International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161
Available at http://inpressco.com/category/ijcet

Research Article

Design and Optimization of Lightweight and HSD Excavator Bucket with Uncertain Load

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Received 25 Feb 2021, Accepted 15 April 2021, Available online 17 April 2021, **Vol.11, No.2 (March/April 2021)**

Abstract

Excavators are used primarily to excavate below the natural surface of the ground on which the machine rests and load it into trucks or tractor. Due to severe working conditions, excavator parts are subjected to high loads. The excavator mechanism must work reliably under unpredictable working conditions. Thus, it is very much necessary for the designers to provide not only a equipment of maximum reliability but also of minimum weight and cost, keeping design. safe under all loading conditions weight and cost, keeping design safe under all loading conditions. It can be concluded that, force analysis and strength analysis is an important step in the design of excavator parts. This paper presents a methodology for lightweight and high-strength design of an excavator bucket under uncertain loading. Uncertain loads are obtained by using the Monte Carlo simulation based on the existing soil-bucket interaction model in which the soil parameters are variable. And the well-known 3-sigma methodology is used for the quantification of the uncertain loads. Excavator bucket modelling is finished by using ANSYS Parameter Design Language (APDL). A multi-objective optimization model aiming to decrease the maximum von Mises stress and to reduce the weight of the bucket is established on the foundations of the uncertain load and the parametric geometry model. The structural shape and topology of the bucket are then designed by using the mixed variable genetic algorithm to solve the established optimization problem. The results show that the presented method can be effectively and efficiently applied for the optimization design of the excavator bucket and that the optimized bucket signifies obvious decreases in the weight and the stress compared with the initial reference model. The proposed methodology for structure optimization design considering uncertain loads not only provides the technical means for the design and development of high-performance bucket but also lays a preliminary theoretical foundation for the optimization design integrated machine-environment interaction.

Keywords: *Monte Carlo simulator, High strength design Ansys parameter design language, digging force*

Introduction

In the era of globalization and tough competition the use of machines is increasing for the earth moving works, considerable attention has been focused on designing of the earth moving equipment's. Today hydraulic excavators are widely used in construction, mining, excavation, and forestry applications. Hydraulic excavators also called diggers. There are many variations in hydraulic excavators. They may be either crawler or rubber-tire-carrier-mounted, and there are many different operating attachments. With the options in types, attachments, and sizes of machines, there are differences in appropriate applications and therefore variations in economic advantages. Excavator digs, elevates, swings and dumps material by the action of its mechanism, which consists of boom, arm, bucket and hydraulic cylinders.

Bucket is used for trenching, in the placement of pipe and other under-ground utilities, digging basements or water retention ponds, maintaining slopes and mass excavation. Due to severe working conditions, excavator parts are subject to corrosive effects and high loads. The excavator mechanism must work reliably under unpredictable working conditions. Structure optimization design based on the deterministic knowledge and ignoring the machine-environment interaction is unable to satisfy the requirements on the high service performance and complex working condition of modern engineering structures. The digging operation using an excavator bucket is a typical and complex soil-bucket interaction process, in which the loads acting on the bucket are uncertain and the stresses in the bucket material are variable due to a constantly changing environment. The traditional deterministic design method takes no account of these uncertainties in loading condition and calculates the design loads under limiting working

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DOI: https://doi.org/10.14741/ijcet/v.11.2.13

condition according to the theoretical or empirical load model. Thus, the high-strength structures are designed at the expense of increased structure weight. However, from the perspectives of saving material and energy and prolonging service life, a lightweight and high-strength bucket structure is generally expected. Fortunately, the probability theory and statistical principle provide a sound mean to treat the uncertainties during the digging process. Furthermore, multi-objective optimization design with the consideration of uncertainties in loads has the potential to achieve the high-performance metrics of the bucket structure.

