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Mathematical Modeling and Fuzzy Control of a Leveling and Erecting Mechanism

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Original scientific paper

The moving process of a leveling and erecting mechanism is complicated, which involves six hydraulic cylinders. The research established mathematical model and optimized the moving process of the leveling and erecting mechanism. Kinematic analysis of the mechanism was accomplished. Mathematical model of the hydraulic system was established. Working scheme was designed consisting of workflow, trajectory planning, leveling strategy and control method. The mechanical, hydraulic and control models were respectively established in Pro/E, ADAMS, AMESim and Simulink software. Co-simulation was carried out to validate the designed scheme. Experiment was completed on a platform. The results of simulation and experiment indicate that the designed scheme is feasible. Fuzzy adaptive PID controller has an excellent effect in controlling the leveling and erecting mechanism.

Key words: Co-simulation, Erecting, Fuzzy adaptive PID control, Leveling, Trajectory planning

Matematičko modeliranje i neizrazito upravljanje mehanizmom za poravnavanje i podizanje. Gibanja mehanizma za poravnavanje i podizanje složeni je proces koji uključuje šest hidrauličkih cilindara. Istraživanje postavlja matematički model i optimizira proces gibanja mehanizma za poravnavanje i podizanje. Provedena je kinematička analiza mehanizma. Postavljen je matematički model hidrauličkog sustava. Radni program načinjen je uključujući tijek rada, planiranje trajektorije, strategiju poravnavanja i metodu upravljanja. Mehanički, hidraulički i upravljački modeli redom su izvedeni u Pro/E, ADAMS, AMESim i Simulink programskim paketima. Provedena je kosimulacija za validaciju načinjenog radnog programa. Eksperiment je proveden na stvarnoj platformi. Rezultati simulacije i eksperimenta ukazuju na izvedivost predloženog radnog programa. Neizraziti adaptivni PID regulator daje odličan efekt pri upravljanju mehanizma za poravnavanje i podizanje.

Ključne riječi: Kosimulacija, podizanje, neizraziti adaptivni PID regulator, poravnavanje, planiranje trajektorije

1 INTRODUCTION

Leveling and erecting mechanism is widely used in engineering. Support way of leveling is divided into three points, four points and six points [1-2]. Leveling strategies contain displacement leveling strategy and angle leveling strategy [3]. More and more intelligent algorithms are used in the control of leveling mechanism. The erecting mechanism with movable back hinged bearing is a novel erecting mechanism. Compared with traditional erecting mechanism it adds horizontal cylinder, and therefore back hinged bearing can move in horizontal direction driven by hydraulic cylinder. The novel mechanism can fulfill the erecting requirements in strictured space. There is little research about the erecting mechanism. Y. B. Feng designed its hydraulic system [4]. Y. Y. Qiao simulated the erecting process with Simulink [5]. However, the above research only simulated the erecting process with alone software and did not carry out experiment validation.

Leveling and erecting mechanism contains mechanical and hydraulic system, and therefore one software cannot completely achieve its features. Co-simulation method with Pro/E, ADAMS, AMESim and Simulink has been widely used in research and simulation of hydraulic steel-belt overwind buffer device [6], variable displacement axial piston pump [7], the composite ABS control of vehicles [8], energy regulation based variable-speed electro-hydraulic drive [9], vehicle suspension systems [10], a robot arm with non-rigid transmission and so on [11]. The simulation results illustrate that co-simulation method has a good application in many areas and can save a lot of modeling time.

There are six hydraulic cylinders in the leveling and erecting mechanism. How to control them in coordination is a difficult problem. Fuzzy logic control has been widely used and can achieve desired effect. P. J. C. Branco [12] and R. K. Mudi [13] investigated using fuzzy control to reduce the influence of nonlinearities and parameter uncertainties in hydraulic systems. E. Detiček [14] presented a hybrid-fuzzy control strategy for position control of the electro-hydraulic linear drive. It was able of adaptation to parameter changes and to deal with nonlinear dynamic behavior associated with hydraulic motion system. M. Y. Kim [15] presented a robust PID like neuron fuzzy controller with online adjusting of controller gains. O. Cerman [16] introduced a method for design of a fuzzy sliding mode controller for electro-hydraulic servo mechanism. The results from above research show that fuzzy control has been successfully used in complex system and has a good performance.

The remaining of the paper is organized as follows. Mathematical model of the leveling and erecting mechanism is established in Section 2. Working scheme was designed in Section 3. In Section 4 and 5, simulation and experimental verification are completed. Section 6 concludes the paper.

2 MATHEMATICAL MODELING OF THE MECHANISM

The composition of the leveling and erecting mechanism is shown in Fig. 1. The leveling mechanism is composed of four single rod piston cylinders. The erecting mechanism with movable back hinged bearing is mainly composed of erecting arm, lock device, rail, slider, erecting and horizontal cylinder. Erecting arm is used to support and erect load from horizontal state to vertical state or back to flat. Lock device is applied to fixing and limiting the load against vertical and lateral movement on erecting arm. Erecting cylinder pushes the load and erecting arm rotating round back hinged bearing. Horizontal cylinder pulls back hinge bearing moving along the rail, realizing load moving in horizontal direction. Two horizontal cylinders are symmetrically arranged to ensure stability.

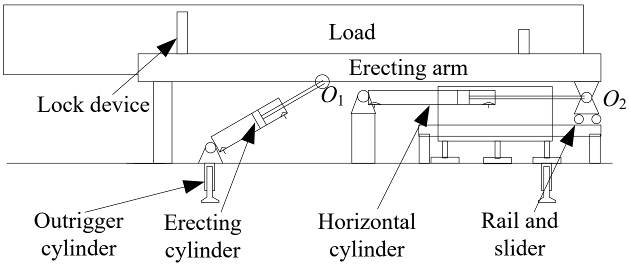


Fig. 1. Composition of the leveling and erecting mechanism

Compared with traditional erecting mechanism, the erecting mechanism with movable back hinged bearing adds rail, slider and horizontal cylinder. It adopts erecting and horizontal cylinders to realize erecting process. Erecting cylinder is used to alter amplitude and horizontal cylinder to transfer horizontal position. The novel erecting mechanism expands the moving form of erecting mechanism.

