Journal of Mechanical Engineering *Vol 20(3), 371-386, 2023*

Influence of Operating Factors on Accurate Digging Depth Control of the Remote-Controlled Explosive Disposal Machine

Dat Duy Nguyen, Dat Van Chu
Le Quy Don Technical University, Hanoi, VIETNAM

*Sy Le Van**
PetroVietnam College, Vung Tau, VIETNAM
**sylv@pvcollege.edu.vn*

ABSTRACT

In this study, a dynamic model of the operating equipment and the hydraulic drive system of the remote-controlled explosive disposal machine were built to ensure both kinetic accuracy of digging path and the effective cutting angle. The Ruppel's control approach was applied to study the dynamics of the whole system and the influence of the arm-controlled signal, the soil digging resistance on the digging control process. In addition, a simulation model of the entire system is also performed to deeply understand the dynamic behaviour.

Keywords: *Remote Controlled Explosive Disposal Machine; Hydraulic System; Digging Depth Control; EDM*

Introduction

In the post-war period, all types of unexploded remnants such as bombs, mines and other explosive ordnances are very dangerous for the human life and society. For each war-damaged country, many national action programs have launched to deal with the consequences of bombs/mines and explosive ordnances. There are many types of explosive ordnances originating from many countries, located at different depths and terrain. The application of the remote-controlled explosive disposal machine (EDM) to clean the landmine contamination is an essential need for every country. This EDM has been

ISSN 1823-5514, eISSN 2550-164X

https://doi.org/10.24191/jmeche.v20i3.23919

Received for review: 2023-01-11
Accepted for publication: 2023-07-18
Published: 2023-09-15

developed by some military manufacturers from developed countries (Figure 1). They were equipped with intelligent and multi-functions to serve complex operations of the bomb/mine excavation process. Although EDMs have been commercialized, there are still many challenges that need in-depth research. In the excavation process, the control operations of drivers are required to avoid any collisions with bombs/mines located under the deep ground. It is extremely difficult to take advantage of the operators' perception (remote control) while they are working in conditions of mental stress. The influence factors such as vibration and acceleration should be eliminated in the control process. In most cases, the operator does not know clearly about the position of the bucket teeth. Therefore, it is necessary to build a control system to track and follow the excavation process to maintain the set digging trajectory in the most accurate way. In the civil construction, this idea has been applied with intelligent excavators manufactured by companies such as Komatsu, Hitachi and Caterpillar [1], [2] using in digging canals, foundations or excavation of construction sites. To apply this idea to bomb/mine clearance, dynamic analysis and control approach of EDM require redesigning and recalculating for the complex operations. In addition, the commercial excavators which identify the digging depth by GPS system is extremely expensive and cannot be used in special sites. Thus, the EDM using in bomb/mine clearance must be integrated with the depth control system to position the digging depth. To build this system, it is necessary to study other methods, kinematics and dynamics of the entire mechanical, electro-hydraulic control system.