Based on the afore mentioned background, the main aim of this research is to find an approach to treat the uncertainties in loads during the digging process and further to use this approach to guide the structure optimization design. Many soil-bucket interactions models have been established (E. Rusinski,*et al* 2015). All these models provide the corresponding lumped-parameter functions to calculate the resistive force. More importantly, these lumped-parameter models lay a solid foundation for online soil-bucket interaction identification (Z. Zou *et al*, 2019), resistive force prediction based on learning method digging process simulation and development of virtual excavation simulator as well as dynamic motion planning for autonomous excavation. An accurate and reliable soil-bucket interaction model used to calculate the design loads is the prerequisite for the effective and credible optimization design of a bucket. Unfortunately, it is difficult to realistically model the soil-bucket interaction due to the complexity of geometric shape of the bucket and the uncertainty of interaction mechanism. Uncertainties in the soil parameters included in the models still cannot be eliminated, even if the well-known existing models are used to estimate the resistive forces. Among all previous works, resistive force prediction based on online learning can identify and modify the model, but it is very time consuming and unsuitable for structure optimization. The existing digging simulation framework can only be used to generate deterministic load profiles for structure analysis and design. Some works provide the methods to determine the maximum theoretical digging forces which the excavator can apply directions of the bucket force space. To quantify the uncertainty in digging resistance, the most probable direction interval of digging resistance based on the experimental results and proposed a set of performance measures to characterize the digging performance of an excavator in this most probable interval. It is worth noting that these methods are used to assess an excavator's digging capability from the perspective of the driving side of the excavator. Thus, the digging capability metric calculated by using these methods is a theoretical limiting force and can only be used as a limiting load for the ultimate strength design of excavator structure. That is to say, these traditional methods only support relatively conservative structure design and do not allow for uncertainties inherent in the load model parameters. So far, the related research integrating the uncertain resistive force model into the bucket structure optimization design framework has not been reported. On the aspect of structure design, Qiu *et al* . conducted the optimal design of an excavator's working device including the boom, stick, and bucket based on multiple surrogate models. The work of Qiu *et al* . still belongs to the field of ultimate strength design. Rusinski *et al* . conducted the research on the investigation and modernization of buckets of surface mining machines and presented an approach to consider the test results in real mining conditions as well as the numerical analysis results of modern numerical tools that support the bucket structure design in the process of bucket structure optimization. The existing research on the bucket structure design mainly focus on ultimate strength design based on the deterministic limiting loads. In order to achieve a satisfactory trade-off between the weight and strength of a bucket, it is necessary to conduct a profound study on the uncertainty optimization design of the bucket structure with the consideration of uncertainties in the soil-bucket interaction process.

This paper takes the soil-bucket interaction into consideration during the process of bucket optimization design. Uncertainties inherent in soil parameters are represented by using the Monte Carlo method to simulate the random distribution characteristics of parameters in uncertain intervals. The existing Park's soil-bucket model (S. Singh *et al* , 1995) is extended to be used in uncertain condition. Furthermore, to quantify the uncertainty of the resistive forces acting on the bucket and obtain the design load indicators with a relatively great possibility and low computational cost, the 3-sigma methodology which has been widely used in robust design optimization of engineering structure is introduced to define the level of load dispersion and determine the design loads. An excavator bucket model with complex geometrical configuration is parametrically represented and modelled by using APDL so as to achieve design automation and integration with a variety of industrial software products. Finally, a framework for the lightweight and high-strength design of an excavator bucket with the integration of uncertain soil-bucket interaction model is developed. The implementation of this optimization framework into the established multi-objective optimization of an excavator bucket is also shown.

