The Modeling and Simulation Analysis on Four Corners Leveling System in Composite Material Hydraulic Press Based on AMESim/ADAMS

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Abstract: - Four corners leveling system is one of the key parts of composite material hydraulic press, whose performances determine the pros and cons of the pressing performances. Electro-hydraulic control system is the most critical aspect in affecting the control characteristics. The kinematics and dynamics models of four corners leveling system based on ADAMS were established, while electro-hydraulic control system model based on AMESim was built. The above-mentioned simulation models formed the united simulation models for four corners leveling system. The effects of key parameters on control characteristics, including the dead zone and hysteresis of proportional valve and the hydraulic cylinder leakage, were analyzed by simulation, and the influence laws of various parameters on the synchronization control precision were obtained. Simulation results show that the single cylinder, double-cylinder or multi-cylinder existing dead zone and hysteresis and leakage can affect the synchronization error. Comparing with the working condition of single cylinder, the multi-cylinder with dead zone, hysteresis and leakage can significantly cause larger synchronization error.

Key-Words: composite material hydraulic press; leveling system; synchronization; AMESim; ADAMS; co-simulation

1 Introduction

With the further development of the aviation industry and modern industry, new composite materials and high-performance fiber composite materials industry are important directions of the development of new materials, which are widely used in aircraft, aerospace, submarines, cars and other high-tech fields. Molding technology is one of the key technologies in the field of composite technology. Especially the compression molding technology, which has the characteristics of technology intensive, highly automated and high-precision, is a top priority in the field of the technology. Currently, mechanized molding composite material production has reached more than 60% of the total output, and the molding method has advantages of high production efficiency and forming precision, smooth surface. Furthermore, complex composite materials products can be once molding, thus it does not affect the performance of composite material products. Composite material hydraulic press is the main equipment in the molding field, which performance directly determines the quality of the composite material products [1,2].

Four corners leveling system is the key part of a large forging hydraulic press, which can avoid slider tilting in the working status, so as to guarantee the accuracy of the upper and lower mold pressing and to ensure the quality of the workpiece. This system plays a decisive role in the slider running precision and the guarantees of product quality [3-6].

In the working processes of the hydraulic press, the eccentric torque is unknown. In the big uneven load plane, four corners leveling system adopts multi-cylinder synchronization control system to keep a level surface. However, the manufacturing of synchronous driving of multi- cylinder is complex and need high matching precision. There is a control problem of large flow multi-cylinder synchronization, which results in difficult control of precise coordination of leveling systems [7].

For multi-cylinder synchronization control system, the control strategy is an important part of the system. In addition, the change of hydraulic system parameters will lead to the change of synchronous control performances and analysis of the influence laws are the premise to achieve high performance control. Consequently, the corresponding mathematical model is built in this article based on the analysis of dynamics and kinematics of composite material hydraulic press which can be obtained from the structure principle of four corners leveling system in composite material hydraulic press. With the co-simulation model of the electro-hydraulic control system, the effect of some key parameters in leveling system, which are the dead-zone, hysteresis of valve and leakage of cylinder, are deeply studied. The analysis can also lay the foundation for the investigations of control strategies in multi-cylinder synchronization [8,9].

2 Structure and Principle

Composite material hydraulic press adopts the combination of three beam and four column structure. Its body fixed to the bottom cross beam and top cross beam by four support beams fixed to the bottom cross beam as well. In order to achieve the overall preload load frame, pull rod is set inside the support beams. Two master cylinders driving the pressing planes and it use the four corners leveling technology to adjust level precision of the plane.

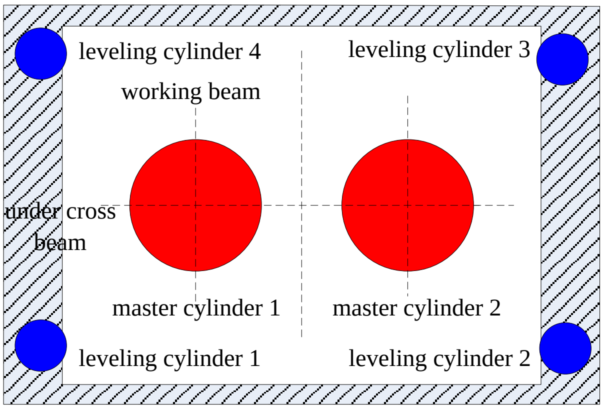
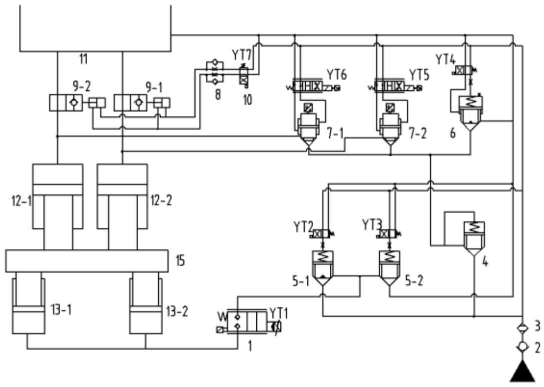


Fig. 1 The position of hydraulic cylinder

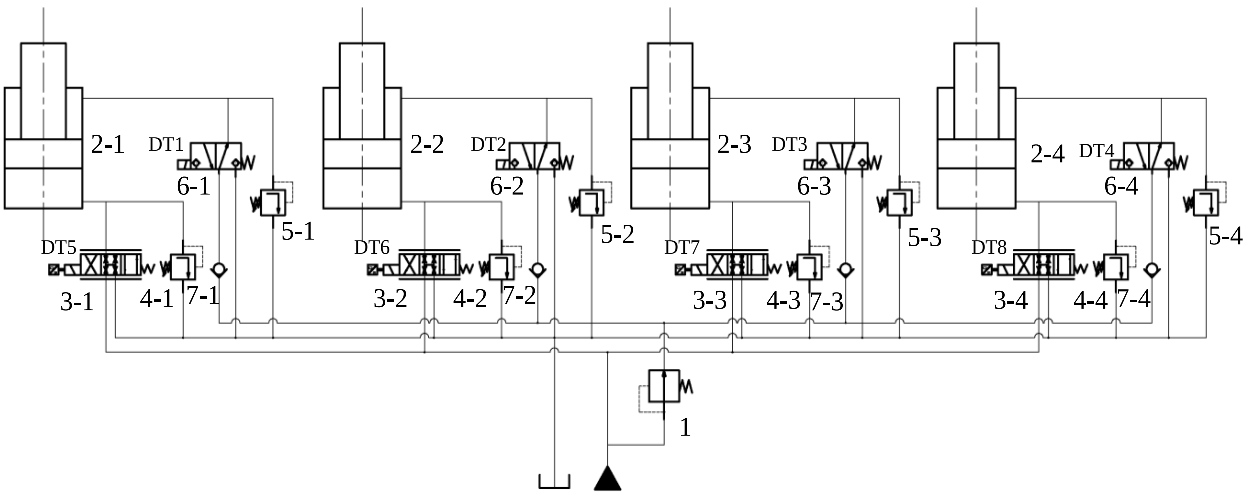
The arrangement of master cylinders and leveling cylinders of composite material hydraulic press are shown in Fig. 1. Two master cylinders symmetry in the geometric center of the beams and four corners leveling cylinders mounted on the bottom cross beam. When the working beam moved down to the designated position, leveling cylinders contacted with the working beam backing plate. In order to achieve flat regulation, the displacement of leveling cylinders is adjusted by control commands. Four corners leveling cylinders of four corners leveling system moved with the control target, which adjusted output force by controlling the valve element to regulate the pressed level surface precision [10].



