Simulation and Analysis of a Kind of Gas-Liquid Linkage System Based on Response Surface Method

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Abstract. The simulation analysis is carried out for a kind of gas-liquid linkage system composed of gas-liquid conversion cylinder. Firstly, the dynamic characteristics of hydraulic system, pneumatic system and pneumatic hydraulic system are compared. Then through batch analysis, the influence of the design parameters of the gas-liquid converter on the system is analyzed. Finally, by using the method of experimental design, the influence of the main parameters of the gas-liquid combined system on its dynamic characteristics is clarified, which provides the basis for the subsequent design and development.

1. Introduction
Fluid transmission is one of the most widely used transmission forms in industry. According to whether the transmission medium is liquid or pneumatic, it can be divided into two types: hydraulic transmission and pneumatic transmission. Usually, the hydraulic system has the advantages of large power transmission, large power weight ratio, stable transmission, but the system is more complex and expensive. The pneumatic transmission system has the characteristics of quick response, low cost, clean and environmental protection, but the output force is small and the stability is poor. When hydraulic transmission and pneumatic transmission are combined into a combined transmission system in a certain way, the advantages of hydraulic system and pneumatic system can be combined.

The purpose of this study is to carry out simulation analysis and experimental design for a gas-liquid combined transmission system composed of a gas-liquid conversion cylinder, to clarify the dynamic characteristics of this system and understand the impact of relevant parameters on the characteristics, so as to provide basis for subsequent design and development.

2. Principle of gas-liquid linkage system
The pneumatic hydraulic system is a combination of hydraulic transmission and pneumatic transmission, as shown in Figure 1. The core element of the system is the gas-liquid conversion cylinder. The element is similar to the hydraulic cylinder, the difference is that the working medium on both sides of the piston is oil and gas. The system is driven by pressure air and controlled by pneumatic reversing valve. Through the piston of the gas-liquid conversion cylinder, the pressure energy of the gas is converted into the pressure energy of the liquid, and the final execution action is completed by the hydraulic cylinder, so that the characteristics of smooth operation and vibration absorption of the hydraulic system can be fully utilized.
According to the actual working conditions, the gas-liquid transfer cylinder can be designed to have the same gas side area and liquid side area. At this time, the gas-liquid transfer cylinder is mainly used to increase the system damping, making the movement more stable. It can also be designed that the area of gas side is larger than that of liquid side. At this time, the gas-liquid conversion cylinder is mainly used to pressurize the system, which makes the actuator obtain more driving force. It can be seen that the ratio of gas side piston area to liquid side piston area is the most important parameter affecting the system.

![Figure 1. Schematic diagram of gas-liquid combined system](image)

### 3. Comparative analysis of three systems

AMESim is a simulation platform supporting multidisciplinary collaborative analysis. Based on the software, three system models of pneumatic hydraulic linkage system, pneumatic system and hydraulic system can be built, as shown in Figure 2. By setting simulation analysis parameters, the three systems can be operated under approximate conditions. Among them, the system pressure of pneumatic hydraulic system and pneumatic system is set as 7bar, and the hydraulic system is set as 10bar. The load mass driven by the three systems is 100kg, and the load is placed horizontally.

![Figure 2. Simulation models of three systems](image)

Carry out simulation analysis on the three systems, the analysis time is 5S, and the calculation step is 0.01s. After the analysis, output the displacement and speed of the load mass block of the three systems respectively, as shown in Fig. 3 and Fig. 4. It can be seen from Figure 3 that the displacement transient process of the hydraulic system lasts for about 2S, and the displacement curve rises gently, showing obvious inertial characteristics, and the final steady displacement is 0.07mm. The transient process of the displacement of the pneumatic system is repeated oscillations for many times, showing obvious elastic characteristics. It does not reach the steady state in the simulation time, but from the trend, it can be judged that the steady-state displacement is about 0.03mm. The displacement curve of the gas-liquid combined system decays rapidly after three small oscillations, and reaches steady state after 1.5s, the reddest displacement is about 0.12mm.
According to the mechanical model, the final steady displacement is the compression of the load spring, which reflects the output force of the three systems. It can be seen from the comparison that the air supply pressure of the pneumatic transmission system and the pneumatic hydraulic linkage system is 7 bar, but the output pressure is significantly higher than that of the pneumatic transmission system due to the effective increase of the area ratio of the pneumatic hydraulic conversion cylinder.

