calculate the theoretical digging force. The test process is as follows:

(1) Adjust the excavation posture of the excavator to the maximum theoretical excavation force posture.

(2) Connect the steel wire rope at one end of the dynamometer to the bucket, and the steel wire rope at the other end to the fixture and make the dynamometer in a tension state.

(3) Adjust the engine speed to the rated pressure of the hydraulic system and keep this state for a certain time and record the reading value of the dynamometer.

Repeat the test for 3 times and take the average value as the test value of the maximum digging force. The test site is shown in Figure 10, and the test results are shown in Table 1.

The above test data show that the error between the calculated value of the maximum theoretical digging force and the measured value of the maximum digging force of bucket digging is 4.5 KN, and the error between the calculated value of the maximum theoretical digging force and the measured value of the maximum digging force of bucket rod digging is 3.3 KN. Since the calculation of the theoretical digging force did not consider the factors such as the back pressure of the hydraulic cylinder, the friction at hinge points and the efficiency of linkage, and the thrust of the hydraulic cylinder needs to overcome the useless work factors such as the back pressure of the hydraulic cylinder and the friction at each hinge point in the test process, the measured value is smaller than the theoretical value, but the error is within a small range. Therefore, it can be considered that the calculated value of the maximum theoretical digging force is consistent with the test value. It shows that the calculation method of theoretical digging force is correct and feasible and further verifies the correctness of the theoretical digging force mathematical models.

4. Conclusion

To solve the limitations of the traditional calculation method of the theoretical digging force of the hydraulic excavator, this paper established the theoretical digging force mathematical models by using the principle of the analytical method and solved it by using Matlab software. Firstly, the theoretical digging force mathematical models of two digging methods of the excavator were established, which were then transformed into the Matlab programming language. The complicated manual solving of the theoretical digging force mathematical models was solved by using the powerful computing function of computer, and the theoretical digging force under any excavator posture was rapidly calculated. The maximum theoretical digging force of the excavator was tested on site in order to verify the correctness of the established theoretical digging force mathematical models. The test data show that the errors between the measured values and calculated values of the maximum theoretical digging force of bucket digging and bucket rod digging were small, which further verifies the correctness of the theoretical digging force mathematical models. The theoretical digging force mathematical models can calculate the theoretical digging force of any digging posture. The calculation program of theoretical digging force mathematical models can help the engineers of excavator manufacturers calculate the digging force quickly. The engineers only need to input the structural parameters of the excavator, the rated pressure of the hydraulic system, and other parameters to calculate the theoretical digging force quickly, which greatly improves the design efficiency.

Based on the theoretical digging force mathematical models established in this paper, the later research work will use Matlab software, Visual Basic programming language, and other software to develop a program for calculating theoretical digging force, so as to provide convenient services for enterprise engineers to calculate the digging force accurately and rapidly. The application of lightweight technology in the field of construction machinery will also be paid more and more attention as energy conservation and environmental protection have been paid more and more attention all over the world. Lightweight plays a vital role in reducing oil consumption, reducing emissions, and improving performance of excavators. Therefore, the future research will focus on the lightweight research around excavators, optimize theoretical digging force, and improve the performance of excavators.

However, there are also deficiencies in this paper. Only single hydraulic cylinder digging was considered when the theoretical digging force mathematical models were established, and when digging, the composite digging method was often adopted, i.e., the hydraulic cylinder of bucket rod and the hydraulic cylinder of the bucket drove the buckets to dig at the same time. It is more complex to establish the theoretical digging force mathematical models of the composite digging method, thus, in-depth research will be carried out on the composite digging method of the excavator, and we will try to establish the theoretical digging force mathematical models of the composite digging method in the follow-up work. [5–15].

Data Availability

The data are available from the corresponding author upon request.

Conflicts of Interest

The author declares that they have no conflicts of interest.

Acknowledgments

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