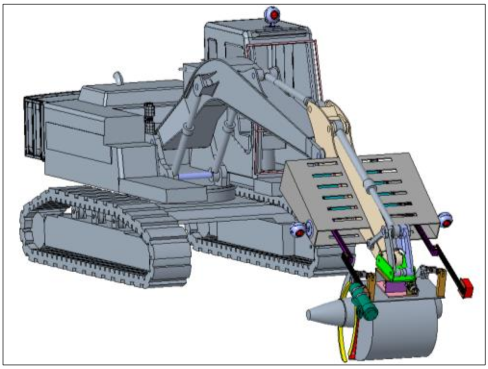

Figure 1: The EDM model

For controlling the depth of excavation, Sukharev et al. [3] introduced an automation control system for working process of a hydraulic single-bucket excavator. The author used the excavation parameters such as digging depth, length and digging direction. The working process of the excavator requires the coordination of three operations with high precision which requires a minicomputer processor attached to the machine. This is exceedingly difficult to do by human control. Haga et al. [4] designed a control system by calculating the position of the bucket tooth head, the speed and movement direction of the bucket. The digging depth is preset from the controller. The author used three sensors for the displacement of bucket cylinder, a lifting angle of the bucket arm, and the base machine tilt. In this method, the bucket position is relatively fixed to the bucket arm, the movement of the bucket is done by the operator and the lifting and lowering operation is controlled automatically according to the speed of the bucket arm movement. As a result, soil shear angle of the bucket is constantly changing which is difficult to obtain an optimal shear angle. Ruppel et al. [5] presented a control method to ensure excavation process according to a given depth. The author uses four angle-sensors or three-cylinder displacement-sensors and one angle-sensor. These sensors are arranged for determining: the inclination of the base vehicle; the angle between the base vehicle and the boom; the angle between the boom and the arm, and the angle between the arm and the bucket. In this method, only the operation of the bucket arm is controlled by the operator while the lifting and lowering operation of the boom, the forward and backward operation of the bucket are automatically controlled by the computer to maintain both the optimal cutting angle and digging depth. This method is the most effective for operations of bomb/mine clearance. For controlling the excavation process of single- bucket hydraulic excavator, most authors focused on automatic control process and control algorithms of excavators during excavation [6]-[8]. Some authors studied the real-time visualization, monitoring of excavation trajectory, and a 3D information display system [9]-[12].

For analysing the excavator behaviours in the kinematics and dynamics aspects, the authors focused on the basic kinematic calculations of the working equipment [5], the precise control of the digging depth of hydraulic excavators [13]-[15], the orbits of points on the working equipment and a working area [2], [16] kinematic modelling and the control system of a hydraulic excavator during excavation [11], [17]. In the recent time, there has not been any study in both kinetic and dynamic aspects for a complete system including hydraulic system, working equipment, and working environment of excavation bucket.

Based on the Ruppel's controlling approach of excavation depth, this paper focuses on kinematic analysis of working structure during digging process. It is required to ensure both the accuracy of bomb/mine excavation process and optimal cutting angle of the bucket. In addition, the influence of the structural errors on the accuracy of the bucket tooth trajectory is also investigated. The established dynamic model of the hydraulic system and the operating devices will be used as an important part of the simulating model. A complete system of EDM is simulated to evaluate the kinematic and dynamic behaviours during the excavation process with a given digging depth by using LMS Amesim software. The real EDM with Ruppel's control method is also manufactured which use the results from kinematic and dynamic analysis.

Kinematics and dynamics of digging depth control

For this problem, dynamic analysis for the working equipment of a EDM was assumed as below things:

i. The weight of arm, gripper, and boom mechanism ($m_1, m_2,$ and m_3) is located at the gravity center of each component.

ii. The deformation of the boom, gripper and arm mechanism were neglected because their stiffness is large enough.

Figure 2 illustrates the calculating diagram of the boom mechanism, gripper and arm mechanism, where: l_1 is the length from revolute joint O_1 of the boom to the gravity center of the boom; l_2 is the length from the revolute joint O_2 of the arm to the gravity centre of the arm; l_3 is the length from the revolute joint O_3 of the gripper mechanism to the gravity center of the gripper mechanism. F_{cy1}, F_{cy2}, and F_{cy3} are the forces triggered off by the cylinders that drive the gripper, arm, and boom mechanism. G_1, G_2, and G_3 are the weight of the gripper, arm, and boom mechanism respectively. The force due to the body weight of the operating equipment is attributed to the rod head of hydraulic cylinder. The friction is applied for hinge joints connecting hydraulic cylinders and structures of the gripper, arm, and boom mechanism as well as in hydraulic cylinders.

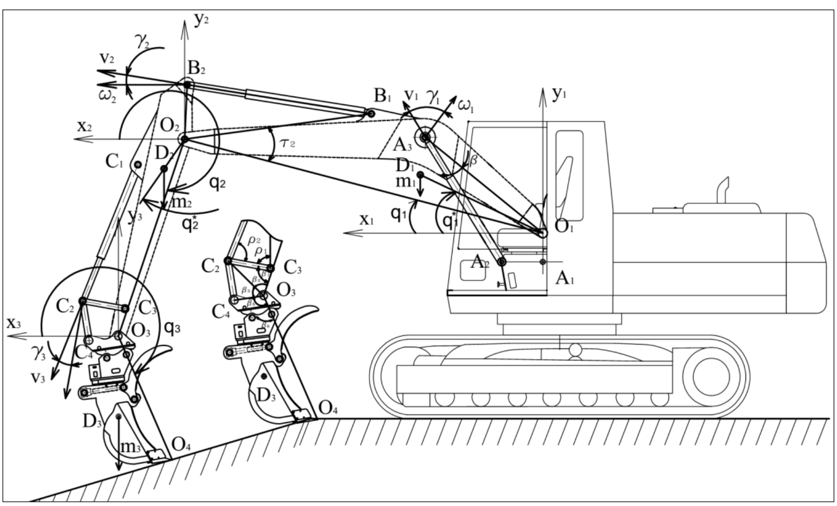

Figure 2: Calculation diagram of working equipment of EDM

The kinematic calculating diagram of the digging depth control during excavation process for the remote-controlled explosive disposal machine is shown on Figure 3.