2.1 Kinematic analysis of the mechanical system

In order to acquire kinematic features of the novel erecting mechanism, kinematic analysis is accomplished firstly. In erecting process the load and erecting arm rotate around back hinged bearing and also move in horizontal direction. Kinematic model is indicated in Fig. 2.

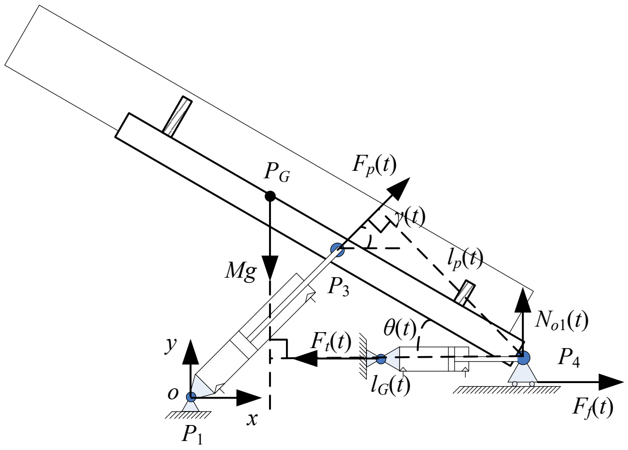


Fig. 2. Kinematic model of the erecting mechanism

In Cartesian coordinate system *oxy*, P_1 is the origin of coordinate system. Supposes coordinate of P_3 is $(x_2(t), y_2(t))$ and coordinate of P_4 is $(x_1(t), y_1(t))$. The following equations can be acquired based on geometric relationship.

$$\sqrt{x_2^2(t)+y_2^2(t)}-l_{ei}=\int_0^t v_2(\tau)d\tau, \tag{1}$$

$$\sqrt{[x_1(t)-x_2(t)]^2+[y_1(t)-y_2(t)]^2}=l_{em}, \tag{2}$$

$$\theta(t)=\arctan\frac{y_2(t)-y_1(t)}{x_1(t)-x_2(t)}, \tag{3}$$

where $\overline{P_1P_3}=l_{ei}$ is the initial length of erecting cylinder and $\overline{P_3P_4}=l_{em}$ represents the distance between two junctions. $\theta(t)$ refers to erecting angle. $v_1(t)$ and $v_2(t)$ are the speeds of two hydraulic cylinder piston rods.

Balance equations of the load and erecting arm are expressed as follows:

$$F_p(t)\cos\gamma(t)+F_f(t)-F_t(t)+F_w(t)=M\ddot{x}_1(t), \tag{4}$$

$$F_p(t)\sin\gamma(t)+N_{o1}(t)-Mg=M\ddot{y}_1(t), \tag{5}$$

$$F_p(t)l_p(t)-Mgl_G(t)+M_w(t)=J_P\ddot{\theta}(t), \tag{6}$$

where $F_p(t)$ is thrust force of erecting cylinder. $\gamma(t)$ represents the angle between thrust force and x positive axis. $F_f(t)$ is friction force between rail and slider. $F_t(t)$ is pull force of horizontal cylinder. $F_w(t)$ is calculated wind load. M represents mass of the load and erecting arm. $N_{o1}(t)$ is support force of rail to slider. $l_p(t)$ is the arm of thrust force to point P_4. $l_G(t)$ is the arm of the load gravity to point P_4. $M_w(t)$ is the moment of calculated wind load. J_P is the moment of inertia on load and erecting arm to point P_4. $l_p(t)$ and $l_G(t)$ are defined as follows:

$$l_p(t) = \frac{l_{em}\sqrt{x_1^2(t)+y_1^2(t)}}{\sqrt{x_2^2(t)+y_2^2(t)}}\left[\sin\theta(t) + \arctan\frac{y_1(t)}{x_1(t)}\right], \tag{7}$$

$$l_G(t) = \overline{P_G P_4}\cos[\theta(t)+\alpha_0]. \tag{8}$$

Take the platform bottom as study object. Four outrigger cylinders' installment position and kinematic analysis of the platform are given in Fig. 3. The forces acting on the bottom of platform include platform gravity, load gravity passed by erecting cylinder and the back hinge bearing, wind load, and so on.

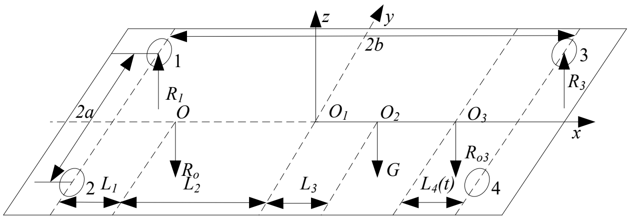


Fig. 3. Kinematic analysis of the platform

Points 1, 2, 3 and 4 represent outrigger cylinder. Transverse span is $2a$ and longitudinal span is $2b$. Point O represents the hinged bearing between erecting cylinder and platform. Point O_1 is geometric center of platform. Point O_2 is gravity center of platform. Point O_3 is contact point of horizontal slider and platform. $R_1(t)$, $R_2(t)$, $R_3(t)$ and $R_4(t)$ are the forces of four outrigger cylinders. $R_o(t)$ and $R_{o3}(t)$ denote the vertical component forces of erecting cylinder and erecting arm hinged bearing. G is gravity of platform. L_1 is the horizontal distance of outrigger 1 to erecting cylinder hinged bearing. $L_4(t)$ is the horizontal distance of outrigger 3 to point O_3.

