Research on the Correction of the Linkage Hydraulic System of the Composite Hydraulic Gripper Used in Coal Mine Rigs

Qingfeng Wang¹,² and Hang Chen¹,²,*
¹ State Key Laboratory of the Gas Disaster Detecting, Preventing and Emergency Controlling, Chongqing, China
² Chongqing Research Institute, China Coal Technology Engineering Group, Chongqing, China

*Corresponding author email: scuch@126.com

Abstract. The research against the defect that the gripper of the rig using a traditional linkage hydraulic system always clips back to damage drill pipes when the rig starts to rotate is presented. The correcting solution of a kinetic pressure feedback system including a damper and an accumulator is described by establishing the transfer function of the linkage system and analysing major factors making the gripper to clip back. Taking the ZYWL-4000SY automatic rig for instance, the linkage hydraulic system after correction is compared with that of before in simulating analysis and the correcting solution is verified by both lab and field tests. The results show that the corrected gripper works well without hurting pipes and the rig operates in good and stable condition. The theoretical foundation and method are provided to design and test the linkage function of the composite hydraulic gripper of other similar rigs.

Keywords: Correction; Linkage hydraulic system; Composite hydraulic gripper; Coal mine rig; Transfer function; Kinetic pressure feedback system; Damper; Accumulator.

1. Introduction
In the early stage, coal mine rigs used to adopt the grippers of the normally closed type and the normally open type (Wang, Zhang, & Lyu, 2019). The former one, which has the advantage of good safety, but is relatively easy to breakdown in continuous drilling, doesn’t have a long using duration and can’t be applied to bigger rigs, is commonly tightened by springs and opened by hydraulic strength. In contrast, the latter one which is able to compensate the lack of the clipping strength automatically, but probably easy to have a slip when unloading pipes because of its principle flaw and has some potential safety hazards when drilling in a big slope angle, is usually opened by springs and closed by hydraulic strength. Meanwhile, for the normally open type requires a fixed clipping center rather than an adjustable one, it can hurt the pipes. Owning the advantages of both of these two types, the composite hydraulic gripper (CHG) has already had a wide application (Ruan, Li, & Zhang, 2016). At present, advanced rigs can drill and unload pipes in collaboration because of the adoption of the linkage hydraulic system, such as the Diamec series of Atlas, the LM series of Boart-longyear and the ZYW series of China Coal Technology Engineering Group. One of the most critical factors to realise the collaboration is the linkage of the gripper, which means the pipes will rotate driven by the chuck on the power head when the rotating system is on, in the meantime, the gripper should open automatically to remove the restriction to the pipes (Shi et al., 2020). In the developing experiment of a new linkage system, CHG has the phenomenon of clipping back as soon as the rig starts to rotate, in
which there are repeated serious frictions between the slips of CHG and the pipes, which would damage the pipes very badly. Based on previous studies on CHG, research against the phenomenon that CHG of the rig which adopts a traditional linkage system always clips back to damage pipes when the rig starts to rotate is presented by analysing the structure, the working principle and the hydraulic system.

2. Structural Features and System Principles of CHG

2.1. Structural Features and System Principles of CHG

There are two most common types of grippers, which are called the normally closed type and the normally open type (Xin, 2016; Zhang, 2019).

![Diagram of grippers](image)

**Figure 1.** Structures of the common types of grippers.

The basic structure of the normally closed gripper is shown in figure 1(a). This type is forced to close normally by the disk springs or some other mechanisms and to open by the hydraulic oil, which is generally considered good in safety and can effectively avoid pipes from falling. But it can’t satisfy the demand of larger drilling rigs for the inherent structural limitation of the disk spring (Liang, 2019). On one hand, the compression changing amount of the disk spring plays a very influential part to the elastic force. On the other hand, the compression amount greatly depends on the size of the slips, so the abrasion of the slips can induce a serious lack of the clipping strength.

The normally open gripper is shown in figure 1(b). This type is forced to open normally under the strength of springs or hydraulic pressure and to close by the pressure which is kept stable by a hydraulic lock. This type has the ability to compensate the lack of the clipping strength caused by the abrasion of the slips automatically. As a result of its normally open structure, it has some potential safety hazards when the rig works in a big slope angle condition.

The basic structure of CHG is shown in figure 2. CHG, composed of the normally closed and the normally open type, almost concentrates all the basic advantages of them. The two of the basic functions of the gripper—keeping pipes from falling and unloading pipes mechanically—can be completed separately by the left and the right part. On one hand, the left part of CHG, which usually adopts the disk spring structure to keep pipes in position when stopping drilling, only needs disk springs in relatively small dimension. On the other hand, the right part always uses a hydraulic cylinder to increase the clipping strength which is needed to unload pipes.