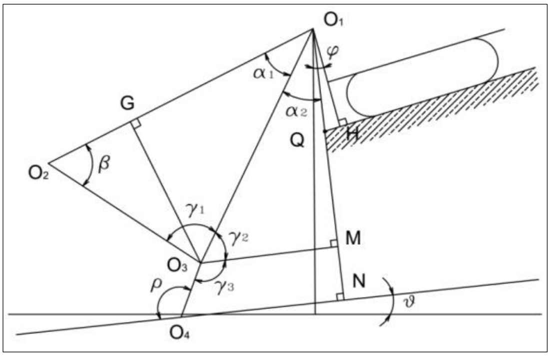

Figure 3: Calculation diagram of digging depth control

where: O_1O_2 is the boom length which is the distance between the revolute joints of the boom and the arm; O_2O_3 is the arm length which is the distance between the revolute joints of the arm and the bucket; O_3O_4 is the bucket length which is the distance from the bucket attachment to the bucket teeth; O_1H is the working height which is the distance from the boom joint to the surface of the machine base; QN is a required digging depth; ρ is a required cutting angle; ϑ is an inclination of the excavation surface; φ is the tilt angle of machine base.

At any point in the working cycle which depends on the angle value of β, the control angles $\alpha = \alpha_1 + \alpha_2 + \alpha_3, \alpha_3 = \varphi - \vartheta$ and $\gamma = \gamma_1 + \gamma_2 + \gamma_3$ are calculated as follows:

$$\alpha = arcsin\frac{O_2O_3 \sin\beta}{\sqrt{O_1O_2{}^2 + O_2O_3{}^2 - 2O_1O_2O_2O_3 \cos\beta}} + \frac{\pi}{2} - \\ - arcsin\frac{\frac{O_1H}{cos(\varphi - \vartheta)} + QN - O_3O_4 \sin\rho}{\sqrt{O_1O_2{}^2 + O_2O_3{}^2 - 2O_1O_2O_2O_3 \cos\beta}} + \varphi - \vartheta \tag{1}$$

$$\gamma = \pi - \beta - arcsin\frac{O_2O_3 \sin\beta}{\sqrt{O_1O_2{}^2 + O_2O_3{}^2 - 2O_1O_2O_2O_3 \cos\beta}} + \\ + arcsin\frac{\frac{O_1H}{cos(\varphi - \vartheta)} + QN - O_3O_4 \sin\rho}{\sqrt{O_1O_2{}^2 + O_2O_3{}^2 - 2O_1O_2O_2O_3 \cos\beta}} + \rho \tag{2}$$

The general driving calculation diagram for the working mechanisms is shown in Figure 4. The cylinder is represented by the moving mass, $m_{p_{i.i}}$, including the weight of the rod and the piston.

The load acting on the cylinders consists of two components: dynamic force which is calculated according to the referenced masses m_{modi}; static force, F_{st}, is determined by the weight of the working mechanism. The transformation from the displacement value of the cylinder to the extrapolated coordinates is determined by the transmission ratio of the mechanisms, i_{xq}.

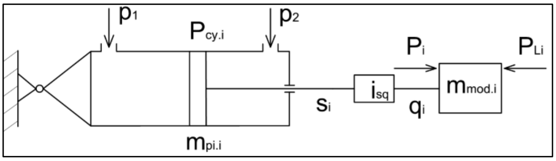

Figure 4: Calculation diagram of working cylinder

Based on the calculation diagram of the working cylinder, the system of equations representing the dynamics of the operating cylinder is as below:

$$F_{cy.i}p_{cy.i} - k_{fri-cy}\frac{ds_i}{dt} - P_{Li} = (m_{mod.i} + m_{pi.i})\frac{d^2 s_i}{dt^2} \tag{3}$$

where: F_i is the force generated by the working cylinders when the mechanisms were rotated; P_{L_i} is the force produced by the external loads acting on mechanisms referring to the working cylinder; m_{mod_i} is the mass referring to the working cylinders; k_i is the number of working cylinders driving each mechanism.