Moment equilibrium equations can be obtained as follows:

$$\begin{aligned} 2R_1(t)2b &= R_o(t)(2b-L_1) + G(b-L_3)+ \\ &+ R_{o3}(t)L_4(t), \end{aligned} \tag{9}$$

$$\begin{aligned} 2R_3(t)2b &= R_o(t)L_1 + G(L_1+L_2+L_3)+ \\ &+ R_{o3}(t)(2b-L_4(t)), \end{aligned} \tag{10}$$

where $R_o(t)$ is the vertical component of $F_p(t)$. $R_{o3}(t)$ is the support force of slide to rail.

Parameters of the mechanism are shown in Table 1.

Table 1. Parameters of the mechanism

Symbol	Value	Unit
M	1000	*Kg*
l_{ei}	1933.42	mm
l_{em}	1110.30	mm
a	1100	mm
b	2400	mm
L_1	900	mm
L_2	1500	mm
L_3	900	mm

2.2 Mathematical model of the hydraulic system

Hydraulic system includes hydraulic pump, relief valve, bidirectional balance valve, hydraulic lock, hydraulic cylinder, electro-hydraulic proportional valve. The discharge flow rate of the pump Q_p is represented by the following equation:

$$Q_p = D_p w_p \eta_v, \tag{11}$$

where D_p is pump displacement. w_p is rotational speed of the motor. η_v is volumetric efficiency.

The relief valve limits the maximum pressure by discharging the flow when the supply pressure exceeds the crack pressure.

Hydraulic control valve used in the system is three-land-four-way spool valve. Flows through the orifices are described by the following equations:

$$q_1 = C_d A_1 \sqrt{\frac{2(p_s - p_1)}{\rho}}, \tag{12}$$

$$q_2 = C_d A_2 \sqrt{\frac{2p_2}{\rho}}, \tag{13}$$

$$q_3 = C_d A_3 \sqrt{\frac{2(p_s - p_2)}{\rho}}, \tag{14}$$

$$q_4 = C_d A_4 \sqrt{\frac{2p_1}{\rho}}, \tag{15}$$

where C_d is discharge coefficient. P_s is supply pressure. P_1 and P_2 are the pressures in the forward and return cylinder chambers. The areas A_1, A_2, A_3 and A_4 are functions of valve displacements and depend on valve geometry.

The oil compressibility influences the dynamics of hydraulic cylinder. The following equations can be obtained by applying the continuity equation to each of the hydraulic cylinder chambers:

$$q_1 = A_5\frac{dy}{dt} + \frac{V_{01} + A_1 y}{\beta_e}\frac{dp_1}{dt} + (C_{ec} + C_{ic})p_1 - C_{ic}p_2, \tag{16}$$

$$q_2 = A_6\frac{dy}{dt} + \frac{V_{02} - A_2 y}{\beta_e}\frac{dp_2}{dt} - (C_{ec} + C_{ic})p_2 + C_{ic}p_1, \tag{17}$$

where V_{01} and V_{02} are pipeline volumes of two cylinder chambers. A_5y and A_6y represent the flow rate as a function of volume change due to the piston motion. β_e is the effective bulk modulus. C_{ic} and C_{ec} denote the internal and external leakage flow coefficient.

The equation of piston motion can be acquired by applying the Newton second law:

$$A_1p_1 - A_2p_2 = m\frac{d^2y}{dt^2} + F, \tag{18}$$

where *m* is the total mass consisting of piston and fluid. *F* represents the entire external load.

Parameters of the hydraulic system are shown in Table 2.

Table 2. Parameters of the hydraulic system

Symbol	Value	Unit
D_p	50	ml/r
w_p	1000	r/min
C_d	0.7	
V_{01}	2.4e-3	m^3
V_{02}	0.0089	m^3
A_5	1.23e-3	m^2
A_6	5.91e-4	m^2
ρ	800	kg/m^3

3 WORKING SCHEME DESIGN OF THE MECHANISM

3.1 Workflow design

The traditional workflow is that erecting process starts after leveling process completion. The leveling process can be divided into three stages based on working principle:

1. No load stage, outrigger cylinders quickly extend to the ground
2. Synchronization extending stage, outrigger cylinders synchronously extend to a certain height
3. Leveling stage, outrigger cylinders move according to relations of horizontal inclination with outrigger cylinder displacement to realize leveling.

The erecting process can be divided into three stages:

1. Early erecting stage. Horizontal cylinder is locked. Erecting cylinder pushes the load and erecting arm rotating round back hinged bearing to a certain angle.
2. Cooperation stage. Horizontal cylinder starts to move when erecting angle attains about $10^\circ \sim 15^\circ$. Erecting and horizontal cylinders move together. The load and erecting arm rotate round back hinged bearing as well as move in horizontal direction.
3. Vertical adjustment stage. Horizontal cylinder ceases when erecting angle attains about $80^\circ \sim 85^\circ$. The load is erected to vertical state by erecting cylinder alone.

In order to save time, firstly, outrigger cylinders quickly extend to the ground. Secondly, outrigger cylinders synchronously extend to a certain height. Thirdly, erecting process starts in leveling stage. Finally, erecting process is completed alone. Hydraulic cylinders move orderly based on the workflow.