1.control valve of bottom cylinder 2.check valve 3. filter 4. cartridge valve 5. cartridge valve 6.dynamic cartridge valve 7. proportion cartridge valve 8. throttle valve 9. prefill valve 10. directional valve 11. oil tank 12.main cylinder 13. bottom cylinder
Fig. 2 Principle diagram of the main system

The hydraulic principle diagram of composite material hydraulic press is as shown in Fig. 2 and Fig. 3. Two main cylinders provide the main driving force to press molding composite materials. The four corners leveling system is independent system relative to the main control cylinder system which can reduce the fluctuation of pressure and flow from the main system. There is constant pressure in the hydraulic cylinder chamber with piston-rod. The displacements of leveling cylinders and the output torque are controlled by the control of pressure of leveling cylinder chambers, so as to control the deflection angel of working beams. Proportional valve starts to work when detecting system feedback the deflection of mobile cross beam and adjust the pressure of cylinder chamber without piston-rod, until mobile cross beam back to horizontal position [12].

Composite material hydraulic press is mainly applied to automobile parts, templates, and other materials composites molding. The molding process includes several stages: fast down, pressing, pressure upkeep, pressure relief and return, etc. In one molding process, the performance of composite material products is directly determined by the leveling precision of the plane.



1. pressure reducing valve 2. leveling cylinder 3. proportional servo valve 4. relief valve 5. relief valve 6. reversing valve 7. check valve

Fig. 3 Hydraulic principle diagram of four corners leveling system

The leakages of main cylinder and leveling cylinder system are caused by the manufacture precision, installation accuracy and structural deformation caused by a variety of friction. Because of the machining error of four corner leveling control valve, the hysteresis and dead zones caused by magnet hysteresis effect, the pressing precision cannot be effectively improved and the synchronous error of electric hydraulic synchronous control system has also been affected.

3 Mathematical Modeling

The mathematical model of multi-cylinder drive electro-hydraulic servo system of composite material hydraulic press was established.

3.1 kinematics and dynamics modeling

In the pressing processes of the composite material hydraulic press, the motion of main cylinders, leveling cylinders and pressing plane are shown in Fig. 4. The center of pressing plane is the origin of the coordinates system and the centers of the cylinders are the origin of the relative coordinates respectively. Then the kinematics and dynamics model of plane were established [4].

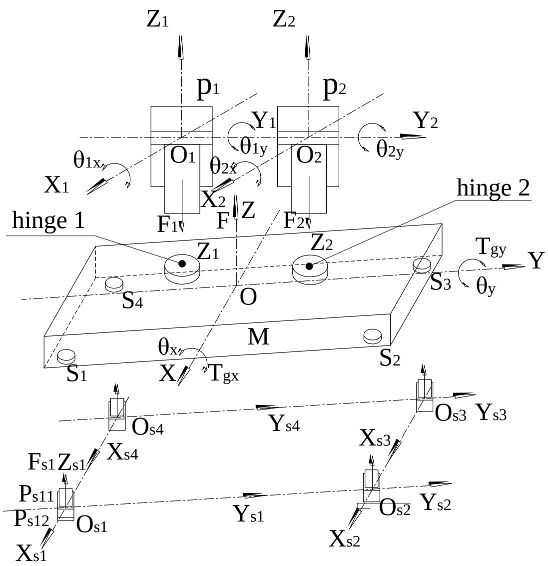


Fig.4 Geometric state of composite material hydraulic press

The load of pressing plane is chose as the research object. The vector positive direction and stress analysis results of the hydraulic cylinders and pressing plane are shown in Fig. 4.The simplified motion of pressing plane have three degrees of freedom (3DOF).Using the Newton's second law, momentum conservation theory and law of the fixed-axis rotation, it can be obtained as[13,14]:

$$\begin{cases} \sum_{i=1}^{2} F_i - \sum_{i=1}^{4} F_{si} + Mg\text{-}F = M\ddot{x} \\ \sum_{i=1}^{2} F_i Z_{iy} - \sum_{i=1}^{4} F_{si} \cdot S_{iy} = J_x \ddot{\theta}_x \\ -\sum_{i=1}^{4} F_{si} \cdot S_{ix} = J_y \ddot{\theta}_y \end{cases} \tag{1}$$

Where Z_{ix} and Z_{iy} are the values of X-axis coordinate and Y-axis coordinate of Z_i in OXY coordinate system (mm); S_{ix}, S_{iy} are the values of X-axis coordinate and Y-axis coordinate of S_i in OXY coordinate system (mm); J_x, J_x are the rotational inertia of x-axis and y-axis in OXY coordinate system (kg/m^2); θ_x, θ_y are the angle of pressing plane of x-axis and y-axis in OXY coordinate system (rad); F indicates the equivalent center load (N).

3.2 the motion equation of four corners leveling hydraulic cylinder

According to the actual working conditions of the molding process of composite material hydraulic press, we simplified pressing plane which is shown in Fig. 5. It reflects the load with asymmetric centroid position. With the posture of pressing plane as the research object, the pressing plane of press will produce a slight rotation which is the main movement of partial load along the OXYZ axis during pressing. S_1,S_2,S_3,S_4 are the vertical displacements of four connection points of leveling plane and Z_1,Z_2 are the vertical displacements of two master cylinders[5]. They can be approximated represented by equation $\left\{Z_0,\theta_x,\theta_y\right\}$ [4]:

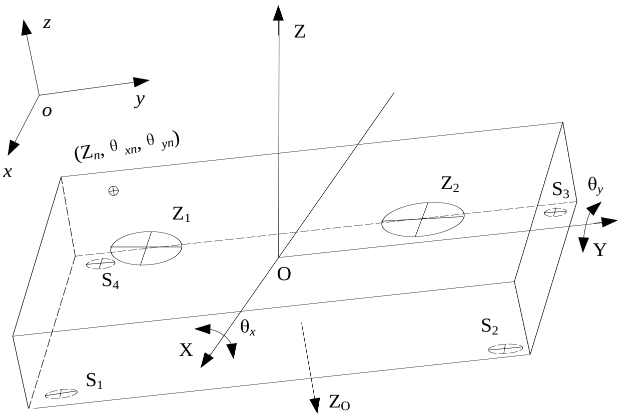


Fig. 5 Location and movement analysis of pressing plane connection point

$$S_{\mathrm{iz}} = Z_O + S_{izo} + S_{iy}\theta_x + S_{ix}\theta_y \tag{2}$$

$$Z_{\mathrm{iz}} = Z_O + Z_{izo} + Z_{iy}\theta_x + Z_{ix}\theta_y \tag{3}$$

Where Z_O is the expansion amount of hydraulic cylinder (mm); S_{izo} is the original location of leveling cylinder contact point; Z_{izo} is the original location of the master cylinder contact point; S_{iz} is Z-axis position of the leveling cylinders contact point; Z_{iz} is Z-axis position of the master cylinder contact point.