The inertia moment, J_{mod_i} is determined as a function which depends on the displacement of the rod $x_{p_{i.i}}$, the excavation resistance of the soil, and the weight of the structures during the excavation. The inertia moments of the excavation-gripper mechanism with respect to rotating axes of $O_3, O_2,$ and O_1 are:

$$J_3 = m_3(l_{O_3D_3}\,cosq_3)^2 \tag{4}$$

$$J_2 = m_2(\frac{l_{O_2O_3}}{2}cosq_2)^2 + m_3(l_{O_2O_3}\,cosq_2 + l_{O_3D_3}\,cosq_3)^2 \tag{5}$$

$$\begin{aligned} J_1 &= m_1(l_{O_1D_1}\,cosq_1)^2 + m_2(l_{O_1O_2}\,cos(\,q_1 - \tau_1) + \frac{1}{2}l_{O_2O_3}\,cosq_2)^2 + \\ &+ m_3.(l_{O_1O_2}.cos(\,q_1 - \tau_1) + \frac{1}{2}l_{O_2O_3}.cosq_2 + l_{O_3D_3}.cos\,q_3)^2 \end{aligned} \tag{6}$$

The modified weights of the excavation-gripper, boom, and arm mechanism referred to the driving cylinders are calculated as follows:

$$m_{mod\,1} = J_1 \frac{1}{(l_{O_1A_3} \cos\gamma_2)^2};\ m_{mod\,2} = J_2 \frac{1}{(l_{O_2B_2} \cos\gamma_3)^2};$$
$$m_{mod\,3} = J_3 \frac{1}{(l_{C_2C_3}.\cos\gamma_3)^2} \tag{7}$$

To determine the static load, Dombrovsky method is used [18], this load is applied to the working cylinders due to the mass of the working structures and the excavation resistance of the soil. The load acting on the cylinder driving the excavation-gripper mechanism is determined by the formula below:

$$P_{L_3} = \frac{m_3 g l_{O_3D_3} \cos q_3 + P_1 l_{O_3O_4} \cos(q_3 + \beta_5) - P_2 l_{O_3O_4} \sin(q_3 + \beta_5)}{l_{O_3C_2} \sin(\beta_1 + \beta_2 - \rho_2)} \tag{8}$$

The tangential component of the excavation resistance is determined by the formula below [18]:

$$P_1 = F.k \tag{9}$$

where: $F = b.c$ is the cross-section area of the soil chip; k is the digging resistance coefficient of the soil; b is the bucket width; and c is the thickness of the soil chip. The normal component of the excavation resistance is determined as follows:

$$P_2 = (0{,}1 \ldots 0{,}2) P_1$$

When excavating with the manual method, the static moment with respect to the rotation axis passed through the point O_2. The load acting on the cylinder driving the excavation-gripper mechanism is determined by the formulas below:

$$\begin{aligned} P_{L_2} = \frac{1}{l_{O_2B_2} \cos(\gamma_2)} \Big(&\frac{1}{2} m_2\, g\, l_{O_2O_3} \cos(q_2) + m_3 g (l_{O_3D_3} \cos(q_3) \\ &+ l_{O_2O_3} \cos(q_2)) + \\ P_1 (l_{O_2O_3} \cos(q_2) &+ l_{O_3O_4} \cos(q_3 + \beta_5)) - P_2 (l_{O_2O_3} \sin(q_2) \\ &+ l_{O_3O_4} \sin(q_3))\Big) \end{aligned} \tag{10}$$

$$P_{L_1} = \frac{1}{l_{O_1A_3} cos(\gamma_2)} (m_1 g l_{O_1A_5} cos(q_1^*) + m_2 g(l_{O_1O_2} cos(q_1^* - \tau_1) + \frac{1}{2} l_{O_2O_3} cos(q_2)) + m_3 g(l_{O_1O_2} cos(q_1^* - \tau_1) + l_{O_2O_3} cos(q_2) + l_{O_3D_{16}} cos(q_3))) \quad (11)$$

The kinematic and dynamic analyses of each component in the EDM were presented in the previous studies [19]-[21]. Consequently, a complete kinematic and dynamic behaviours for entire hydraulic system to drive the working equipment were integrated for ensuring both dynamic accurate of digging path and the effective cutting angle at the same time. A diagram of dynamic calculation for each element (main pump, main valve, and EPPR valve) and a dynamic calculation diagram of the entire hydraulic system are shown [19]. In this diagram, the displacements $s_1, s_2,$ and s_3 of the cylinders are converted into feedback signals to reduce the valve of the electric proportional pressure.