Soil-Bucket Interaction Modelling

The digging process is affected by many variable factors, such as rough and changing terrains, uncertain soil properties, complex geometric shape of the bucket, and different operation styles used by operators who have different operating preferences and experiences. Therefore, it is difficult to establish a comprehensive and accurate theoretical model of the excavator digging process that can realistically reflect the soil-bucket interaction mechanism. To obtain the information of variability in operation, uncertainty in soil properties, and fluctuations in environment, and further to achieve human-machine-environment fusion, some external detection apparatus (transducers, radar detectors, and cameras) have been widely used in autonomous excavation. However, during the design phase, all this uncertain information cannot be obtained; thus, a model that can be used to realistically simulate the digging process is essential for determination of design loads of bucket design. Traditional theoretical digging forces are defined as the forces generated at the bucket lip or cutting edge when operating the bucket or stick cylinders independently, as shown in Figure 1. The traditional bucket digging force and stick digging force are calculated by taking into consideration hydraulic pressure limit and excavator stability limits including tipping and slipping limits. Since the soil-bucket interaction relationship is oversimplified in the traditional method, it cannot be used to guide the detailed design of the bucket structure. Among all developed soil-bucket interaction models, Park's resistance model (S. Singh *et al* , 1995) is selected in this research as the basic model to predict the soil resistive forces. Park's model (S. Singh *et al* , 1995) is better suited to simulate the soil-bucket interaction for the following reasons.

1.It is a 3D analytical resistance model extended based on Perumpral's model, whose soil failure model is close to 3D soil failure geometries.
2. It incorporates the excavator bucket shape. The influences of a bucket's constitutive parts such as two side plates and cutting plate on the soil-bucket interaction can be analysed and modelled individually and then added to the resultant resistance force by solving the limit equilibrium equations of the 3D soil failure wedge. Resistance model adding the influences of bucket shape can be used to determine the design loads in the process of bucket structure design.

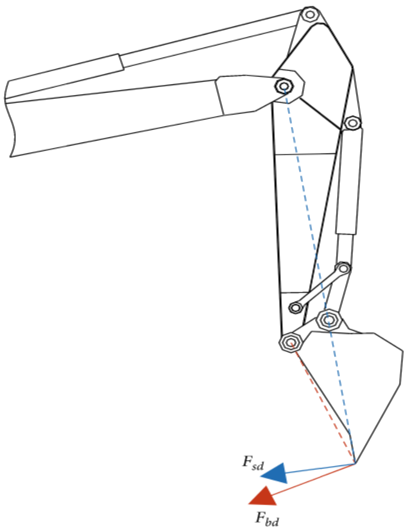


Fig 1.0: Theoretical digging forces

Plates and cutting plate on the soil-bucket interaction can be analyzed and modelled individually and then added to the resultant resistance force by solving the limit equilibrium equations of the 3D soil failure wedge. Resistance model adding the influences of bucket shape can be used to determine the design loads in the process of bucket structure design.

Soil-Bucket Interaction Model

In Park's resistance model, the soil rupture surface is assumed as a flat shape and the separated soil body is considered as an idealized failure wedge, as shown in Figure 2. illustrates the soil failure wedge and all the forces acting on its surfaces. Among all constitutive surfaces, the surfaces acfd and bcfe, respectively, represent the terrain surface and the failure surface, the surface abed is the contact surface between the bucket cutting plate and soil failure wedge, and the surfaces abc and def are the side rupture surfaces. Figure 2 illustrates a bucket sketch, in which the surfaces abg and deh are both the contact surfaces between the soil failure wedge and the side plates of the bucket. In this resistance model, the force components acting on the wedge are completely considered. ese force components include the cohesion force CF1 acting on the failure surface bcfe, the frictional forces SF1 and SF2, respectively, acting on the surface bcfe and the side rupture surfaces abc and def, the adhesion force Fad acting on the contact surface abed, the adhesion-cohesion force ACF acting on the two side rupture surfaces, and the gravitational force W and the surcharge Q. All factors which have effects on the resistive force are considered except for the inertia force compared with the previous resistance model when digging speed is low or not considered. In addition, the forces FN and Fr2 are the normal forces, respectively, acting on the failure surface □bcfe and the contact surface abed, and the force RS is the resistive force acting on the contact force abed. The resistive force RS can be solved by conducting the static equilibrium analysis for the soil failure wedge, as follows:

$$RS = Fad.Cos(\beta+\rho+\emptyset) + (W+Q).Sin(\alpha+\rho+\emptyset) + Sf2 + 2ACF + CF1).Cos\emptyset/Sin(\beta+\rho+\delta+\emptyset) \text{...eq1}$$

where α is the slope angle of the terrain surface, β is the angle between the cutting plate and the terrain surface, ρ is the soil failure angle, and δ and Ø are, respectively, the soil-metal friction angle and soil internal friction angle. In equation (1), all the individual force components have the same representations with the corresponding terms in Park's model except for the term Q representing the surcharge. For the sake of simplification, similar terms will not be listed in this research. The surcharge Q is determined by the volume of the soil swept by the bucket, and its representation is written as.

$Q = r.g.VS \dots\dots\dots\dots\dots\dots eq2$

where r is the soil density, g is the gravitational acceleration, and VS is the volume of the soil swept by the bucket.

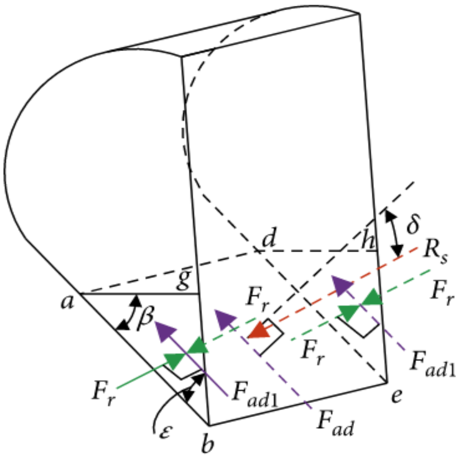


Figure 2.0: Soil-Bucket Interaction model Bucket sketch.

According to the action and reaction relations of all force components, the forces acting on the bucket are also given in Figure 2 the forces acting on the bucket cutting plate include the adhesion force F_{ad} and the resistive force RS, and the side plates of the bucket encountered the adhesion force Fad1 and the normal force F_r. The expression of the resistive force R_S has been given in equation (1).

Static Strength Analysis of Excavator Bucket

Figure 6 shows the schematic diagrams of the bucket. In Figure 6, t_i(i=1, 2,.....5) represent the thickness parameters of the constitutive plates of the bucket, l_i(i=1,2,.....12) represent the length parameters,$\theta i(i = 1,2,\dots 3)$ are the angle parameters, $r1$ *and* $r2$ are the radius parameters of the arc plates. Optimization process of the bucket involves design automation, integration of multiple industrial software products, and data exchange of different software products; thus, APDL is used for parametric geometry modelling of the bucket. APDL command flow has good portability and benefits structure reanalysis, so it is suitable for the optimization design of the complex bucket structure. the solid bucket model obtained by using APDL. Table 3 lists material properties of the bucket

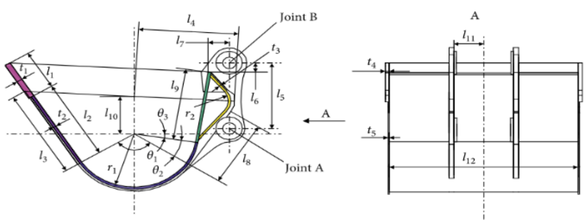


Figure 3.0: Schematic diagrams of the bucket

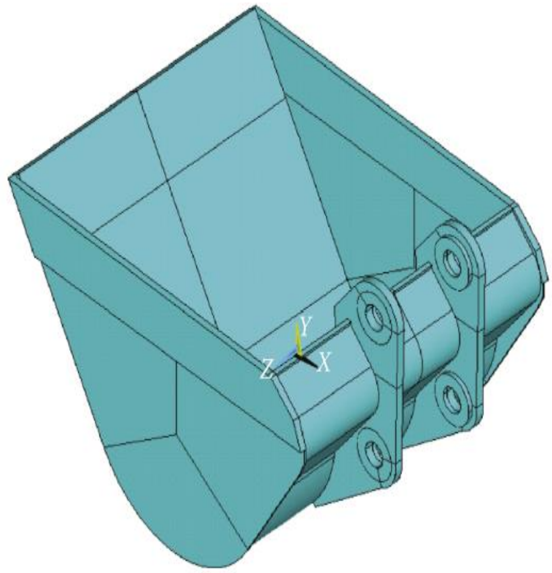


Figure 3.0: Solid bucket model using APDL.