In the press-forming process, the points on one plane are select to analyze. Contact points of four corners leveling plane contact with the lower surface of the pressing plane and not separate. Select three points S_1, S_2, S_3 which are not in the same line in the contact points S_1, S_2, S_3, S_4 to form a set. These three points combine to a minimum set of points of pressing plane gesture. According to the equation (2) to define $x_q = \left[x_{s1}, x_{s2}, x_{s3}\right]^T$ .Therefore, x_q and $\left\{Z_0,\theta_x,\theta_y\right\}$ have the following relation [4,11,14]:

$$x_q = \begin{bmatrix} 1 & S_{1y} & S_{1x} \\ 1 & S_{2y} & S_{2x} \\ 1 & S_{3y} & S_{3x} \end{bmatrix} \begin{bmatrix} Z_o \\ \theta_x \\ \theta_y \end{bmatrix} = L_q \begin{bmatrix} Z_o \\ \theta_x \\ \theta_y \end{bmatrix} \tag{4}$$

Contact point S_4 can be expressed in linear relationship of x_q:

$$x_4 = \begin{bmatrix} 1 & S_{4y} & S_{4x} \end{bmatrix} \begin{bmatrix} Z_o \\ \theta_x \\ \theta_y \end{bmatrix} = \begin{bmatrix} 1 & S_{4y} & S_{4x} \end{bmatrix} L_q^{-1} x_q = R_a x_q \tag{5}$$

Order $\begin{bmatrix} 1 & S_{4y} & S_{4x} \end{bmatrix} L_q^{-1} = R_a$ and $\left\{x_{s1}, x_{s2}, x_{s3}\right\}$ are linearly independent; Z_1, Z_2 and S_1, S_2, S_3, S_4 are not in the same plane and there is no corresponding linear relationship.

$x = \left\{x_{s1}, x_{s2}, x_{s3}, x_{s4}\right\}^T$ is defined as the leveling cylinder position vector. We can get the relation between the x_q and x by equation (4) and (5):

$$x = R_c L_q = \begin{bmatrix} I_{3\times 3} \\ R_a \end{bmatrix} x_q \tag{6}$$

3.3 mathematical model of electro-hydraulic control system

With the hydraulic cylinders of four corners leveling system as the research object, the forces in each direction are shown in Fig. 2. Assuming the hydraulic cylinders of four corners leveling system only have vertical downward movement. In this case, it can be obtained according to Newton's second law：

$$p_{\mathrm{si1}} A_{\mathrm{si1}} + m_{si} g - m_{si} \ddot{x}_i = p_{\mathrm{si2}} A_{\mathrm{si2}} + B_{sip} \dot{x}_{si} - F_{si} \tag{7}$$

Where F_{si} is the equivalent force of the master cylinder pressing force and reaction load force on point S_i (N); m_{si} is the quality of the hydraulic cylinder piston; $A_{\text{si}1}$ is the equivalent area of the four corners leveling cylinders' upper chamber; $A_{\text{si}2}$ is the equivalent area of the four corners leveling cylinders' lower chamber(mm^2); $p_{\text{si}1}$ is the pressure of the four corners leveling cylinders' upper chamber; $p_{\text{si}2}$ is the pressure of the four corners leveling cylinders' lower chamber(bar).

It uses high frequency proportional valves to control four corners leveling system. The dynamic equation of hydraulic cylinders S_i can be represented by equation (8):

$$\dot{p}_{sl} = \frac{4\beta_e}{V_{si}}\left[Q_{Si} - C_{si}p_{sil} - A_{si1}\dot{x}_{si}\right] \tag{8}$$

Equation (1) is the mechanical equation of system, equation (7) is the motion equation of hydraulic piston-cylinder and equation (8) is the pressure dynamic equation. These three equations are the three main equations of the gesture of pressing plane. Define load force vector of the contact points of leveling cylinders and pressing plane for $f = \left[f_{s1}, f_{s2}, f_{s3}, f_{s4}\right]^T$, make the equation (1) and equation (8) for：

$$\begin{cases} L_\text{f} f + M_g = M_L \ddot{x}_q \\ R - B_p \dot{x} + f = m\ddot{x} \end{cases} \tag{9}$$

Where:

$L_f = \begin{bmatrix} 1 & 1 & 1 & 1 \\ S_{1\text{y}} & S_{2\text{y}} & S_{3\text{y}} & S_{4\text{y}} \\ S_{1x} & S_{2x} & S_{3x} & S_{4x} \end{bmatrix}$ is the arm of the force F;

$M_g = \begin{bmatrix} Mg \\ 0 \\ 0 \end{bmatrix}$ is the gravity matrix of pressed flat and working beam;

M_L=diag$\left(\left[M \quad J_x \quad J_y\right]\right)L_q^{-1}$ is the Inertia Matrix of pressed flat and working beam;

R=$\begin{bmatrix} p_{s12}A_{s12} - p_{s11}A_{s12} - m_{s1}g - F_{s1} \\ p_{s22}A_{s22} - p_{s21}A_{s22} - m_{s2}g - F_{s2} \\ p_{s32}A_{s32} - p_{s31}A_{s32} - m_{s3}g - F_{s3} \\ p_{s42}A_{s42} - p_{s41}A_{s42} - m_{s4}g - F_{s4} \end{bmatrix}$ is the combined load force matrix of hydraulic cylinder;

B_P=diag$\left(\left[B_{s1P} \quad B_{s2P} \quad B_{s2P} \quad B_{s4P}\right]\right)$ is the viscous damping coefficient matrix of hydraulic cylinder;

m=diag$\left(\left[m_{s1} \quad m_{s2} \quad m_{s2} \quad m_{s4}\right]\right)$ is the mass matrix of levelling cylinder.

4 Simulation Modeling and Analysis

4.1 the united simulation modeling based on ADAMS and AMESim

The mathematical model of mechanical parts of composite material hydraulic press is based on ADAMS, which sets the motion pair in the model and the displacement and speed of the piston rod as state variables. At the same time, the simulation model of electro-hydraulic control system based on AMESim takes AMESim as the master software and converts the ADAMS model of mechanical part module export to AMESim[19]. ADAMS will deliver the calculation of the displacement and velocity of the piston rod to the model of AMESim, where the stress of the piston rod is calculated and then export to ADAMS to form united simulation model as shown in Fig. 6.