3.2 Trajectory planning of leveling and erecting process

Erecting process generally uses the uniform acceleration and deceleration planning method. Due to the acceleration curve is not continuous, there is flexible impact in erecting process. Acceleration selection is quite conservative and erecting time is long. We adopt composite sine function to plan erecting angle to solve the problem. θ_0 is the initial value of erecting angle and θ_1 is the final value. Erecting time is T, $\tau = t/T$. θ_t is determined by the following expressions:

$$\theta(t) = (\theta_1 - \theta_0)s(\tau), \tag{19}$$

$$s(\tau) = \begin{cases} \frac{k}{4\pi}\left[\tau - \frac{\sin(4\pi\tau)}{4\pi}\right], & 0 \le \tau < \frac{1}{8}, \\ \frac{k}{4\pi}\left[\tau + \frac{2}{\pi} - 9\cos(\frac{4\pi\tau}{3} - \frac{\pi}{6})/4\pi\right], & \frac{1}{8} \le \tau < \frac{7}{8}, \\ \frac{k}{4\pi}\left[\tau + \frac{4}{\pi} - \frac{\sin(4\pi\tau - 2\pi)}{4\pi}\right], & \frac{7}{8} \le \tau \le 1. \end{cases} \tag{20}$$

Constant $k = 4\pi^2/\pi + 4$.

Horizontal cylinders pull back hinged bearing moving along horizontal direction. Requirement of horizontal cylinder is that curves of displacement, velocity, acceleration and impact change smoothly and avoid mutation. We adopt polynomial interpolation method to plan displacement of horizontal cylinder. S_0 is the initial value and S_1 is the final value. Moving time is *T*. *S*(*t*) is given by:

$$S(t) = (S_1 - S_0)s(\tau), \tag{21}$$

$$s(\tau) = -20\tau^7 + 70\tau^6 - 84\tau^5 + 35\tau^4. \tag{22}$$

Movement of outrigger cylinder is divided into two stages. Before outrigger cylinder touching ground, the load of outrigger cylinder is small. Give it a step signal in order to achieve quickly extending. After outrigger cylinder touching ground, the load of outrigger cylinder is heavy. We adopt cycloidal curve to plan the movement of outrigger cylinder. R_0 is the initial value of outrigger cylinder displacement and R_1 is final value. Moving time is T. $R(t)$ can be written as follows:

$$R(t) = (R_1 - R_0)s(\tau), \tag{23}$$

$$s(\tau) = \tau - \frac{1}{2\pi}\sin 2\pi\tau. \tag{24}$$

3.3 Principle of leveling strategy

Mathematical analysis on leveling process is accomplished to acquire quantitative relationship between horizontal inclination and displacement of outrigger cylinder. Suppose horizontal inclinations of X axis and Y axis are α and β. The purpose of leveling is enabling horizontal surface coincidence with platform surface, so that α and β are zero. Established coordinate system is presented in Fig. 4. OX_0Y_0 is horizontal coordinate system and OXY is platform coordinate system.

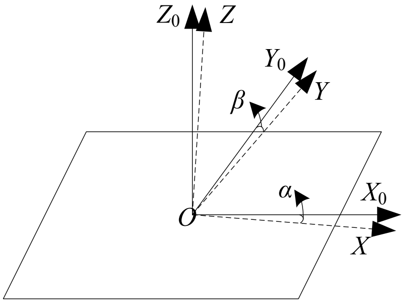


Fig. 4. Established coordinate system

Assuming α and β are not zero, transformation matrixes of two coordinate systems are as follows:

$$R_1^0 = \mathrm{ROT}(x,\alpha)\mathrm{ROT}(y,\beta), \tag{25}$$

$$\mathrm{ROT}(x,\alpha) = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{bmatrix}, \tag{26}$$

$$\mathrm{ROT}(y,\beta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & \sin\beta \\ 0 & -\sin\beta & \cos\beta \end{bmatrix}. \tag{27}$$

Equation of initial coordinate system transformation to platform coordinate is obtained as follows:

$$\begin{aligned}(i',j',k')^T &= \mathrm{ROT}(y,\beta)\mathrm{ROT}(x,\alpha)(i,j,k)^T \\ &= \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ -\sin\beta\sin\alpha & \cos\beta & \sin\beta\cos\alpha \\ -\cos\beta\sin\alpha & -\sin\beta & \cos\beta\cos\alpha \end{bmatrix}(i,j,k)^T.\end{aligned} \tag{28}$$

In actual leveling process, transverse and longitudinal inclinations are small. Suppose horizontal inclination variation in leveling process is small. Ignore high order infinitesimal, we can obtain $\cos\alpha = \cos\beta = 1$, $\sin\alpha = \alpha$, and $\sin\beta = \beta$. The following equation can be obtained:

$$(i',j',k')^T = \begin{bmatrix} 1 & 0 & \alpha \\ 0 & 1 & \beta \\ -\alpha & -\beta & 1 \end{bmatrix}(i,j,k)^T. \tag{29}$$

Coordinates of the four outrigger cylinders in OX_0Y_0 are: outrigger cylinder 1 $(L_a/2, -L_b/2, 0)$, outrigger cylinder 2 $(L_a/2, L_b/2, 0)$, outrigger cylinder 3 $(-L_a/2, -L_b/2, 0)$ and outrigger cylinder 4 $(-L_a/2, L_b/2, 0)$. Coordinates of outrigger cylinders in OXY obtained based on (29) are: outrigger cylinder 1 $(L_a/2, -L_b/2, -L_a\alpha/2 + L_b\beta/2)$, outrigger cylinder 2 $(L_a/2, L_b/2, -L_a\alpha/2 - L_b\beta/2)$, outrigger cylinder 3 $(-L_a/2, -L_b/2, L_a\alpha/2 + L_b\beta/2)$ and outrigger cylinder 4 $(-L_a/2, L_b/2, L_a\alpha/2 - L_b\beta/2)$.