To investigate the relations of the structure stress and the loads based on the parametric bucket model, finite element analysis (FEA) under a series of deterministic load groups is conducted. As shown in Figure 3, joints A and B are the hinge points connecting the stick and bucket; thus, their axial degrees are fixed, and the rest of degrees are released. It is assumed that all the force components acting on the bucket (as shown in Figure 2) are distributed uniformly on the corresponding contact surfaces between the soil and bucket. That is to say, all the forces are applied to the corresponding acting surfaces in the form of pressures. Figure 4 shows the variation of the maximum structure stress *Smax* for the forces acting on the bucket. There are the analysis results of 8 groups of deterministic load cases. In Figure 4, LG1~LG8 are the labels of the load cases. It is obtained that the larger resistive loads will result in the larger maximum structure stress. It can also be summarized that the resistive force is the major component influencing the magnitude of the maximum structure stress. The load group LG8 with the maximum digging depth and digging angle is listed in Table 2, and the FEA results under this load condition are given in The maximum stress of the bucket structure exceeds the yielding stress according to the analysis results; thus, plastic deformation will occur on the bucket. Improved design of the bucket can enhance the structure strength.

Table 1.0: Material properties of the bucket

Material	Density (kg/m³)	Poission's ratio	Youngs's modulus (MPa)	Yielding stress (MPa)
ST345	8.05×10^3	0.4	2.26×10^3	348

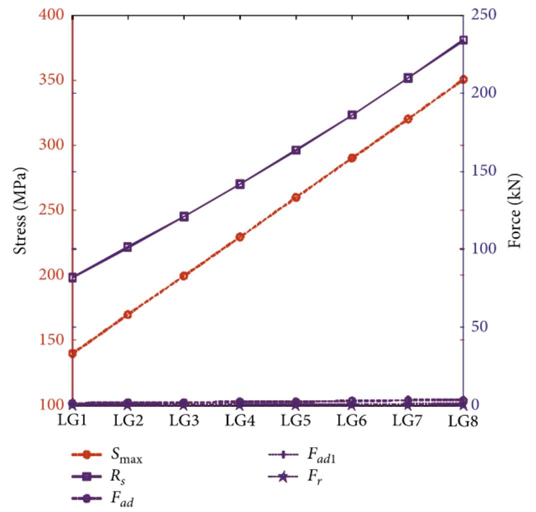
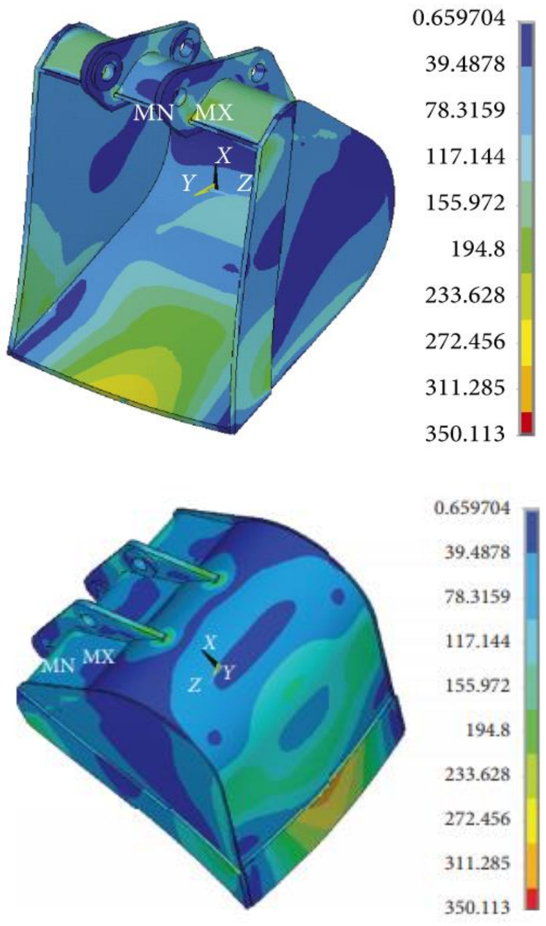