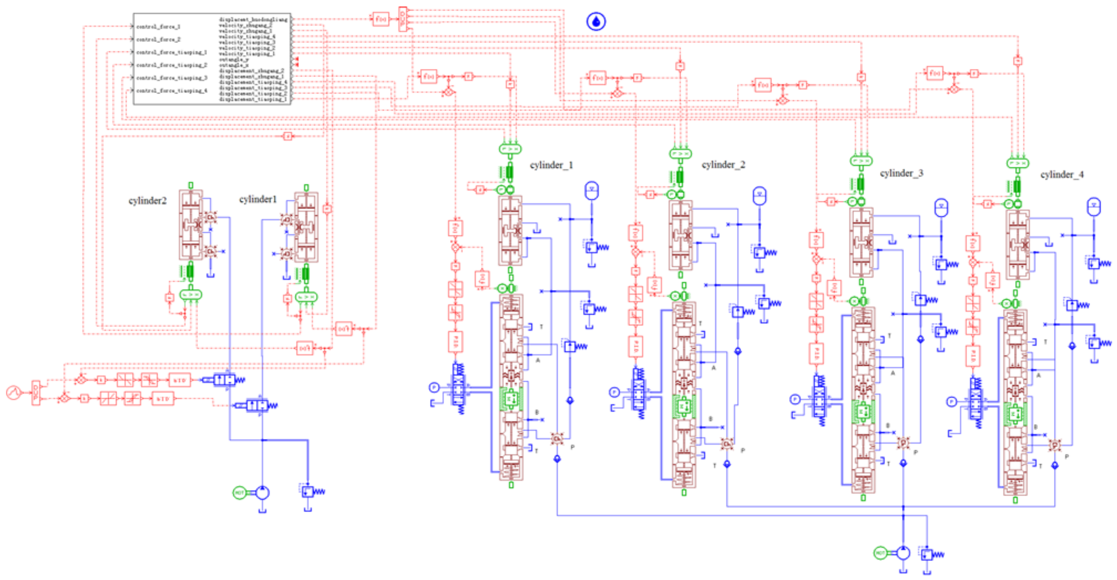


Fig. 6 Combined simulation model based on ADAMS and AMESim

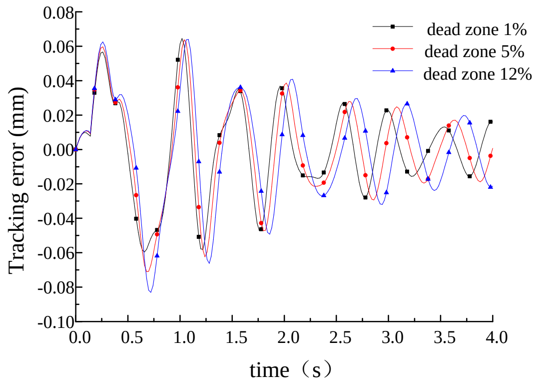
4.2 analysis of united simulation

The most critical part in the four corners leveling system is hydraulic control system whose characteristics of the control valve and hydraulic cylinder have great influence on the synchronization accuracy. Therefore, analyzing the influence laws of dead zone and hysteresis of proportion valve and the leakage of hydraulic cylinder to synchronization characteristics based on the united simulation model can provide theoretical basis for the subsequent system design.

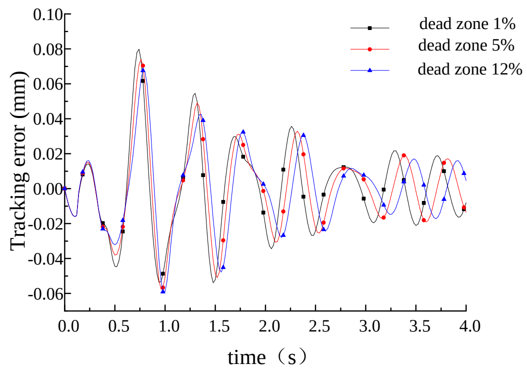
4.2.1 dead zone characteristics

Proportional valve has dead zone in general, and the dead zone has a significant effect on system control characteristics. Based on the united simulation model above, the influence laws of the proportional valve dead-zone of the united simulation model to the synchronization precision of four corners leveling system can be analyzed. The dead zone in the control valves of leveling cylinders is set to 1% ~ 12%, and the 1%, 6% and 12% is chosen as the reference points. The impact of dead zone on synchronization error is analyzed through three working conditions: (1) the control valve of the leveling cylinder 1 had dead-zone, (2) two leveling cylinders had dead-zone and (3) three leveling cylinders had dead-zone.

Setting dead zone in the control valve of leveling cylinder 1, the simulation result is as shown in Fig. 7. Figure (a) and (b) show that when the dead zone in leveling cylinder 1 is 12%, the tracking error increases by 50% while tracking error of leveling cylinder 2 changes 3% (All the results are compared with those without dead zone). In this case, the tracking error of leveling cylinder 1 with dead zone experiences a big change, the tracking error of leveling cylinder 2 with none change of merely 3%.



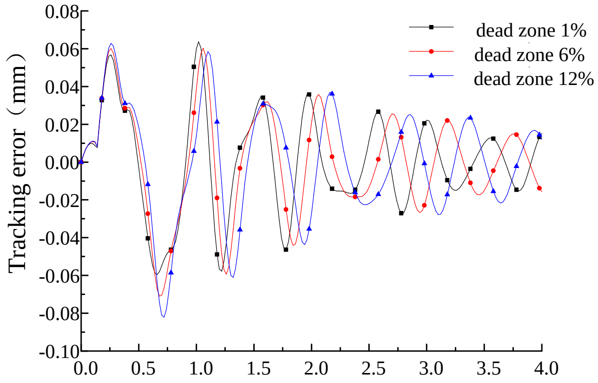
(a)Tracking error of cylinder1



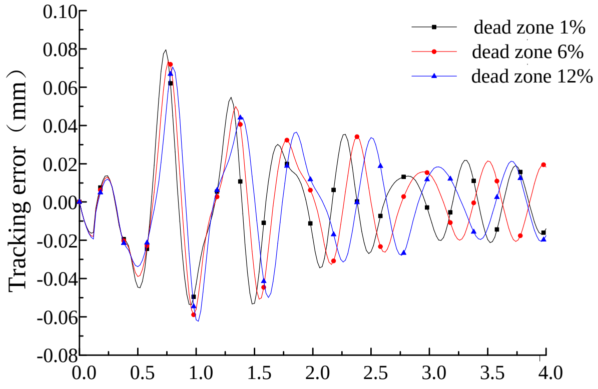
(b)Tracking error of cylinder 2

Fig. 7 Dead zone features of leveling cylinder 1

Setting the dead zone in the control valve of leveling cylinder 1 and 2 to 1% ~ 12% and taking 1%, 6% and 12% for reference point as well, the simulation results are as shown in Fig. 8. Figure (a) and (b) suggest that when dead zone exists in both leveling cylinder 1 and 2, the precision of pressing plane is affected by dead zone. The dead zone is set to 12%, the tracking error of the cylinder 1 increases by 30.5% and the tracking error of the cylinder 2 increases by 12%.



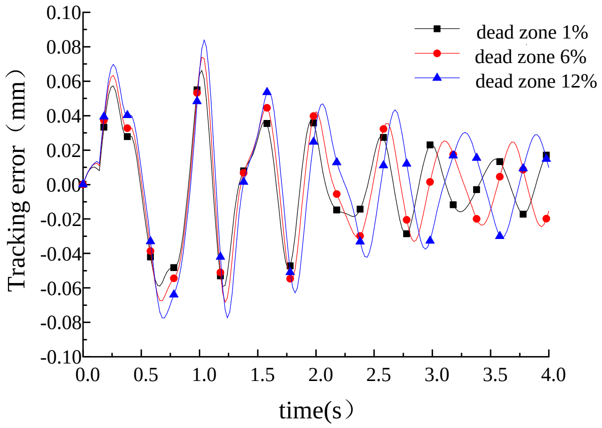
（a）Tracking error of cylinder 1



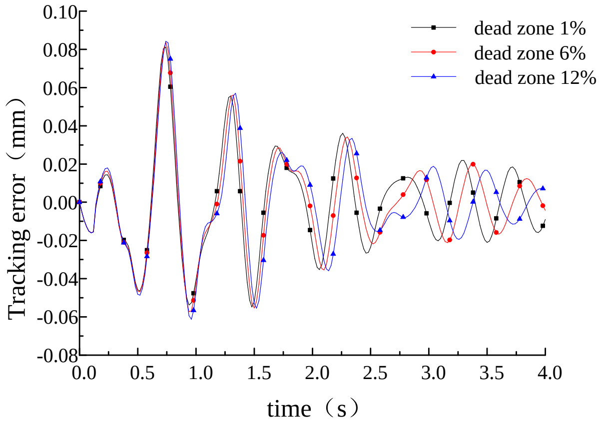
（b）Tracking error of cylinder 2

Fig. 8 Dead zone features of leveling cylinder 1 and 2

Synchronous setting the dead zone in electro-hydraulic control valves of leveling cylinder 1 and 3 to 1% ~ 12% and taking 1%, 6% and 12% for reference points, the simulation results are as shown in Fig. 9. In figure (a) and (b), the dead zones in the hydraulic control valves have a larger influence on the control precision. When the dead zone is 1%, the precision of four corners leveling system plane is within 0.02 mm. While the dead zone in leveling cylinder 1 is 12%, the system tracking error increases by 64.8%. At the same time the speed of four corners leveling system turns to slow down, and the dead zone increases, system tracking error increases as well. Finally the system tends to be stable and does not appear divergent.