![Diagram of CHG](image)

**Figure 2.** Structure of the composited hydraulic gripper.

2.2. Working Principle of the Linkage System of CHG

The schematic diagram of the linkage hydraulic system of the CHG is shown in figure 3. It is working as following steps (Wang, & Chen, 2018). At first, the hydraulic motor of the power head starts to
rotate after the controlling signal. In the meantime, the same pressure forcing the hydraulic motor to
revolve pushes the hydraulic control valve to open, so that the oil from the constant pressure source $P_S$
enters the left part of CHG. Under the pressure, CHG conquers the elastic strength of disk springs to
open automatically. Then the rig begins to drill forwards. Once the power head stops rotating, CHG
will close immediately because the hydraulic control valve will return to its origin status.

![Image of hydraulic system](image.png)

1- hydraulic motor; 2- power head; 3- drill pipe; 4-CHG; 5-hydraulic control valve

**Figure 3.** Linkage hydraulic system of CHG.

### 2.3. Reasons Causing CHG to Clip Back

It is easy to find out from figure 2 that the hydraulic control valve is in charge of manipulating CHG to
close or open while the constant pressure source $P_S$ is in charge of providing the power for CHG to
open. So there are two possible factors which could induce CHG to clip back when the rig starts to
rotate.

1. **Unstable constant pressure source.** When the rig starts to rotate, the pressure of the constant
pressure source $P_S$ which drives CHG to open is unstable because it is disturbed by the pressure from
the rotation system. As a result, CHG will clip back very soon after opening for lacking the strength to
keep it open stably.

2. **Vibration of the controlling pressure of the hydraulic control valve.** The hydraulic control valve
returns to the original status for the reason of the vibration of its X port pressure (i.e. controlling
pressure), which is caused by the pressure from the rotation system. Then the pressure keeping CHG
to open will be suddenly cut off so as to make CHG to clip back.

After repeated tests, there is not obvious vibration of the pressure of the constant pressure source $P_S$,
while the pressure of the X port shows very obvious fluctuation. So the second one is the major reason
to induce CHG to clip back.

### 3. Analysis of the Drilling Linkage System of the CHG

According to the working principle of the linkage system, while the hydraulic motor is rotating, the
rotating oil circuit of the motor provides not only the pressure which drives the motor to rotate
continuously, but also which works as the controlling signal of the hydraulic control valve. Based on
the theoretical analysis of hydromechanics to the system, relevant key equations are listed.

The load torque balance equation of the hydraulic motor is:

$$ P_f V_g = J \frac{d^2 \theta_m}{dt^2} + G \frac{d \theta_m}{dt} + T_L $$

(1)

where $P_f$ is the rotating pressure; $V_g$ is the placement of the hydraulic motor; $J$ is the total rotational
inertia to converted the shaft; $\theta_m$ is the rotating angle; $G$ is the spring load stiffness; $T_L$ is the load
torque converted to the shaft.

The flow continuity equation of the hydraulic motor when rotating is:

$$ Q_m = V_g \frac{d \theta_m}{dt} + C_m P_f + \frac{V_g}{K_y} \frac{d P_f}{dt} $$

(2)
where $Q_m$ is the total flow of the motor; $C_m$ is the leakage factor of the motor; $V_m$ is the volume of the pipes and the high pressure room of the motor; $K_y$ is the elastic modulus of the oil volume.

The force balance equation of the core of the hydraulic control valve is:

$$P_x A = m\frac{d^2x}{dt^2} + B\frac{dx}{dt} + Kx$$  \hspace{1cm} (3)

where $A$ is the cross sectional area of the valve core; $m$ is the mass of the core; $x$ is the placement of the core; $K$ is the stiffness of the spring; $B$ is the kinematic viscosity resistance factor.

The inertia force and the viscous resistance generated by the mass of the core and the moving velocity are extremely tiny compared with the spring force (Khan et al., 2021), so that the former two terms of the right side of equation (3) can be neglected to simplify equation (3) as:

$$P_x A = Kx$$  \hspace{1cm} (4)

The flow continuity equation of the hydraulic control valve is:

$$Q_x = A\frac{dx}{dt} + C_f P_y + \frac{V_f}{K_y} \frac{dP_y}{dt}$$  \hspace{1cm} (5)

where $C_f$ is the leakage factor of the valve; $V_f$ is the volume of the pipes and the high pressure room of the valve.

