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The Hardware-In-Loop Simulation Research on Trajectory Control and Modeling Parameter Estimation of Working Device of Hydraulic Excavator

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***Abstract*—The retrofitted electro-hydraulic system for hydraulic robotic excavator was introduced. According to the principle and characteristic of LUDV system, the model of electro-hydraulic system was derived, simplified and verified by relative experiment. Trajectory controller prototype was designed based on incremental theory of trajectory controlling to verify the accuracy of the controlling. Trajectory controller and VR software compose Hardware-In-Loop simulation environment. Under the circumstances, the level straight digging experiment of model trajectory controlling was set .Good control effect was achieved by adjusting controlling parameters, finally anticipated controlling requirement can be accomplished by trajectory controller prototype system. By analyzing the structure and load-bearing of boom, the method and equations of estimation for such parameters, the range of flow gain coefficient (Kq) was given on the base of experiment identification. It shows that the foundation for the trajectory tracking and accurately location control of excavator's manipulator is laid.**

Key words: Electro-hydraulic proportional system; Parameter estimation; The hardware-in-loop simulation; Trajectory control; Open graphics library; Hydraulic excavator

I. INTRODUCTION

Due to their versatility and convenience, the hydraulic excavators currently dominate construction equipment fleets operating at most civil engineering work sites. Mechanical-electrical integration, automation have been the development direction of construction machinery, so the automation of hydraulic excavators have gradually become a focus of national research [1] [2]. The automatic control of working devices have turned into a hot topic at home and abroad[3]. The paper focuses on researching the simplified model of hydraulic system's working device, model parameter estimation method and formulas estimation ,started from the dynamics of the electro-hydraulic proportional valve, the system's flow equation, continuity equation and force balance equations.

Semi-physical simulation is also known as hardware-in-loop simulation. One part of the system is the actual one and computer simulation is applied in the other part. Semi-physical simulation links the controller physical and model of control object (mathematical simulation) together to implement experiment on a computer simulation. The controller's dynamic, static characteristics and non-linear factors can be truly reflected in the test. Accordingly, it is a more realistic simulation of experimental techniques [4]. Experiments develop the kind of trajectory control physic as the prototype, which also combine with a self-designed virtual reality VR software to carry out the semi-physical simulation. The purpose is to verify the trajectory control strategy of the prototype, and lay the foundation for the development of the actual product [5].

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II. TEST EXCAVATOR'S INTRODUCTION AND SEMI-PHYSICAL SIMULATION PLATFORM STRUCTURE

Object of study in this paper is a backhoe hydraulic excavator (see Figure 1).In trajectory control, the working device is seen as a 3 degree of freedom mechanical hand (boom, arm and bucket equipped with inclination sensors respectively), bucket tip's control traces desired trajectory, which is called target value. In the actual control process, the action of boom, arm and bucket cylinder are controlled by computer program, to coordinate action of three hydraulic cylinders, and ultimately working device tracks target trajectory.

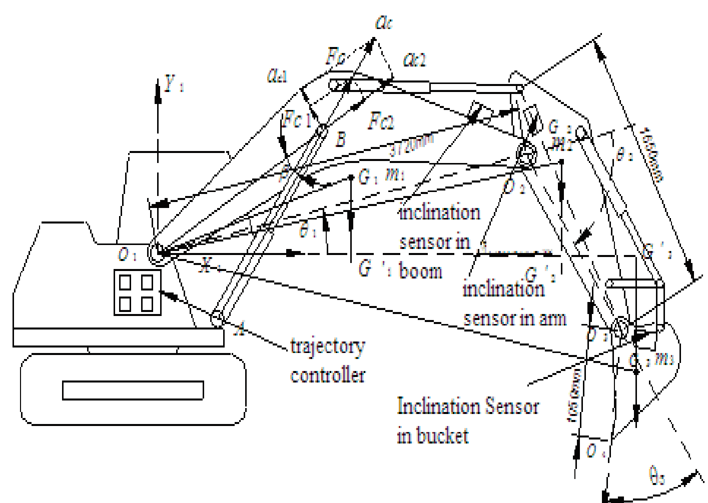


Fig.1. Schematic diagram of excavator manipulator

This paper uses SWE85 hydraulic excavator, made by Sunward Intelligent Machinery Co.Ltd, as a platform for the robot transformation. Through installation of the electro -hydraulic proportional pressure-reducing valve in the original system, electro-hydraulic pilot circuit replaces the original hydraulic pilot circuit. The modified electro -hydraulic proportional system is shown in Figure 2. Test platform uses Load Independent Flow Distribution system made by Rexroth (the following is referred as LUDV).