Suppose adjustment height of each outrigger cylinder is z_1, z_2, z_3 and z_4. We can get the following relationships from calculated coordinates of outrigger cylinders:

1. If outrigger cylinder 1 is the highest, then

$$\begin{gathered} z_1 = 0,\ z_2 = L_b\beta,\ z_3 = -L_a\alpha, \\ z_4 = -L_a\alpha + L_b\beta, \end{gathered} \tag{30}$$

2. If outrigger cylinder 2 is the highest, then

$$\begin{gathered} z_1 = -L_b\beta,\ z_2 = 0,\ z_3 = -L_a\alpha - L_b\beta, \\ z_4 = -L_a\alpha, \end{gathered} \tag{31}$$

3. If outrigger cylinder 3 is the highest, then

$$\begin{gathered} z_1 = L_a\alpha,\ z_2 = L_a\alpha + L_b\beta,\ z_3 = 0, \\ z_4 = L_b\beta, \end{gathered} \tag{32}$$

4. If outrigger cylinder 4 is the highest, then

$$\begin{gathered} z_1 = L_a\alpha - L_b\beta,\ z_2 = L_a\alpha,\ z_3 = -L_b\beta, \\ z_4 = 0. \end{gathered} \tag{33}$$

3.4 Control method selection

Traditional control method lack adaptability and flexibility and is suitable for solving linear and simple control problem [18]. Leveling and erecting system is nonlinear and time-varying. It is hard to control the system using traditional control method. Intelligent control strategy combines artificial intelligence and control theory to adapt to uncertainty and complexity [19]. Intelligent control has the functions of abstracting, learning, reasoning and decision-making. It can make corresponding response according to the environment changes. Important branches of intelligent control are fuzzy control, expert control, genetic algorithm and neural network control [20].

The parameters of leveling and erecting system change frequently affected by gravity, external load and friction. PID control algorithm has good stability and reliability. It is the most widely used controller in industry, and it has satisfactory control effect for linear system. But the parameters of PID control method cannot change online and it is difficult to acquire great control precision to control nonlinear system. Fuzzy control algorithm transforms experts and operators' experience into control rules. Fuzzy control algorithm has the advantages of adapting to uncertainty and complexity. It is usually associated with traditional control method and has practical value and great development potential [21]. Fuzzy control algorithm can alter parameters based on a set of control rules which are expressed by utilizing fuzzy mathematics method [22].

As discussed above, we adopt fuzzy adaptive PID control method to control leveling and erecting process. PID control method is connected with fuzzy control method and then the parameters of PID control method can change based on circumstance [23]. Fuzzy adaptive PID control method can make full use of operators' successful nonlinear experience and excellent PID control method effect. It can improve precision and achieve better effect compared with PID control and fuzzy control [24]. The structure of fuzzy adaptive PID controller is shown in Fig.5. Its input variables are error *e* and error change rate *ec*, which are blurred and exported to fuzzy inference module with fuzzy rules. Output variables are ΔK_P, ΔK_I, ΔK_D through defuzzification and they are respectively added to initial values K_{P0}, K_{I0}, K_{D0}. All of the variables are implied as linguistic values and defined with seven linguistic values which are: *NB*-negative big, *NM*-negative medium, *NS*-negative small, *ZO*-zero, *PS*-positive small, *PM*-positive medium, *PB*-positive big [25].

Table 3 shows the fuzzy control rules which were concluded in accordance with the PID control characteristics and operators' experience.

The parameters of the fuzzy adaptive PID controller are shown in Table 4.

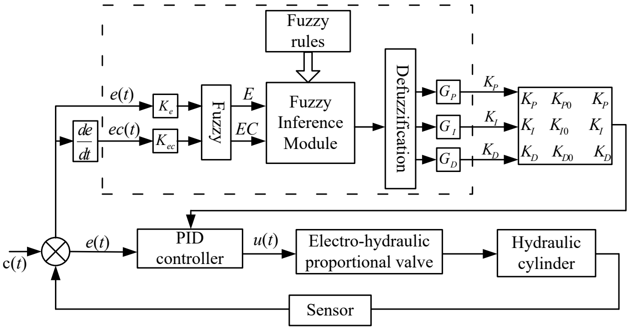


Fig. 5. The structure of fuzzy adaptive PID controller

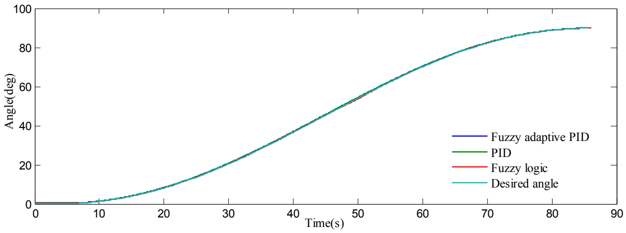
Table 3. Fuzzy control rules

ec / ΔK_P ΔK_I ΔK_D / **e**	***NB***	***NM***	***NS***	***ZO***	***PS***	***PM***	***PB***
NB	*PB/NB/NS*	*PB/NB/PS*	*PM/NM/PB*	*PM/NM/PB*	*PS/NS/PB*	*ZO/ZO/PM*	*ZO/ZO/NS*
NM	*PB/NB/NS*	*PB/NB/PS*	*PM/NM/PB*	*PS/NS/PM*	*PS/NS/PM*	*ZO/ZO/PS*	*NS/ZO/ZO*
NS	*PM/NB/ZO*	*PM/NM/PS*	*PM/NS/PM*	*PS/NS/PM*	*ZO/ZO/PS*	*NS/PS/PS*	*NS/PS/ZO*
ZO	*PM/NM/ZO*	*PM/NM/PS*	*PS/NS/PS*	*ZO/ZO/PS*	*NS/PS/PS*	*NM/PM/PS*	*NM/PM/ZO*
PS	*PS/NM/ZO*	*PS/NS/ZO*	*ZO/ZO/ZO*	*NS/PS/ZO*	*NS/PS/ZO*	*NM/PM/ZO*	*NM/PB/ZO*
PM	*PS/ZO/NB*	*ZO/ZO/PS*	*NS/PS/NS*	*NM/PS/NS*	*NM/PM/NS*	*NM/PB/NS*	*NB/PB/NB*
PB	*ZO/ZO/NB*	*ZO/ZO/NM*	*NM/PS/NM*	*NM/PM/NM*	*NM/PM/NS*	*NB/PB/NS*	*NB/PB/NB*