When the linkage system is working, all the flow of the valve and the motor is provided by the pump, so the total flow balance equation is:

$$Q_z = Q_m + Q_t$$  \hspace{1cm} (6)

After doing the Laplace transformation to equation (1), (2) and (4)—(6), following equations are obtained:

$$\begin{cases}
P_t(s) V_f = J\theta_m s^3 + G\theta_m s + T_i(s) \\
Q_m(s) V_f = V_f \theta_m s + C_m P_t(s) + \frac{V_m}{K_y} P_y(s) s \\
P_t(s) A = Kx(s) \\
Q_t(s) = A\dot{x}(s) s + C_f P_y(s) + \frac{V_f}{K_y} P_y(s) s \\
Q_z(s) = Q_m(s) + Q_t(s)
\end{cases}$$  \hspace{1cm} (7)

The load born by the power head is a constant value when the rotation system starts, that is, $T_i(s)=0$, so all of the intermediate variables in the equation (7) can be eliminated. Then making $P_t(s)$ to devide $Q_z(s)$, the transfer function of the linkage system is:

$$\frac{P_t(s)}{Q_z(s)} = \frac{Js + G}{J(A^2 + \frac{V_f}{K} + \frac{V_m}{K_y})}$$  \hspace{1cm} (8)

It is easy find out from equation (8) that the linkage system of CHG is a typical second order system which includes a differential element and an oscillation element (Wei, Zheng, Huang, Gao, & Liu, 2021). According to the damping ratio formula of the second order system, the damping ratio is:
5. Selection of the Correcting Solution

The reason to cause CHG to clip back has already been found, so it is clear that the pressure vibration of the X port needs to be reduced to eliminate the back-clipping. One of the direct and effective means is to rise the damping of the linkage system.

It can be found from equation (7) and (8) that there are several ways to increase the damping, including to decrease $J$, $K$ or $V_g$ or to increase $A$. But these are in lack of feasibility because the structure of the rig has to be adjusted quite a lot. After comprehensive consideration, a method in which a kinetic pressure feedback system composed of a damper and an accumulator is adopted is introduced into the linkage system, shown in figure 4. By this method, some small adjustments to the valve are necessary instead of big modifications to the rig.

![Figure 4. Linkage system of CHG after correction.](image)

1- hydraulic motor; 2- power head; 3- drill pipe; 4- CHG; 5- hydraulic control valve; 6- accumulator; 7- damper

5. Simulation Comparison

5.1. Simulation of the System before Correction

In order to compare the linkage systems before and after correction, a model of ZYWL-4000SY automatic rig is used as an example in simulation. Its main relevant parameters are listed in table 1.

| Parameter                        | Value | Unit       |
|----------------------------------|-------|------------|
| Max load torque                 | 4000  | N•m        |
| Break-out torque                | 300   | N•m        |
| Range of output speed           | 70 ~ 240 | r/min   |
| Placement of the pump           | 80    | ml/r       |
| Placement of the hydraulic motor| 160   | ml/r       |
| Transmission ratio of the power head | 7.491   | /         |
| Total rotational inertia        | 2.13  | kgm²       |
| Spring stiffness of the valve   | 0.02  | N/m        |
| Leakage factor of the motor     | 0.25  | L/MPa      |
| Leakage factor of the valve     | 0.005 | L/MPa      |
The linkage system before correction is converted into the simulation model in software AMESim, shown in figure 5. Based on the actual working situation of the rig, a step signal is added to make it start to rotate (Liang, Tian, Zheng, & Jiao, 2015). So a step signal input is set to occur at the 5th second. The analysis result of the pressure at the X port of the hydraulic control valve is shown in figure 6.

![Figure 5. Simulation model of the linkage system before correction.](image)

There is a fierce vibration of the pressure at the X port. Besides, two peak values occur almost as soon as the simulation started so that the valve core is set back by the strength of the spring. As a consequence, CHG clips back when the rotating system started. Another phenomenon which can be found out is the entire process lasts for 2—3 seconds, which indicates that CHG clips back repeatedly rather than once and the amplitude decreased gradually.

5.2. Simulation of the System after Correction
The system in figure 5 can be transformed into the model shown in figure 7. Considering the structure of the rig, an accumulator whose spring is $\Phi 30/30$ mm (diameter/length) and stiffness is 20 N/m and a damper whose diameter is 3 mm and length is 1.5 mm are added into the system.

The simulating result is shown in figure 8. It is clear that the pressure of the X port goes up very fast and stably to the working pressure without obvious vibration at the starting moment. So it can be concluded that the corrected system has fast response and stable controlling pressure (Li et al., 2018).