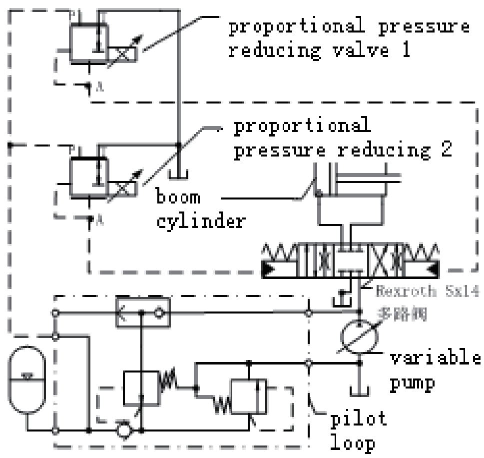


Fig.2. The retrofitted electro-hydraulic system of excavator

A Semi-physical simulation platform

Semi-physical simulation platform is shown in Figure 3, the right of fig.3 is the trajectory controller's prototype. Incremental control algorithm is used in trajectory control strategy, through the USB-CAN interface it develops the VR software in the PC, and transfers control and feedback signals, which form hardware loop structure, under Semi-physical simulation experiment environment. In every step of the operation process, the upper computer VR model obtains current value from trajectory controller, the new location is obtained by kinematics calculating, and the value of new point passes back to trajectory controller. The angle signal is further processed by trajectory controller, it gets new current value through the recursive incremental control algorithm ultimately, the value sends back to upper computer VR software by USB-CAN interface. These form a closed-loop control. The output of control current value drives VR model to achieve a good trajectory control effect, because of prototype adjusts control parameters continuous -ly.

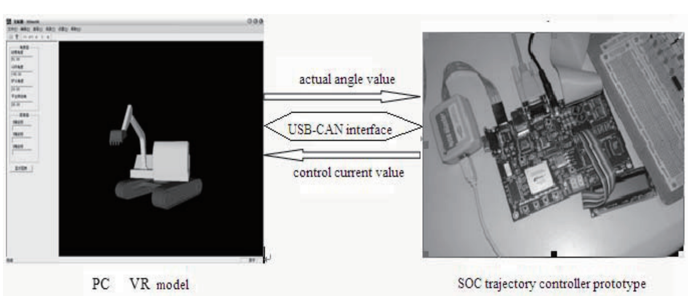


Fig.3. Semi-physical simulation platform

B Trajectory Control Strategy

Mechanical hydraulic system of hydraulic excavator has large inertial mass, a number of non-linear factors are included, which make the trajectory tracking control difficult to the motor-driven articulated industrial robot, but traditional PID control will increase much more difficulty of parameters adjustment. Therefore, experiments use a recursive incremental control strategy based on stick, that is, arm hydraulic cylinder moves at a constant speed, boom and bucket hydraulic cylinders track the corresponding action, to achieve linear movement of bucket tip[6][7]. Suppose the length of boom, arm and bucket hydraulic cylinder are , respectively, l_2, l_3 and l_4,and the next target length are l_{2n} , l_{3n} and l_{4n}, the length of last sampling point are l_{20} , l_{30} and l_{40},control variables of last point are i_1 , i_2 and i_3, new control variables are i_{1n} , i_{2n} and i_{3n} ,dead zone value of valves are i_{10} , i_{20} , i_{30} .