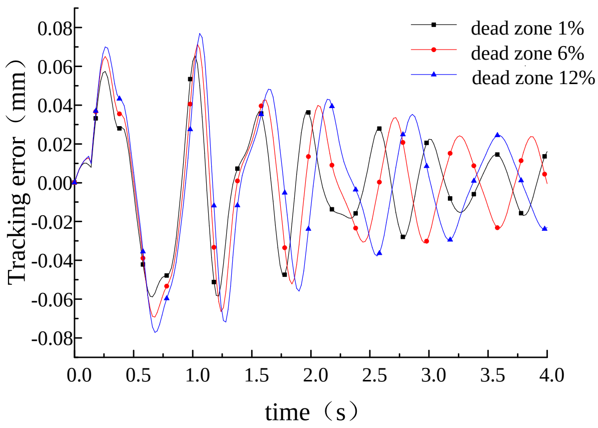
（a）tracking error of cylingder 1



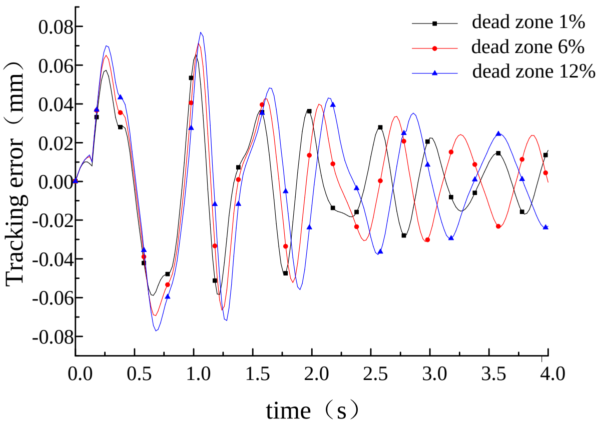
（b）tracking error of cylingder 2

Fig. 9 Dead zone features of leveling cylinder 1 and 3

In the four corners leveling system, when the dead zone exists in the control valve of the leveling cylinder 1 ~ 3 synchronously, the simulation results are shown in Fig. 10. The dead zone features of leveling cylinder 1 are as shown in figure (a). The system tracking error increases with the enlargement of dead zone in control valve and the system tracking error is 0.03 mm when dead zone is 12%, which is 52% larger than that in non-dead zone state. The dead zone features of leveling cylinder 2 are as shown in figure (b). The leveling precision of system experiences a small change of 14% comparing with that in non-dead zone state, but the regulating speed of four corners leveling system decreases.

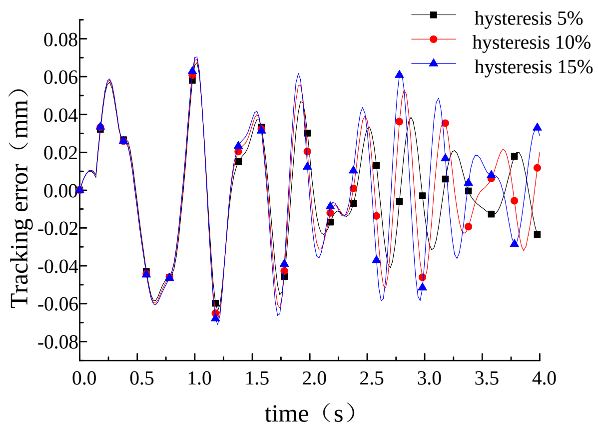


（a）Tracking error of cylinder 1

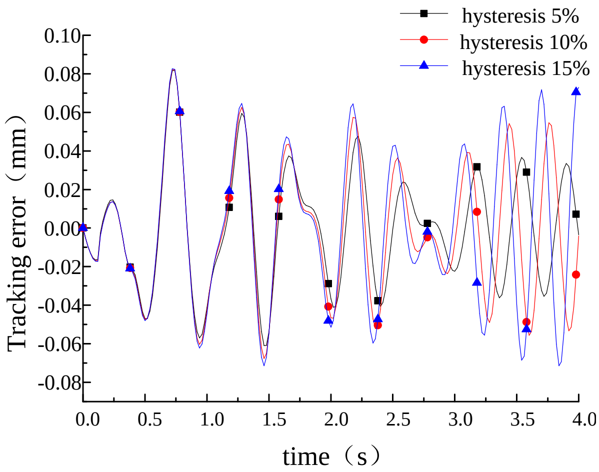


（b）Tracking error of clinder 2

Fig. 10 Dead zone features of leveling cylinder 1~3



（a）tracking error of cylinder 1



（b）tracking error of cylinder 2

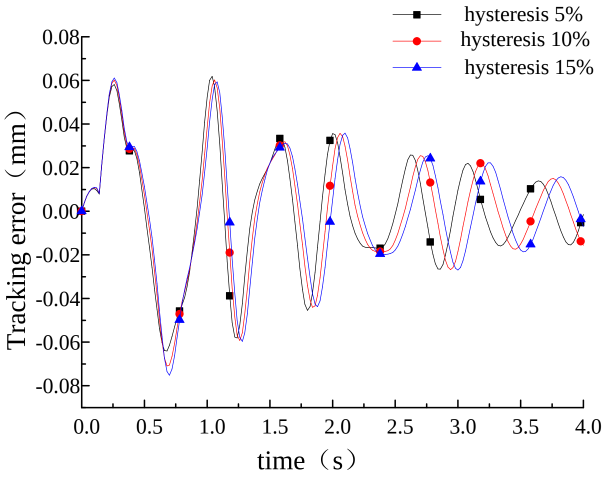
Fig. 11 Hysteresis characteristics of leveling cylinder 1

4.2.2 hysteresis characteristics

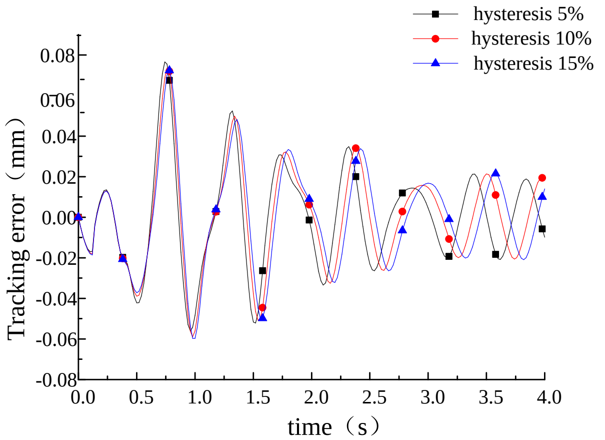
For electro-hydraulic servo system, the hysteresis of the control valve is one of the most important parameters affecting controlling features. The tracking error features of the system are analyzed when the control valve hysteresis are set respectively to 5%, 10% and 15%.

Setting the hysteresis of control valve of leveling cylinder 1 to 5%, 10% and 15%, the tracking error of leveling cylinder 1 is as shown in Figure 11(a). For four corners leveling system, the greater the hysteresis of leveling cylinder 1 is, the larger the tracking error will be. When the hysteresis of control valve increases from 5% to 15%, the tracking error enlarges by 63.4%. Though the variation of error is big, the system does not appear to be unstable. When control valve of leveling cylinder 2 owns a hysteresis, the characteristics of tracking error are as shown in figure (b). At this time the control valve hysteresis of leveling cylinder 2 is set, but the changes of the leveling system and plane system lead to the changes of leveling system tracking error of leveling cylinder 2.