The influence of operation factors on the accuracy of digging depth.

Initial setup for dynamic simulation

The integrated dynamic behaviors of the complete system during the excavation established in the above part were utilized for evaluating the dynamic behaviors in the excavation process by using LMS Amesim software [22]-[24]. Elements in the main hydraulic system, control hydraulic system and working equipment are designed from the LMS Amesim libraries as shown in Figure 5 and Figure 6.

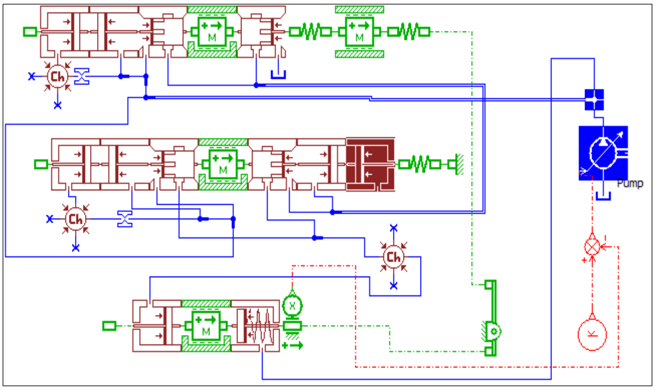

Figure 5: Simulation of the main pump with control LS-PC

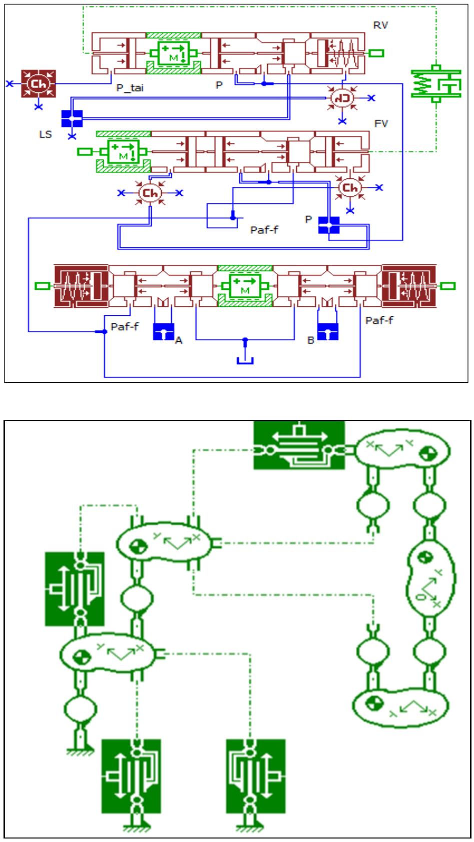

Figure 6: Simulation of the main valve and the working equipment

The input data for simulating the dynamic excavation process of EDM, the initial parameters were given as below:

i. The base machine stands on a horizontal plane, the digging angle $\varphi = 0°$ and inclination angle $\vartheta = 5°$;

ii. The pumps in the hydraulic driving system are hydraulic pump HPV 95 which has maximum operating pressure $p_{max} = 350$ bar, the specific flow of 95 cc/rev; the diameter of PC and LS valves is 10 mm with a NO mode;

iii. The control pump uses mechanical feedback control is gear pump which has the specific flow of 36 cc/rev and maximum operating pressure at 30 bar;

iv. Main valve has a spool diameter of 25 mm and electric proportional reducing valve has a main spool diameter of 10 mm, maximum operating pressure at 50 bar and electrical control signal $i_{max} = 800$ mA.