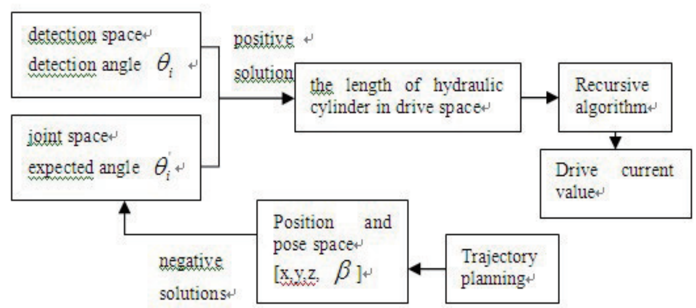


Fig.4. Trajectory control theory of the controller

If $|l_2 - l_{20}| > 0, i_1 > i_{10}$,

Then $k_1 = (l_2 - l_{20})/(i_1 - i_{10})$.

If $|l_3 - l_{30}| > 0, i_2 > i_{20}$,

Then $k_2 = (l_3 - l_{30})/(i_2 - i_{20})$.

If $|l_4 - l_{40}| > 0, i_3 > i_{30}$,

Then $k_3 = (l_4 - l_{40})/(i_3 - i_{30})$

k_1 , k_2 and k_3 are Scale factor, i_2 is given, so

$$i_{1n} = k_2(l_{2n} - l_2)(i_{2n} - i_{20})/k_1(l_{3n} - l_3) + i_{10} \quad (1)$$

$$i_{3n} = k_2(l_{4n} - l_4)(i_{2n} - i_{20})/k_3(l_{3n} - l_3) + i_{30} \quad (2)$$

Firstly, a certain step is set in horizontal and vertical direction in the control, then the goal expectation of boom, arm, bucket rotation angle are obtained, the values of l_{2n}, l_{3n} and l_{4n} are obtained, based on the drive space kinematics equations. By equation (1) and (2) it can be observed that the controlled current value of arm i_{2n} is fixed, the boom and bucket's current value, i_{1n} and i_{3n} track i_{2n} changes. After these steps the control of three hydraulic cylinder is achieved. Figure.4 is the control block diagram. Recursive incremental control algorithm is the same as digital PID algorithm in practical applications, considering spool dead zone compensation is needed, in addition, setting the value of i_{2n} ,the largest and the smallest control value of i_{1n} and i_{3n}, continuous adjustments can achieve good control effect. Accordingly, the number of adjustable parameters and difficulty relative to PID algorithm can be reduced.

C The implementation of virtual reality VR software based on OpenGL

OpenGL is a high performance open graphics library technology, which provides the basic 3D graphics unit, and a very clear graphics function. It also has a powerful 3D modeling capabilities, as well as the frame buffer animation technology, which let real-time interactive operation come true. OpenGL has a superior performance graphics programming application interfaces, which can be widely used in various computer systems, and gradually become an accepted 3D graphics development standards, the features that have nothing to do with hardware can make it implemented on different hardware platform [8]. Therefore, OpenGL technology is used in experiment to develop VR software.

1) *Achieve excavator 3D model by VR software*

OpenGL only provides the way of basic points, lines and polygons to construct 3D model. Excavators'3D model is so complex that graphics function in OpenGL is not enough, so it is build in another way. First, five main parts are drawn: undercarriage, rotating platforms, boom, arm, bucket by three-dimensional mapping software Pro / E. It exports file in OBJ format, which is the data to draw 3D model. Then it processes documents class under the OpenGL, read the class of file and convert to the point, line, surface information which can deal with, finally it achieves 3D model [8]. Furthermore, in order to achieve the model succession movement [9] [10], this paper adopts a "nested matrix stack" method, which achieves 3D model between out of the stack operations and into the stack operations.

2) *Technology of software development*

Double-buffering technology. In order to generate a smooth 3D animation models, it uses the foreground and background buffer cache, background buffer cache calculates the scene and produces animation, while the foreground show picture which has been drawing by background, thus it enhances continuity and movement of the hydraulic excavator's 3D animation.

Achieve USB-CAN communication function. To ensure real-time nature, it uses multi-threaded programming, which utilizes the thread mechanism to control data's receiving and transmit [11]. It is an important data transmission interface in simulation.