When the hysteresis in the proportion control valves of leveling cylinder 1 and 2 are set respectively to 5%, 10% and 15%, the simulation results are as shown in Fig. 12. In this case, the variations of response precision of pressing plane are small. Though the hysteresis in control valves of leveling cylinder 1 and 2 of four corners leveling system grow bigger, the tracking error is barely changed. The smaller the hysteresis is, the faster the four leveling system adjust and the shorter the adjustment cycle is in the rated time.



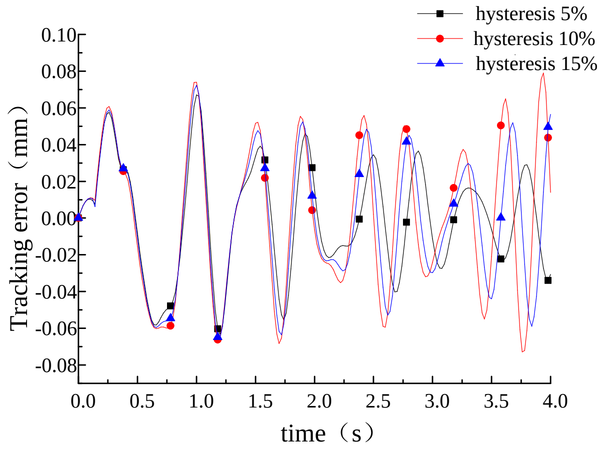
（a）tracking error of cylinder 1



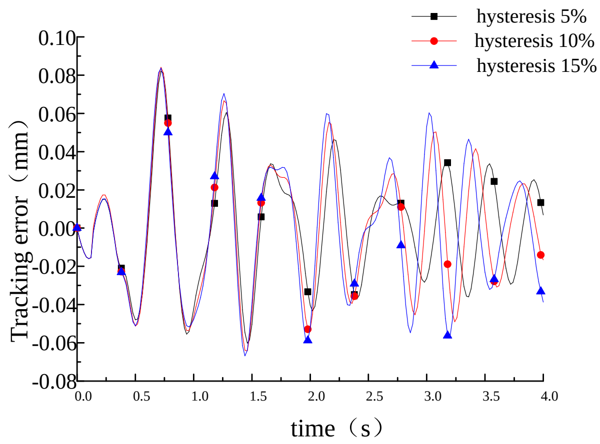
（b）tracking error of cylinder 2

Fig. 12 Hysteresis characteristics of leveling cylinder 1 and 2

When the hysteresis in the control valves of leveling cylinder 1 and 3 are set to 5%, 10% and 15%, the simulation analysis results are shown in Fig. 13. The tracking errors of the simulation results of leveling cylinder 1 are shown in figure (a). The larger hysteresis the control valve is, the worse the control performance is, and the poorer the leveling performance is. With 15% of the hysteresis in control valve of leveling cylinder 1, the tracking error of leveling cylinder 1 increases by 1.5 times. The performance of the tracking error of leveling cylinder 2 is shown in figure (b). When the hysteresis in control valves change from 5% to 15%, the tracking error of leveling cylinder 2 increases by 81.7%.



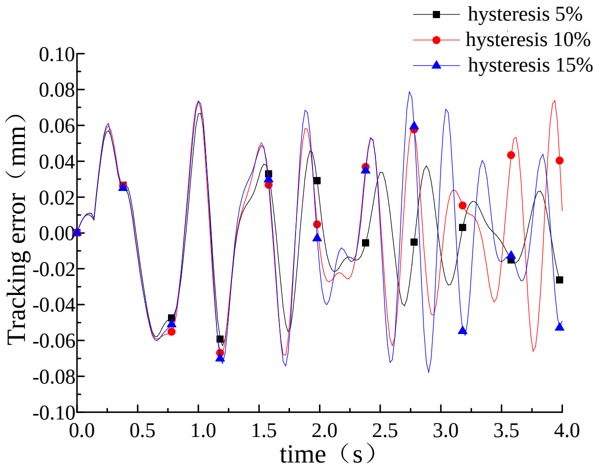
（a）tracking error of cylinder 1



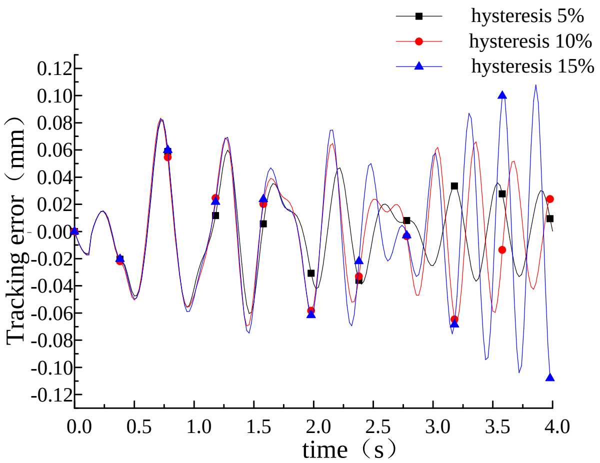
（b）tracking error of cylinder 2

Fig. 13 Hysteresis characteristics of leveling cylinder 1 and 3

When the hysteresis of the control valves of leveling cylinder 1 ~3 are set to 5%, 10% and 15%, the simulation results are shown in Fig. 14. As we can see from figure (a) and (b), when the hysteresis of control valves change from 5% to 15%, the tracking errors of leveling cylinder 1 and 2 change by 4.1 times and 1.73 times respectively. When the hysteresis is more than 10%, the cylinders of four corners leveling system become unstable and the tracking errors show an increasing tendency. The phenomenon shows that the four corners leveling system fails and lost its leveling effect with poor system performance. When the hysteresis is 5%, the system can be stable within the tracking error of + / - 0.02 mm, but its tracking error is larger than those under non-hysteresis conditions. Therefore, when the control valves of multiple leveling cylinders have a great hysteresis at the same time, the leveling performance of system becomes poor significantly.



（a）tracking error of cylinder 1



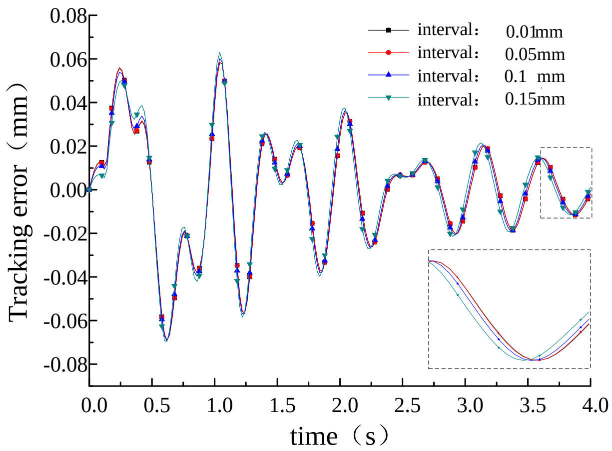
（b）tracking error of cylinder 2

Fig. 14 Hysteresis characteristics of leveling cylinder 1 to 3

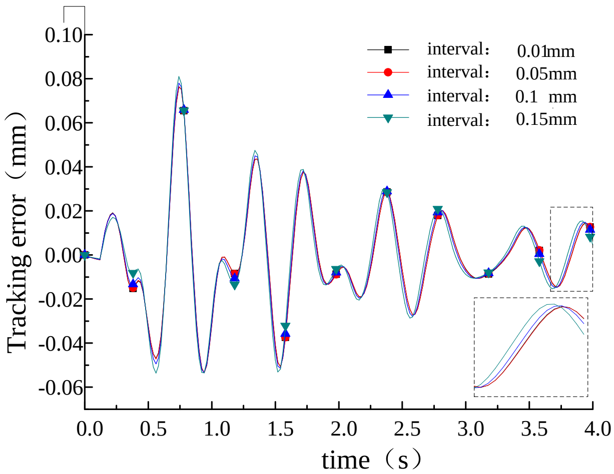
4.2.3 leakage characteristics of hydraulic cylinder

The leakage of hydraulic control system for hydraulic cylinder is inevitable, so it is crucial for us to study the influence of the leakage of hydraulic cylinder to the performance of four corners leveling system. This paper studies the effect of leakage existing in single hydraulic cylinder, double leveling hydraulic cylinders and three leveling hydraulic cylinders for the pressing plane precision of four corners leveling system .