Figure 4.0: The relations of structure stress and loads.

Table 2.0: Deterministic loads with the maximum digging depth and digging angle (LG8).

Load Name	Resistive Force	Adhesion Force F_{ad1} (kN)	Adhesion Force F_{ad}(kN)	Normal Force(kN)
Value	265.850	1.219	3.450	0.40



(b)

Figure 5.0 (a,b): FEA results based on the deterministic load group LG8

The established geometry model using APDL in this section provides a solid foundation for the optimization design of an excavator bucket. In addition, it is validated that the maximum structure stress and the loads acting on the bucket are positive correction. This further verifies that it is rational to use the upper limits $\mu + 3\sigma$ of the loads acting on the bucket with the maximum digging depth and digging angle as the design loads.

Conclusion

The FEA and optimization is versatile tool for designing the backhoe attachment in Lightweight and HSD excavator. To carry out the modeling and FE analysis of an excavator, various software used by researchers like ANSYS, MATLAB, ADPL etc. according to their ease of user friendliness and accuracy of results. In this paper, a framework to achieve high-strength and lightweight optimization design of the bucket under uncertain loading is introduced. A new design approach that can achieve good trade-off between the bucket weight and structure stress is also given. Since the novel method takes uncertainties inherent in the soil-bucket interaction model into account and uses 3-sigma methodology to quantify these uncertainties, it can ensure the optimized bucket has good working performance even if the working environment is variable and uncertain. The results of the supplied example also show that the optimized bucket has higher strength and lighter weight under uncertain loading. In the future work, the proposed framework will be used to develop a new bucket. Furthermore, the framework which can be used for the uncertain optimization design of the working attachment including the boom, stick, and bucket will be developed.

References

E. Rusinski, L. Cegiel, A. Michalczyk, P. Moczko, J. Olejarz, and D. Pietrusiak (2015), "Investigation and modernization of buckets of surface mining machines," Engineering Structures, vol. 90, pp. 29–37

Z. Zou, J. Chen, and X. Pang (2019), "Lightweight and high-strength optimization design for a fully parametric working attachment of a hydraulic excavator based on limiting theoretical digging capability model," Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, vol. 233, no. 14, pp. 4819–4835

S. Blouin, A. Hemami, and M. Lipsett (2001), "Review of resistive force models for earthmoving processes," Journal of Aerospace Engineering, vol. 14, no. 3, pp. 102–111

B. Park (2002), "Development of a virtual reality excavator simulator: a mathematical model of excavator digging and a calculation methodology," Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, Ph.D thesis.

A.-O. Kwame and F. Samuel (2011), "Efficient cable shovel excavation in surface mines," Geotechnical and Geological Engineering, vol. 29, no. 1, pp. 19–26

C. P. Tan, Y. H. Zweiri, K. Althoefer, and L. D. Seneviratne (2005), "Online soil-bucket interaction identification for autonomous excavation," in Proceedings of the 2005 IEEE International Conference on Robotics and Automation, pp. 3576–3581, ISIE, Barcelona, Spain

S. Singh (1995), "Learning to predict resistive forces during robotic excavation," in Proceedings of the 1995 IEEE International Conference on Robotics and Automation, pp. 2102–2107, ISIE, Nagoya, Aichi, Japan