![Figure 7. Simulation model of the system after correction.](image)

6. Lab Tests and Field Application
A ZYWL-4000SY automatic rig, shown in figure 9(a), is used to do the lab test. The test is processed as following steps:
- Open the chuck and the gripper and put the pipes through them.
- Set the hydraulic system into the linkage status.
- Start the power head begin to rotate.
- After a few seconds’ rotating, turn off the rig and take off the pipes.

The CHG clips back repeatedly as soon as the power head begin to rotate and the slips hit the pipes fiercely. There are clear scratches on the pipe, shown in figure 9(b).

![Figure 9. Lab test of the system before correction.](image)

(a) (b)

A new hydraulic control valve on the top of which a spring accumulator is integrated is used to correct the linkage system, shown in figure 10. Then the lab test is operated with the same steps. CHG don’t clip back any more this time and there isn’t any scratch on the surface of the pipe. So using a kinetic pressure feedback system to correct the linkage system can eliminate the back-clipping phenomenon effectively.

![Figure 10. (a) Hydraulic control valve with an accumulator and (b) Corrected control console.](image)

(a) (b)

7. Conclusions

(1) Against the defect that CHG of the rig using the traditional linkage hydraulic system always clips back to damage drill pipes when the rig starts, it is discovered that the controlling pressure vibration of the hydraulic control valve resulted by the rotating oil way of the hydraulic motor is the main reason.

(2) After analysis, it is found that the linkage hydraulic system of CHG is a typical second-order system and low damping is the main factor inducing the pressure vibration. The correcting solution is to introduce a kinetic pressure feedback system composed of a damper and an accumulator of which main parameters have been confirmed.

(3) It is verified by simulations, lab tests and practical application that the corrected system is stable and responds fast without obvious pressure vibration.

(4) In the future, the strength of the spring of the accumulator could be studied to make the pressure stable more quickly.
Acknowledgments
This work was supported by the National key R & D program (Grant No.2018YFC0808000) and the special fund for scientific innovation and entrepreneurship of Tiandi Science and Technology Co., Ltd. (Grant No. 2020-TD-ZD014), which are gratefully acknowledged.

References
[1] Khan, K., Sohaib, M., Rashid, A., Ali, S., Akbar, H., & Basit, A., et al. (2021). Recent trends and challenges in predictive maintenance of aircraft’s engine and hydraulic system. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*.
[2] Liang, C.M. (2019). Design of top open and close style clamp for directional drilling rig. *Safety in Coal Mines, 50*, (08), 114-119.
[3] Liang, L.C., Tian, J.J., Zheng, H., & Jiao, S.J. (2015). A study on force transmission in a hydraulic support under impact loading on its canopy beam. *Journal of China Coal Society, 40*, 2522-2527.
[4] Li, M.S., Ye, J., Xie, B., Yang, S., Zeng, B.G. & Liu, J. (2018). Design and test of electric-hydraulic confluence valve in double pump confluence system. *Transactions of the Chinese Society for Agricultural Machinery, 49*, (09), 353-360.
[5] Ruan, S.G., Li, X.Z. & Zhang, L. (2016). Design and analysis of automatic centering normally-closed compound hydraulic clamper. *Mining Safety & Environmental Protection, 43*, (06), 81-83.
[6] Shi, Z.J., Yao, K., Yao, N.P., Li, Q.X., Tian, H.L., Tian, D.Z., & et al. (2020). 40 years of development and prospect on underground coal mine tunnel drilling technology and equipment in China. *Coal Science and Technology, 48*, (04), 1-34.
[7] Wang, Q.F., & Chen, H. (2018). Development and prospect on intelligent drilling technology and equipment for gas drainage. *Industry and Mine Automation, 44*, (11), 18-24.
[8] Wei, Z., Zheng, L., Huang, L., Gao, W., & Liu, R.. (2021). Prediction and analysis of diesel engine combustion noise using transfer function method. *International Journal of Automotive Technology, 22*(03), 665-676.
[9] Wang, Q.F., Zhang, S.Z. & Lyu, J.J. (2019). Research on self-adaptive unloading linkage system of duplex hydraulic holder of coal mine drilling rig. *Coal Mine Machinery, 40*, (06), 40-43.
[10] Xin, D.Z. (2016). Development and experimental research of ZYW-4000G high-speed drilling machine. *Mining Safety & Environmental Protection, 43*, (04), 27-30.
[11] Zhang, G. (2019). Principle design and simulation analysis of hydraulic-controlled hydraulic boosting for normally closed gripper. *Coal Mine Machinery, 40*, (07), 76-78.