The operating cylinder has operating parameters such as: cylinder diameters of D_1=105 mm, D_2=115 mm, D_3=95 mm; rod diameter d_1=70 mm, d_2=75 mm, d_3=65 mm; cylinder strokes of l_1=990 mm, l_2=1175 mm, l_3=885 mm. Parameters of parts of operating equipment has: O_1O_2=3.992 m, O_2O_3=2.214 m, O_3O_4=1.457 m, m_1=936 kg, m_2=410 kg, m_3=50 kg.

Simulating Results and Discussion

The simulated results with The Ruppel's control approach for the complete hydraulic system are shown on Figures 7-10. The control approach must satisfy both the accurate dynamic behavior (digging path) and the optimal cutting angle during bomb/mine excavation process. The study of the excavation process is carried out in two cases:

i. Studying the influence the control delay of the electric joystick (the degree of quick/slow open when controlling the joystick) on the accuracy of digging depth, assumed in the case of no excavation resistance of the soil;
ii. Studying the influence the soil excavation resistance on the accuracy of digging depth for each soil layer.

The first case as shown in Figure 7, the period from 0 to 5 seconds is the control signal to move the bucket teeth into the starting position of digging operation by lowering the boom; keeping the position relative to the lifting arm of bucket hand and bucket. It is understood that current of 400 mA is supplied from the electric control hand to the pressure relief valve to control the lifting and lowering cylinder and the current of 680 mA and 560 mA are also supplied from the electric control hand to the proportional pressure relief valve to control the bucket arm and the bucket is remained the same the position. Then the absolute angular displacements (q_1, q_2, and q_3) of all three mechanisms of boom, arm and bucket change accordingly (Figure 8).

This control process results in moving the excavator bucket from the elevation of the coordinates (4.7 m; -0.4 m) to the starting position of the digging operation at the coordinates (3.78 m; -2.88 m) corresponding to the segment of AB (Figure 9), the excavation process is started from point B as above cases.

From the time of 5 seconds, the excavation process is operated according to the method and the kinematic relationships with the control delay of 1 second as shown on Figure 7. It is understood that the control signal from the electric control hand supplied a current from from 680 mA to 900 mA during 1 second to the EPPR valve to control the bucket arm. Then, to ensure the digging depth with the given surface inclination, the control signal is supplied to the proportional piezoelectric relief valve to control the boom and the bucket changes respectively from 400 mA to 430 mA and from 560 mA to 390 mA with a corresponding delay of 1 second. Thus, Figure 8 showed that three driving cylinders operate with the same delay of 4 s to achieve the required value of rotation angle (q_1, q_2, and q_3) corresponding to BC segment of the bucket tooth displacement in the working plane (Figure 9).