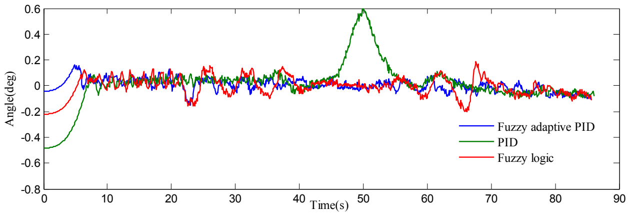
Table 4. Parameters of the controller

Symbol	**Value**
K_e	5
K_{ec}	2.5
G_P	30
G_I	80
G_D	5

In order to investigate the performance of fuzzy adaptive PID controller, numerical simulation was performed in Simulink software. The values of PID controller parameters and the initial values of fuzzy adaptive PID controller parameters are the same. Figure 6 shows simulation results of erection angle controlled by the fuzzy logic, PID and fuzzy adaptive PID controllers respectively. Figure 6(a) presents desired and actual erection angle curves. Figure 6(b) illustrates the tracking errors of desired and actual erection angles. It is clearly shown that the angle tracking error of fuzzy adaptive PID controller is the smallest. Fuzzy adaptive PID controller clearly performs better than fuzzy logic and PID controllers.



(a) Desired and actual erection angle



(b) Tracking error of erection angle

Fig. 6. Simulation results of erection angle controlled by different controllers

4 CO-SIMULATION OF THE MECHANISM

Leveling and erecting mechanism is a complex mechanical and hydraulic integration system. Mechanical model is established in Pro/E and ADAMS software. Hydraulic model is established in AMESim software. Control model is established in Simulink software. Simulink is the main simulation environment, and AMESim and ADAMS are assistant simulation environment. Real-time data is exchanged through software interface, and models in ADAMS and AMESim are exported to Simulink [26] [27].

4.1 Mechanical model in ADAMS

Three dimensional modeling ability of ADAMS is limited, but it can import model from other advanced CAD software [28]. Mechanism/Pro is an interface module to connect Pro/E and ADAMS. It adopts seamless connection with Pro/E and transmits model to ADAMS/View to conduct comprehensive kinematic analysis. Mechanical model is shown in Fig.7.

4.2 Hydraulic model in AMESim

Firstly select the appropriate model from model database and connect them, then establish model in accordance with the sequence of “sketch mode”, “sub-model mode”, “parameter mode” and “run mode” in AMESim [29]. Hydraulic models of the erecting and leveling system are indicated in Fig.8 and Fig.9. Figure 8 is hydraulic model of erecting system and Figure 9 is hydraulic model of leveling system.

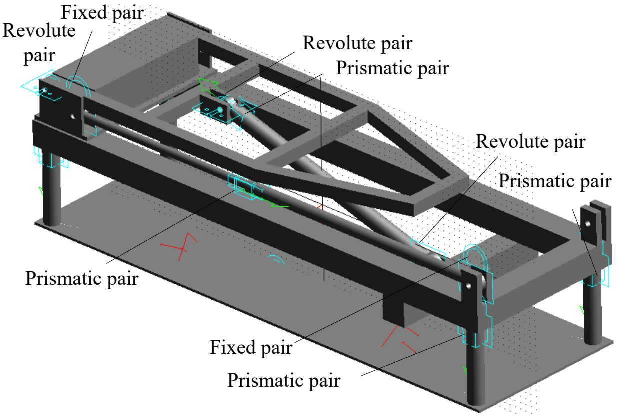


Fig. 7. Mechanical model in ADAMS

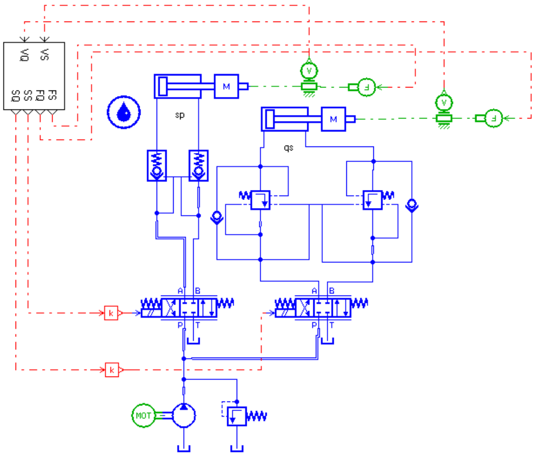


Fig. 8. Hydraulic model of erecting system in AMESim

4.3 Co-simulation result and analysis

Figure 10 shows simulation model of leveling system established in Simulink. Planned curves are desired displacement curves of outrigger cylinder piston rod. There are four fuzzy adaptive controllers which control outrigger cylinders. The input of fuzzy adaptive controller is displacement error. The output is control signal of electro-hydraulic proportional valve. The inputs of hydraulic model are control signals of electro-hydraulic proportional valves. The output is piston rod displacement.