Setting the leakage clearance of hydraulic leveling cylinder 1 to 0.01 mm, 0.05 mm, 0.1 mm and 0.15 mm, we can get the tracking errors of leveling cylinder 1 and 2 through united simulation. If the clearances change, the tracking errors of pressing plane change correspondingly, but the tracking errors of leveling cylinder 1 and 2 change little as shown in Fig. 15. So we conclude that the leakage of hydraulic cylinder with single hydraulic cylinder has tiny effect on the system.



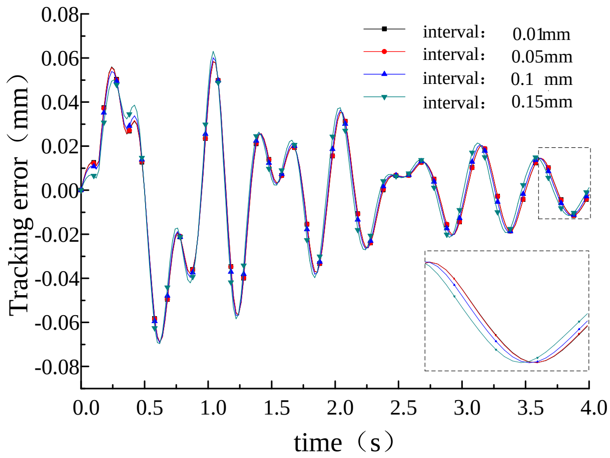
（a）tracking error of cylinder 1



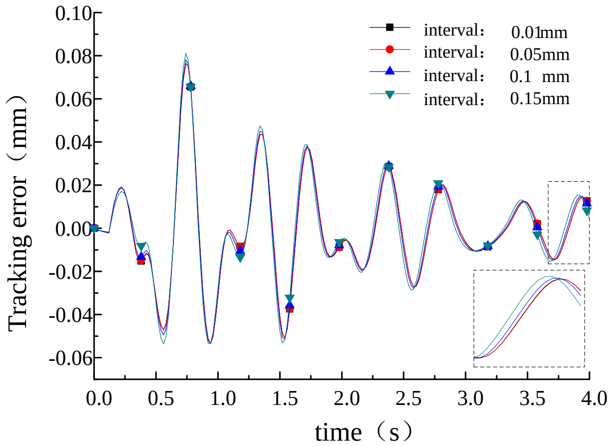
（b）tracking error of cylinder 2

Fig. 15 Tracking errors of leveling cylinder 1 and 2

The leakage clearances of hydraulic leveling cylinders are set respectively to 0.01 mm, 0.05 mm, 0.1 mm and 0.15 mm. Because manufacturing technique of the leveling cylinder with the maximum leakage clearance of 0.15 mm is poorer than its machining and installation, the simulation analysis of the leakage clearance of 0.15 mm can explain the practical problems. Due to the leaking of hydraulic cylinders, different clearances of the hydraulic cylinders own different tracking errors. As shown in Fig. 16, the leakage clearances in leveling cylinders range from 0.01 mm to 0. 1 mm, the tracking error of leveling cylinder 1 is not obvious. However, when clearance is 0.15 mm and the leakage flow rate is 3.3 L/min, the tracking error increases by 3%. If leveling cylinder 2 has the same condition, the tracking error increases by 5.1%.



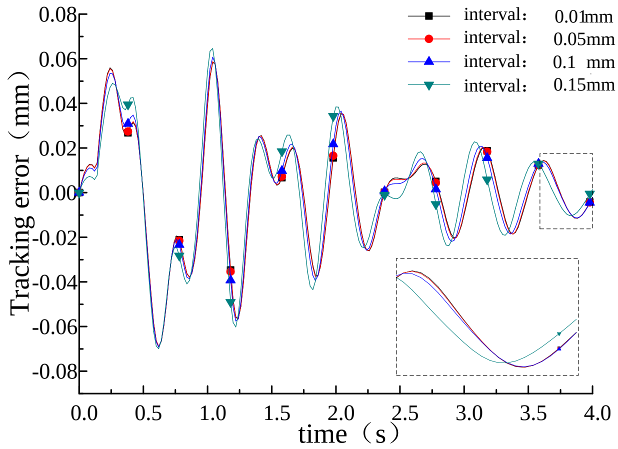
（a）tracking error of cylinder 1



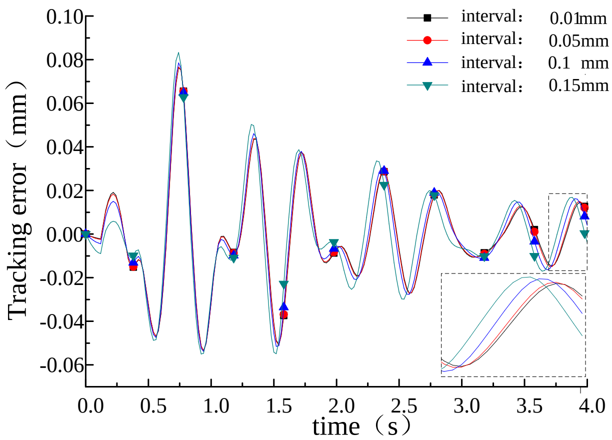
（b）tracking error of cylinder 2

Fig. 16 Tracking errors of leveling cylinder 1 and 2

The clearance of leveling cylinder 1 and 3 are set respectively to 0.01 mm, 0.05 mm, 0.1 mm and 0.15 mm, as shown in Fig. 17. There is a big leakage when the clearance is set to 0.15 mm and the tracking error of the corresponding leveling cylinder will change. Tracking error of leveling cylinder 1 is ranged within 0.6%. Tracking error of leveling cylinder 2 is ranged within 12%.