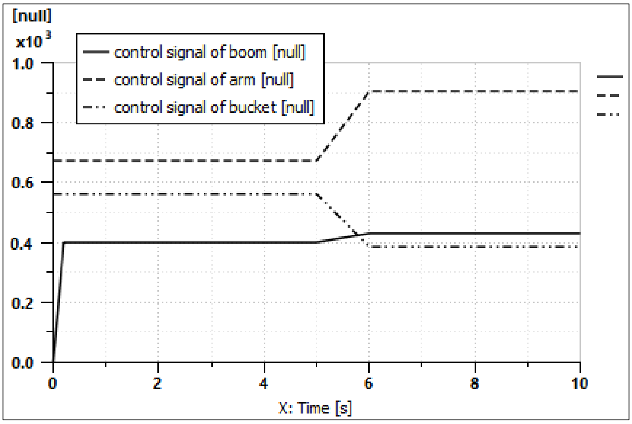

Figure 7: Control signal of the boom, arm, and bucket

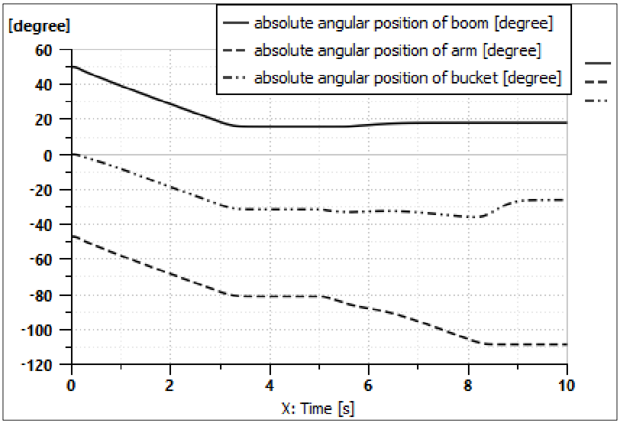

Figure 8: Angular positions of the boom, arm, and bucket

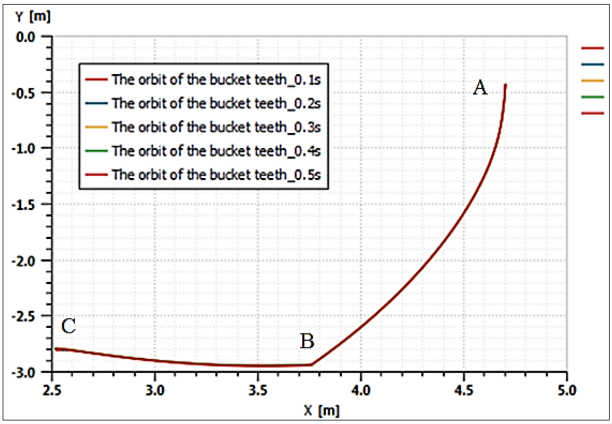

Figure 9: A orbit of bucket teeth in the working plane with different control delays

At the same time, according to this graph (Figure 9), it is found when changing the control signal from the electric control hand supplying to the proportional piezoelectric relief valve to control the bucket at different levels of delay (0.1-0.5 seconds; etc.) does not affect the displacement trajectory of the bucket teeth in the working plane (coreponding to the segments of AB and BC). It means that digging depth for each soil layer (segments of BC) completely coincides. At the same time, with an inclination angle of the digging surface of 50^{o}, the error of the excavation depth for each soil layer is small which is in the range of ±5 cm in accordance with the standard SNiPom4.02-91.

The bucket control process with different digging resistance is shown in Figure 10. While the digging resistance is below 2500 N, the position of the bucket teeth follows the required trajectory with the allowable error according to SNiPom4.02-91 standard. However, while the digging resistance value is above 2500 N, the position of bucket teeth follows the different trajectories with the larger digging error (over ±10 cm), which does not meet the initial requirements. The EDM used for practical experiments is shown in Figure 11.

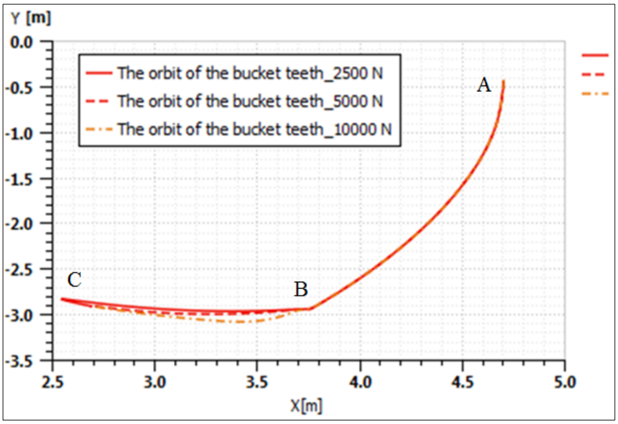

Figure 10: The orbit of the bucket teeth in the working plane at different digging resistances

Figure 11: The EDM using for practical experiments

Conclusion

The kinematic analysis for the control of digging depth by using the Ruppel's approach was presented in this study. In addition, a dynamic analysis for the entire system of the EDM including both the operating equipment system and the hydraulic driving system occurring the digging control process was also performed. This complete dynamic model is simulated on LMS Amesim environment to deeply understand the dynamic behaviour and the influence of the arm control signal, the digging resistance of the soil in the digging control process. It showed that the control of digging process has two main external influences including the operator's control and excavation resistance. The delay level of operator's control does not affect the accuracy of the digging depth, while the excavation resistance has a significant influence. Therefore, in practice to ensure the accuracy of the excavation process, it is necessary to dig each thin layer of soil so that the digging resistance is not too great. According to the calculation with a value of 2500 N, the digging resistance will correspond to each chip thickness: for first class soil - 10 cm, for second class soil - 7 cm, for third class soil - 4 cm, for forth class soil - 2.5 cm. For hard soils, it is very difficult to ensure the accuracy of the digging depth; therefore, the soil needs to be softened before digging.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

Funding

This work received no specific grant from any funding agency.

Conflict of Interests

All authors declare that they have no conflicts of interest

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