Hash table data structure. To achieve 3D model's motion controlled by keyboard, hash table data structure is used. When key is pressed, the message process function OnKeyDown ( ) will assign that corresponding element as 1, when the button pop-up, it is 0. So in the timer processing function OnTime ( ), the state of button in the keyboard can find through checking hash values, and make the appropriate treatment.

III. ELECTRO-HYDRAULIC PROPORTIONAL SYSTEM MODEL

A Dynamic characteristics of electro -hydraulic proportional valve

The transfer function between Electro-hydraulic proportional valve's spool displacement and the input current can be simplified to a first-order link.

$$X_v(s)/I_v(s) = K_I/(1+bs) \qquad (3)$$

K_I is proportional valve current gain, b is inertia time constant. $I_v=I(t)-I_d$, $I(t)$ is proportional valve control current, I_d is the initial operating current.

B The flow equation of electro-hydraulic proportional valve

The principle of LUDV system [12] works out valve flow equation, as the (4), (5) below,

$$Q_1 = C_d W X_v \sqrt{\frac{2}{\rho}\Delta P_1} = \begin{cases} C_d W X_v \sqrt{\frac{2}{\rho}\Delta P}, I(t) \ge 0 \\ -C_d W X_v \sqrt{\frac{2}{\rho}(P_1 - P_r)}, I(t) < 0 \end{cases} \qquad (4)$$

$$Q_2 = C_d W X_v \sqrt{\frac{2}{\rho}\Delta P_2} = \begin{cases} -C_d W X_v \sqrt{\frac{2}{\rho}(P_2 - P_r)}, I(t) \ge 0 \\ C_d W X_v \sqrt{\frac{2}{\rho}\Delta P}, I(t) < 0 \end{cases} \qquad (5)$$

As shown in Figure 5, regardless of how the load changes, *ΔP* remains at 2.0MPa. It shows traffic flow through the valve and the valve opening area is proportional. Therefore (4) can be simplified as follows,

$$Q_1 = K_q X_v(t) \text{ , } I(t) \ge 0 \text{ , } K_q = C_d W \sqrt{2\Delta P/\rho} \qquad (6)$$

K_q is Valve flow gain coefficient，□ΔP＝2.0MPa.

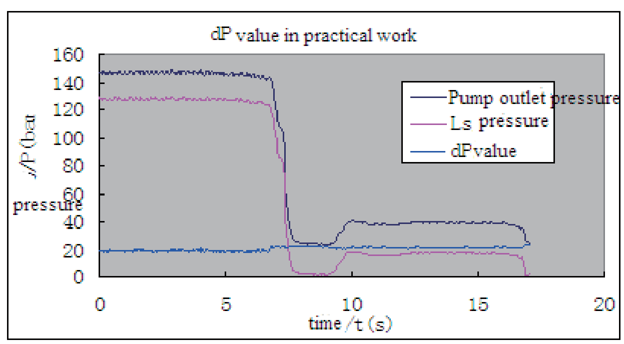


Fig.5. Value of *ΔP*

C Simplified model of electro-hydraulic proportional system

Ignoring leakage effects, when the no-rod cavity goes into oil and the rod cavity oils out, the continuity equation of hydraulic cylinder is obtained [5]:

$$Q_1 = A_1\dot{y} + V_1 \cdot \dot{P}_1/\beta_e \quad Q_2 = A_2\dot{y} - V_2 \cdot \dot{P}_2/\beta_e \qquad (7)$$

Hydraulic cylinder force balance equation:

$$F = p_1A_1 - p_2A_2 = M\ddot{y} + B_c\dot{y} + F_l \qquad (8)$$

(6)-(8) in Laplace transform, it can be derived electro-hydraulic proportional system, a simplified model[12] [13] as follows:

$$Y(s) = [b_I X_v(s) + b_f sF_l(s)] / s(a_0 s^2 + a_1 s + a_2) \quad (9)$$

$b_I = \beta_e K_q (A_1 V_2 + V_1 A_2^2 / A_1)$, $b_f = V_1 V_2$, $a_0 = V_1 V_2 M$, $a_1 = B_c V_1 V_2$, $a_2 = \beta_e (V_2 A_1^2 + V_1 A_2^2)$.