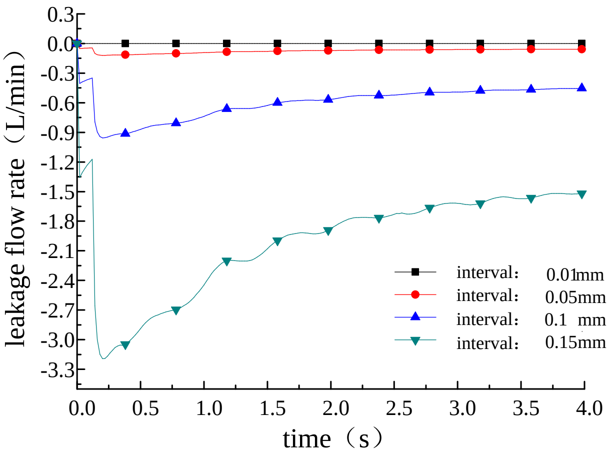
（a）tracking error of cylinder 1



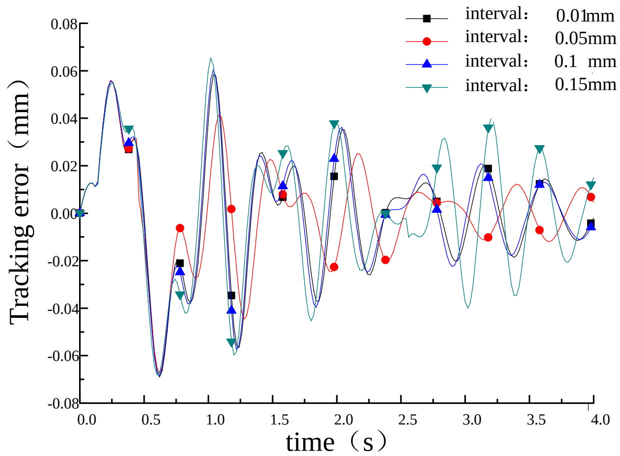
（b）tracking error of cylinder 2

Fig. 17 Tracking errors of leveling cylinder 1 and 2

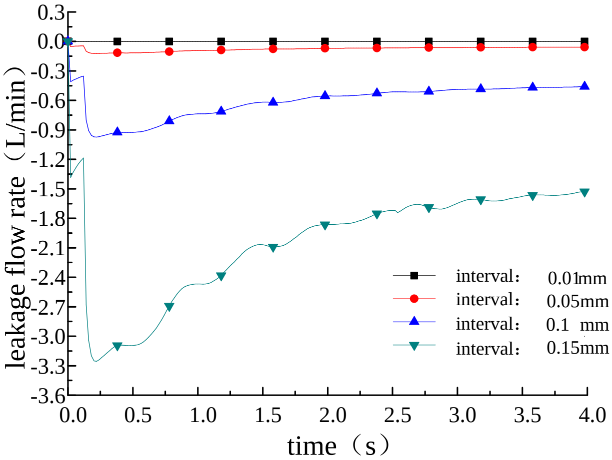
Setting the leakage clearance of leveling cylinder 1 ~ 3 to 0.01 mm, 0.05 mm, 0.1 mm and 0.15 mm, the simulation results are as shown in Fig. 18. The figure (a) ~ (c) respectively show various leakages in the pressing process of leveling cylinder 1 ~ 3. The differences of the leakage flow rates between leveling cylinder 1 ~ 3 are large, and maximum difference is 30%. Due to the differences between the hydraulic cylinder leakages, the tracking errors of leveling cylinder 1 to 3 are shown in figure (d) ~ (f). Comparing with the original one without leakage, the tracking error of leveling cylinder 1 finally increases by 84.4%, the tracking error of leveling cylinder 2 increases by 90.9% and the tracking error of leveling cylinder 3 increases by 80.5%. The larger the leakage of hydraulic cylinder and the more number of the leaking hydraulic cylinder are, the worse the pressing plane level precision is.



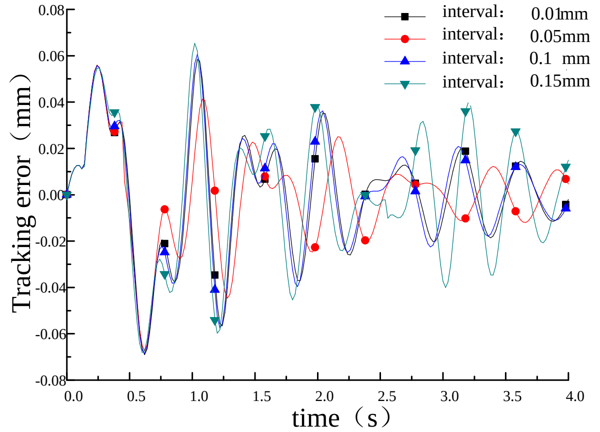
（a）Leakage flow of cylinder 1



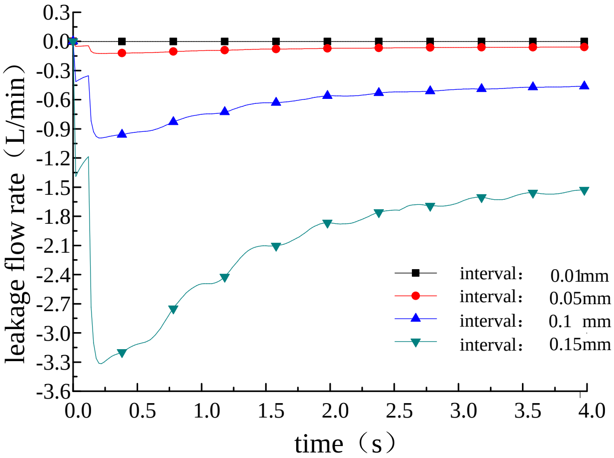
（d）tracking error of cylinder 1



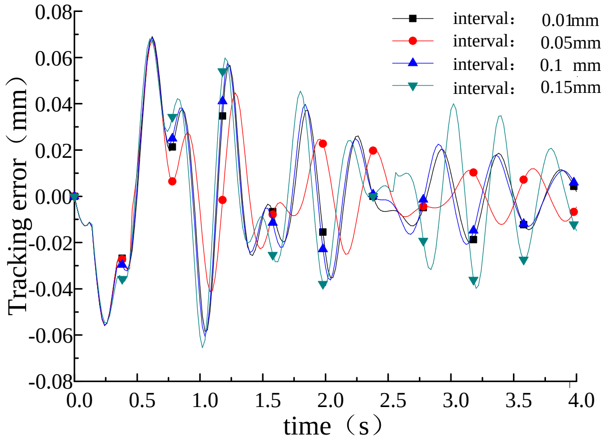
（b）Leakage flow of cylinder 2



（e）tracking error of cylinder 2



（c）Leakage flow of cylinder 3



（f）tracking error of cylinder 3

Fig. 18 Tracking errors and leakage rate of leveling cylinder 1 ~ 3

5. Conclusions

Through the simulation analysis based on co-simulation model, we can obtain the influence laws of control valve dead zone, hysteresis and the leakage of hydraulic cylinder to characteristics of leveling control system.

(1) Dead zone characteristics of proportional valve have a great influence on the property of the leveling system. The tracking error of leveling cylinders increases by 50% with only single cylinder and control valve that had dead zone of 12%. When the dead zone of leveling cylinder 1 and leveling cylinder 2, leveling cylinder 1 and leveling cylinder 3 are both 12% at the same time, the tracking error increases to 64.8%; when the dead zone of leveling cylinder 1 ~ 3 are 12%, the largest tracking error increases by 52%.

(2) The hysteresis of control valve plays a great role on the control precision of leveling system. When hysteresis of single cylinder and control valve exist in the system, the tracking error of cylinder 2 can also be affected. The tracking error expands 1.5 times when leveling cylinder 1 and 3 control valves have hysteresis at the same time. The tracking error can be 4.1 times to the original one when leveling cylinder 1 ~ 3 exist synchronous hysteresis. To sum up, the hysteresis of control valve cannot be more than 5%.

(3) Leakage flow error is 30% when various leveling cylinders' leakage rates are different and leakage clearances are the same. There is the certain effect of the leakage in the leveling system but the effect rules are tiny. When the leveling cylinder 1 ~ 3 have the same leakage at the same time, the uncontrolled error of the pressing plane has appeared, and the controllable performance of pressing plane become worse.

Acknowledgements

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