Displacement simulation result of outrigger cylinder piston rod is shown in Fig. 11. Figure 11(a) is actual dis-

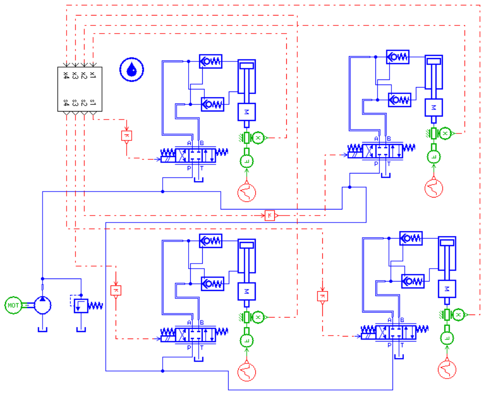


Fig. 9. Hydraulic model of leveling system in AMESim

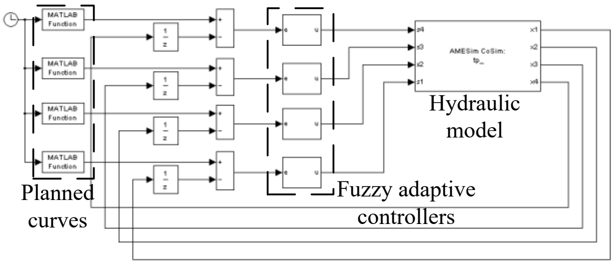
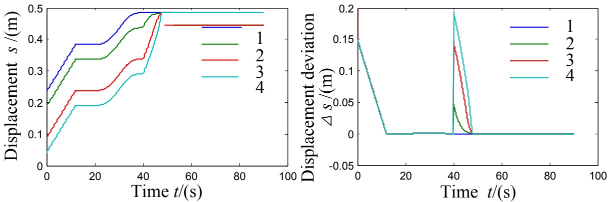


Fig. 10. Simulation model of leveling system

placement curves in simulation process. Figure 11(b) is displacement error curves. By the simulation results we can obtain that leveling process is divided into three stages. In no load stage (0 s∼20 s) outrigger cylinders extend rapidly and displacement error decreases from 0.14 m to 0 m. In synchronization extending stage displacement error is nearly zero and synchronization precision is great. In leveling stage outrigger cylinder 1 is the highest point. Displacement error is different in 40 s. Displacement error of outrigger cylinder 1 is 0 m. Displacement error of outrigger cylinder 2 is 0.05 m. Displacement error of outrigger cylinder 3 is 0.05 m. Displacement error of outrigger cylinder 4 is 0.02 m. Displacement error decreases gradually from 40 s to 50 s. Displacement error is zero at end. Simulation results indicate that leveling strategy and control algorithm have a good performance.

Simulation model of erecting system established in Simulink is indicated in Fig. 12. Planned curves are desired erecting angle and displacement curves of horizontal cylinder piston rod. There are two fuzzy adaptive controllers which separately control erecting and horizontal cylinders. Hydraulic model is established in AMESim and is compiled in S function that can be transmitted to Simulink. Mechanical model is established in ADAMS and transmitted to Simulink by software interface. The inputs of



(*a*) Displacement of outrigger cylinder

(*b*) Displacement deviation of outrigger cylinder

Fig. 11. Displacement simulation result of outrigger cylinder

fuzzy adaptive controllers are the error of planned erecting angle and displacement of horizontal cylinder piston rod with actual value in simulation process. The output is control signal of electro-hydraulic proportional valve. The inputs of hydraulic model are control signals of electro-hydraulic proportional valve and hydraulic cylinder. The output is piston rod speed signal. The input of mechanical model is piston rod speed signal. The outputs are erecting angle, displacement of horizontal cylinder piston rod and hydraulic cylinder load.

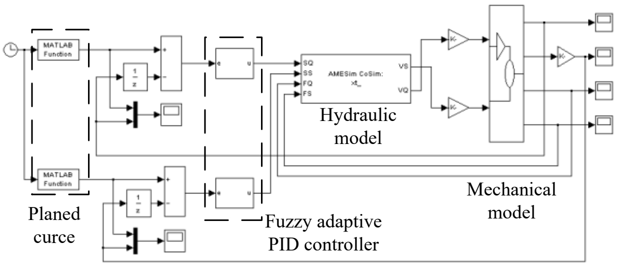
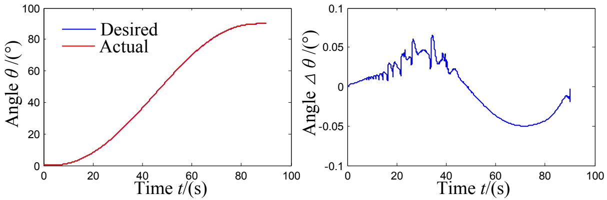


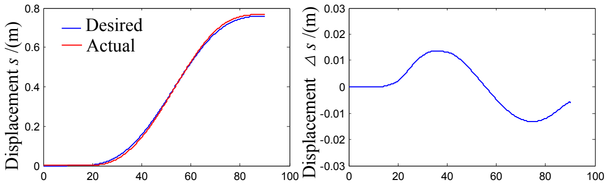
Fig. 12. Simulation model of erecting system

Figure 13 depicts simulation result of erecting angle. Figure 13(a) is desired and actual erecting angle curves in simulation process. Figure 13(b) is the error of desired erecting angle and simulation result. Figure 14 presents simulation result of horizontal cylinder piston rod displacement. Figure 14(a) is desired and actual displacement curves in simulation process. Figure 14(b) is the error of desired displacement and simulation result. By the simulation result we can obtain that erecting angle and displacement of horizontal cylinder piston rod change smoothly. The error of erecting angle is controlled in 0.06°.The displacement error of horizontal cylinder piston rod is controlled in 0.014 m. The control precision is great and satisfy control target of erecting process. Compared erecting angle with displacement result of horizontal cylinder piston rod it is obtained that the erecting angle curve doesn't change greatly at the start and the end of horizontal cylinder movement. It indicates that the impact of two hydraulic cylinders is little.