IV. Parameter Estimation and Functional Simulation

A Parameter estimates Kq

When working device is running, the flow meter can be used to measure flow. Figure.6 is a step response curve of hydraulic cylinder in boom, the curve also verify that equation (3) is correct. Through the test curve, combined with equation (3) and (6), the range of K_q can identify. It can also identify KqK$_I$ = 2.825×10^{-4} m^3/s/A from figure.5， time constant b＝0.1946s.So the scope of K_q is obtained through experiment.

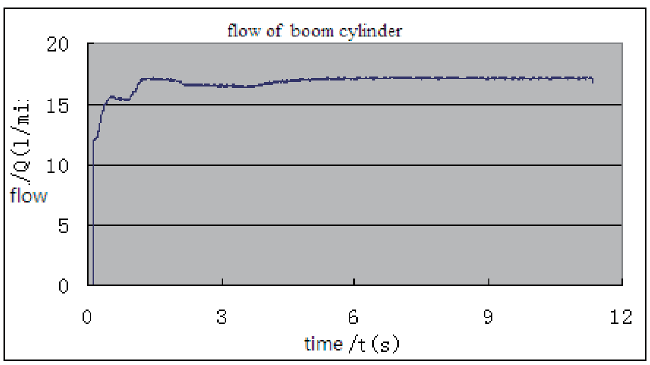
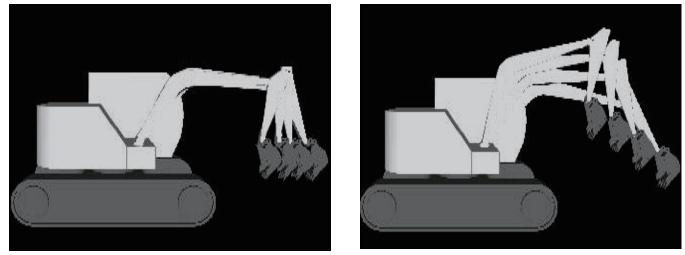


Fig.6. Flow of boom cylinder

B Function Simulation of VR software

The virtual reality of VR software achieves three functions: excavator is manipulated by keyboard simulation, auto -digging demonstration and automatic digging simulation. The interface of software is shown in Figure.3 (left). Software is tested according to three functions above, Figure 7 (a) (b) represent trajectory results of auto-digging the level of horizontal lines and with 30° angle. The results show that it can achieve function requirements. This experiment mainly uses auto-digging simulation feature, which can get proportional valve's current value from the lower computer controller. According to the transformation calculations of simulation model, movement data of 3D models, 3D animation on screen, curve of simulation data are obtained.



(a) (b)

Fig.7. Straight-line trajectory model Effect Picture of VR

V. Semi-Physical Simulation Test

Upper computer PC connects prototype of trajectory controller through USB-CAN interface in the simulation experiment, and its communication mode is full-duplex form. It also sends out a new angle value of working device, trajectory controller transmits real-time control current value, which constitute the hardware in the loop structure. The hardware is shown in Figure.7 in the debugging experiment.

For real-time simulation, simulation system requires the study system to keep state consistent, behaviour consistent and time consistent. Loop simulation connecting the actual equipment and real-time is the basic requirement of semi-physical simulation [14] [15]. In the trajectory controller, the prototype system operates task schedule to ensure real-time through real-time operating system, PC host is multi-thread program, which also guarantees real-time simulation. This experiment which sets the level of excavator working trajectory is a straight line away from the inside to outward movements, bucket tooth tip Z-coordinates remain -100cm. Bucket runs from 500cm to 300cm in the X-axis, Y-axis coordinate remains 0, the displacement process is divided into 150 time steps, every step is 1.33cm. Recursive control parameters need to adjust simulation repeatedly in control algorithm, the purpose of tracking control is achieved finally.