It can be seen from Fig. 4 that the speed characteristics of the three systems are as follows: the starting speed of the hydraulic system is less than 0.1 m/s, with the slowest response; the starting speed of the pneumatic transmission system is about 0.28 m/s, with fast response but poor stability. The start-up speed of the gas-liquid linkage system is more than 0.6 m/s, the reaction speed is the fastest, and it can decay rapidly after reaching the steady state. It can be seen that the pneumatic hydraulic system has a good combination of the quick response of the pneumatic system and the smooth transmission of the hydraulic system.

4. Batch processing analysis of gas-liquid converter parameters
In the gas-liquid linkage system, the most important design parameter is the ratio of gas side piston area to liquid side piston area, which is directly related to the output force of the system. In order to obtain the relevant laws, the simulation model was analyzed in batch. Set the liquid side piston diameter to 30 mm and the gas side piston diameter to a series of values from 50 to 100. The influence of this parameter on the displacement and velocity of the system is analyzed by batch processing.

According to the displacement results of batch analysis, the larger the piston area on the gas side is, the larger the output force is, so the larger the displacement of the hydraulic cylinder is, as shown in Figure 5. It can be seen from the observed speed results that the larger the piston area on the gas side is, the larger the speed oscillation amplitude is and the longer the adjustment time is, as shown in Figure 6.
5. Experimental design and response surface construction

Response surface design is a method to effectively establish the relationship between test indexes and continuous variables through a small amount of test data. Its basic idea is to express a complex unknown function relationship by approximately constructing a polynomial model with a clear expression form in a small area. Based on experimental design and mathematical statistics, this method not only considers the random error of experiment, but also computes simply. It is an effective way to solve the problem.

In order to investigate the coupling effect between variables, a complete second-order response surface model including cross terms is adopted, such as formula (1).

\[ y(x) = \alpha_0 + \sum_{i=1}^{k} \alpha_i x_i + \sum_{i=1}^{k} \alpha_{ii} x_i^2 + \sum_{i<j}^{k} \alpha_{ij} x_i x_j + \varepsilon \]  

(1)

Where, \( k \) is the number of design variables, \( x_i \) is the design variable, \( \alpha_i, \alpha_{ii}, \alpha_{ij} \) are polynomial coefficients; \( \varepsilon \) is the error.

Three variables, i.e. gas side piston area, gas-liquid piston cylinder mass and throttle valve orifice diameter, are selected and recorded as \( X_1, X_2 \) and \( X_3 \).

Take the displacement value of hydraulic cylinder after the system enters into steady state as the response value, which is recorded as \( Y_1 \). Take the amplitude of hydraulic cylinder speed after the system enters into steady state as the response value, which is recorded as \( Y_2 \).

Central composite design is the most commonly used second-order response surface experimental design method. This method is a popular second-order response surface experiment design method. It combines the traditional interpolation node distribution with the full factor or partial factor design, and can provide more information with as few experiments as possible. The samples are determined based on the central composite design, and table 1 can be obtained through simulation calculation.

| Number | \( X_1/\text{mm} \) | \( X_2/\text{kg} \) | \( X_3/\text{mm} \) | \( Y_1/\text{m} \) | \( Y_2/\text{m/s} \) |
|--------|----------------|----------------|----------------|----------------|----------------|
| 1      | 60             | 2              | 4              | 1.69326140262100e-01 | 7.42570825780130e-03 |
| 2      | 80             | 2              | 4              | 2.99600777223400e-01 | 9.15194970868420e-02 |
| 3      | 60             | 4              | 4              | 1.69286775547948e-01 | 6.70528750938598e-03 |
| 4      | 60             | 2              | 6              | 1.69409002512690e-01 | 1.96775918536033e-02 |
| 5      | 80             | 4              | 4              | 2.99596515093547e-01 | 9.3649635507512e-02 |
| 6      | 60             | 4              | 6              | 1.69211092029852e-01 | 1.85241132740101e-02 |
| 7      | 80             | 2              | 6              | 2.99879006122525e-01 | 3.4234169729362e-02 |
| 8      | 70             | 3              | 5              | 3.0176181599733e-01 | 8.7664472863441e-03 |
| 9      | 80             | 4              | 6              | 2.99767984837697e-01 | 8.74336248845790e-02 |
| 10     | 50             | 3              | 5              | 1.17533231491602e-01 | 1.61177219199742e-02 |
| 11     | 70             | 1              | 5              | 2.30208040016919e-01 | 1.08542031690402e-02 |
| 12     | 90             | 3              | 5              | 3.00006985176924e-01 | 8.76793667829930e-02 |
| 13     | 70             | 5              | 5              | 2.30202846808352e-01 | 7.99687016325457e-03 |
| 14     | 70             | 3              | 3              | 2.3037996719155e-01 | 2.67173074785365e-03 |
| 15     | 70             | 3              | 7              | 2.30043947449978e-01 | 1.39809535315417e-02 |