(*a*) Desired and autual erection angle (*b*) Angle error

Fig. 13. Simulation result of erecting angle

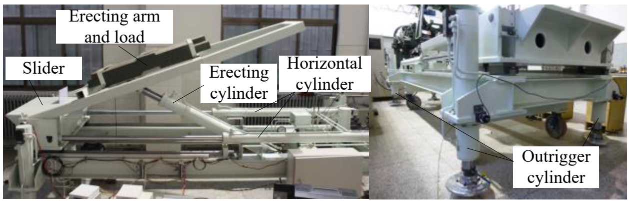


(*a*) Displacement of horizontal cylinder piston rod (*b*) Displacement error

Fig. 14. Simulation displacement result of horizontal cylinder piston rod

5 EXPERIMENTAL VERIFICATION

Our research team designed an experimental platform that can realize desired movement. Mechanical constitution is presented in Fig.15. Measurement and control system of experimental platform are established using virtual instrument technology. We choose the hardware of PXI-1044 case and PXI-6259 multifunction data acquisition card and software of LabVIEW to program.

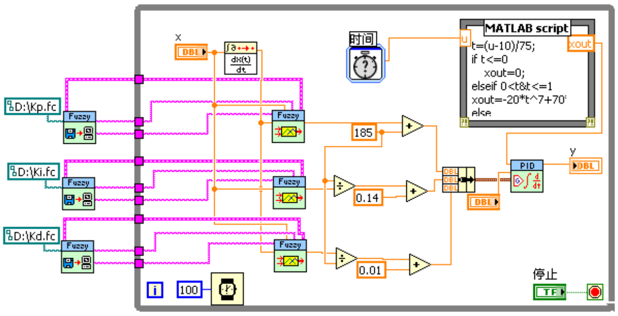


(*a*) Erecting mechanism (*b*) Leveling mechanism

Fig. 15. Mechanical constitution of the mechanism

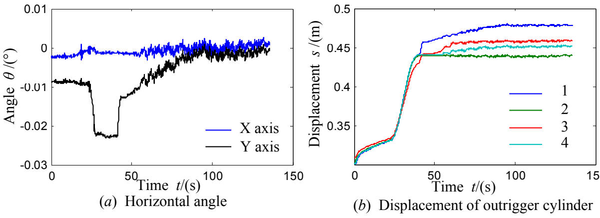
Figure 16 shows the program of fuzzy adaptive controller in LabVIEW software. It contains fuzzy interface module and PID controller. It is programmed in accordance with the structure shown in Fig. 5.

Figure 17 shows leveling experiment result. Figure 17 (a) is horizontal inclination curves. Figure 17 (b) is displacement curves of outrigger cylinders. In no load stage (0 s∼20 s) horizontal inclination keep a constant and outrigger cylinders extend rapidly. In synchronization extending stage horizontal inclination increases. It is caused by the uneven ground. In leveling stage, displacement error increases while horizontal inclination decreases.



```
MATLAB script
t=(u-10)/75;
if t<=0
    xout=0;
elseif 0<t&t<=1
xout=-20*t^7+70'
else
```

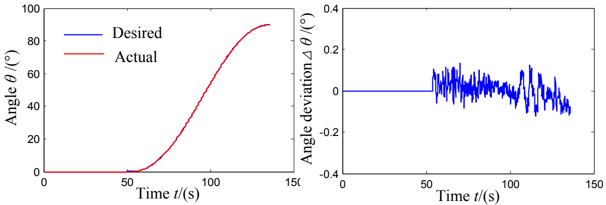
Fig. 16. Program of fuzzy adaptive controller



(*a*) Horizontal angle (*b*) Displacement of outrigger cylinder

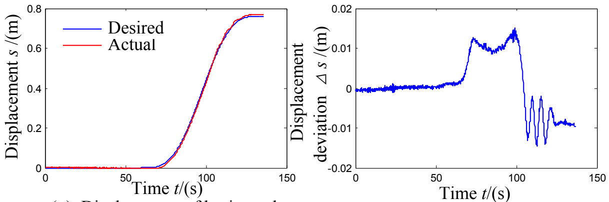
Fig. 17. Experiment result of leveling process

Experimental erecting angle result is indicated in Fig.18. Figure 18(a) is desired and experimental erecting angle curves. Figure 18(b) is the error curve of desired and experimental erecting angle. Experimental displacement result of horizontal cylinder piston rod is shown in Fig.19. Figure 19(a) is desired and experimental displacement curves. Figure 19(b) is the error curve of desired and experimental displacement. Erecting cylinder starts to move in 50 s and erecting angle error is controlled in 0.1°. Horizontal cylinder starts to move in 60 s and displacement error is controlled in 0.015 m. The mutual effect of leveling and erecting is little and the designed scheme has a good performance.



(*a*) Erection angle (*b*) Angle deviation

Fig. 18. Experimental result of erecting angle



(*a*) Displacement of horizontal cylinder piston rod

(*b*) Displacement error

Fig. 19. Experimental displacement result of horizontal cylinder piston rod

6 CONCLUSIONS

The research designed the moving process of a leveling and erecting mechanism. Mathematical models of mechanical and hydraulic systems were respectively established. Working scheme was designed. Co-simulation method was adopted to test the scheme with Pro/E, ADAMS, AMESim, and Simulink. Experimental verification was completed on a platform. The results demonstrate that the leveling and erecting mechanism can move based on the designed scheme. Fuzzy adaptive PID controller has a precise effect applied in control of the leveling and erecting process. Angle leveling strategy is suitable for the leveling mechanism. Simulation and experiment results are basically identical. It demonstrates that co-simulation method can improve modeling efficiency.

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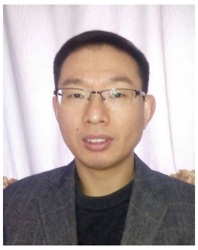

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