The above simulation adjusts the control parameters, the motion state of excavator model is observed through USB-CAN interface, and the control effect curve is drawn out which verify the rationality of control algorithms and estimate the resulting tracking error. Boom angle adjustment is relatively small, the resulting angular error is also small, so the angle of theoretical value basically corresponds to the actual value. But arm and bucket's large angle changes would produce a certain tracking error, that because the angular velocity greatly change in the bucket movement process, it will inevitably affect the angle of curve in defined step circumstances, the theoretical calculation and the actual values are shown in figure.8. From figure.9 it can be observed that control current signals of boom and bucket are always change, but signals of arm trends to be a constant value. Boom and bucket are tracking arm. Figure.10 shows a horizontal line trajectory tracks the target with step change, the first is large fluctuation, but quickly stabilized, the curve is less sensitive in the middle process, and the control effect is relatively stable. From the tracking curves and analysis of the action implementation by VR models in the virtual prototype, the purpose of automatic straight line trajectory control is achieved, motion control system can work in desired control requirements, the simulation of experiments to a certain extent prove that the prototype system is correct [16].

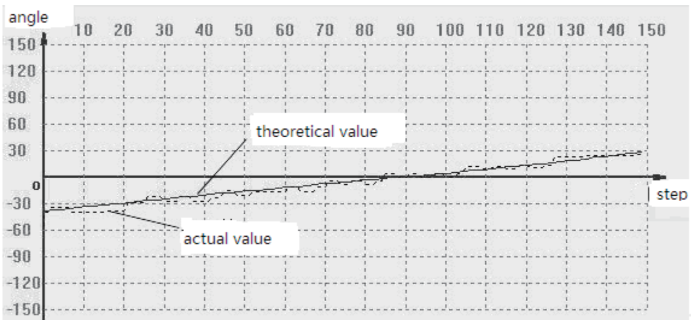


Fig.8. Bucket's tracking curves of theoretical angle value

and the actual value

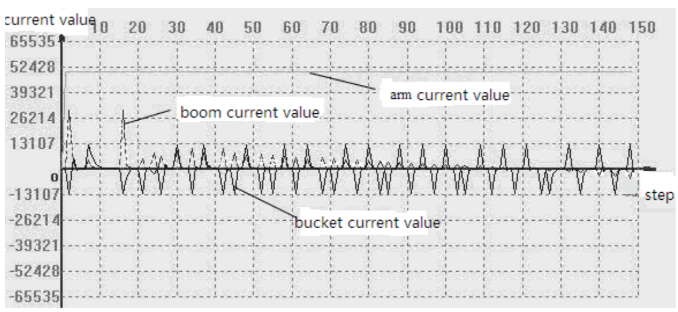


Fig.9 Movement device's tracking curve of current values

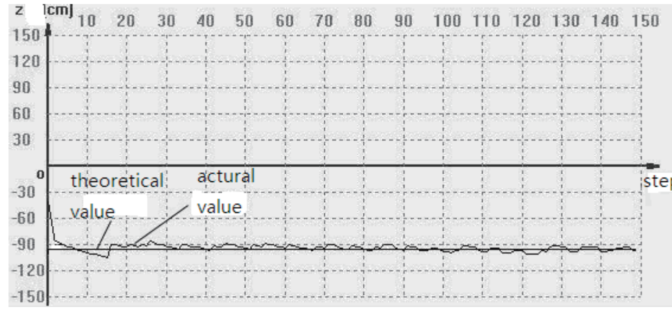


Fig.10 Tracking curve of horizontal trajectory

VI. Conclusion

1. Combining of the characteristics of test machine hydraulic system in this paper, the model of electro-hydraulic proportional system is established, the system's simplified model is also obtained. There are some unknown key parameters in the model, paper gives the range of variation of their value respectively by theoretical derivation and experimental methods, and tests are used to validate this model. So designing practical controller is applicable.

2. To verify the correctness of excavator control strategy, experiment also designs the semi-physical simulation platform. It is easy to use incremental recursive control algorithm to research trajectory control strategy which is based on lower computer controller. At the same time, through the data exchange of USB-CAN interface and upper Computer Simulation VR software based on OpenGL, it is sure that controller prototype can achieve the desired trajectory control results through trial and error debugging, and therefore, proves the correctness of the control system design.

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