According to Table 1, the response surface model of each response variable can be obtained:

\[ Y_i = X A_i X^T \]  

(2)
\[ Y_2 = X A_2 X^T \]  \hspace{1cm} (3)

Where, \( X = [1, x_1, x_2, x_3] \) \( A_1 \) and \( A_2 \) are coefficient matrix.

\[
A_1 = \begin{bmatrix}
-0.4983 & 0.0073 & 0.0032 & 0.0052 \\
0.0073 & -6.4258e-5 & 7.6835e-7 & 2.7598e-6 \\
0.0032 & 7.6835e-7 & -0.0011 & -1.6523e-5 \\
0.0052 & 2.7598e-6 & -1.6523e-5 & -0.0011 \\
\end{bmatrix}
\]

\[
A_2 = \begin{bmatrix}
-0.0929 & -0.0027 & 0.0136 & 0.0341 \\
-0.0027 & 7.1507e-5 & -1.2411e-5 & -0.0002 \\
0.0136 & -1.2411e-5 & -0.0035 & -0.0005 \\
0.0341 & -0.0002 & -0.0005 & -0.0037 \\
\end{bmatrix}
\]

It can be seen from Fig. 7 and Fig. 8 that the steady displacement of hydraulic cylinder in gas-liquid linkage system is mainly determined by the area ratio of gas-liquid conversion cylinder, and the influence of piston mass and orifice diameter can be ignored. The larger the area ratio of the gas-liquid conversion cylinder is, the larger the output force of the cylinder is. The relationship between the two is mainly linear.

**Figure 7.** Response of \( Y_1 \) to \( X_1 \) and \( X_2 \)

**Figure 8.** Response of \( Y_1 \) to \( X_1 \) and \( X_3 \)

**Figure 9.** Response of \( Y_2 \) to \( X_2 \) and \( X_3 \)

**Figure 10.** Response of \( Y_2 \) to \( X_1 \) and \( X_2 \)
It can be seen from Figure 9 that the relationship between the steady displacement of the hydraulic cylinder of the pneumatic hydraulic linkage system and the piston mass and the orifice diameter presents a concave quadric surface. When the mass of piston and the diameter of throttle are in the middle, the displacement is the smallest. It can be seen from Figure 10 and Figure 11 that the area ratio of the gas-liquid conversion cylinder mainly affects the speed fluctuation of the hydraulic cylinder of the gas-liquid linkage system, and the throttle diameter can also have a certain impact on the speed fluctuation, and the smaller the throttle diameter is, the smaller the speed fluctuation is. It can be seen from Figure 12 that the relationship between the speed fluctuation of hydraulic cylinder in the pneumatic hydraulic linkage system and the piston mass and the orifice diameter presents a convex quadric surface. When the mass of piston and the diameter of throttle take the middle value, the velocity fluctuation is the biggest.

6. Conclusion
The simulation analysis is carried out for a kind of gas-liquid combined transmission system composed of gas-liquid conversion cylinder. Firstly, the dynamic characteristics of hydraulic system, pneumatic system and pneumatic hydraulic system are compared. Then through batch analysis, the influence of the design parameters of the gas-liquid converter on the system is analyzed. Finally, by using the method of experimental design, the influence of the main parameters of the gas-liquid combined system on its dynamic characteristics is clarified, which provides the basis for the subsequent design and development.

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