Analysis and application of a new noise test system for the hydraulic motor

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Abstract
The loading system of the existing hydraulic motor performance test platform is complicated, the interference is too much, and it is not suitable to measure the hydraulic motor noise level. In this paper, a new platform for measuring the sound pressure level of the hydraulic motor noise is designed. It satisfies the requirement of simplification and less interference in other parts of the noise test except for the test object and ensures the accuracy of test results. This paper firstly introduces the hydraulic system and its principle, calculates the relations of the flow, pressure and power theoretically and verifies them with AMEsim. Then the control part, mechanical structure and semi-anechoic room of the hydraulic system are introduced and the method in the noise experiment is also explained. Finally, the noise level of a bent-axis type hydraulic piston motor is measured in the semi-anechoic room. The background noise and hydraulic motor noise under different conditions are tested by the Danish BK acoustic test system to verify the functionality and stability of the test platform and the noise spectrum, the efficiency of hydraulic system and the effect of the power recovery are analyzed.

Keywords: Hydraulic motor, Less interference, Noise test, Semi-anechoic room, System design

1. Introduction

With the development of the hydraulic industry, hydraulic systems are developing in the areas of high speed, high pressure and heavy load. The emergence of high-pressure pumps and high-torque hydraulic motors has made the vibration and noise problems of hydraulic systems more and more serious, which seriously restricts the development of hydraulic technology (Ding et al., 2018). Noise not only deteriorates the environment, but also affects the health of the operator and damages hydraulic components (Liu et al., 2010; Tessier-Sherman et al., 2017; Zhang et al., 2019).

The hydraulic motor is the actuator in the hydraulic system and is one of the main noises in the hydraulic system. The hydraulic motor converts hydraulic energy into mechanical energy and outputs it. When used for high speed, high pressure and heavy load, the vibration and noise generated by the hydraulic motor will be more serious (Zhang et al., 2015; Lin et al., 2018; Lu et al., 2018; Lu et al., 2019). Therefore, it is of great significance to research on the noise characteristics of the hydraulic motor to reduce the noise level. Hydraulic motor airborne noise level test is an important means of determining noise levels, identifying motors’ advantages and disadvantages, improving the structural design, improving system performance, and facilitating product upgrades. In order to effectively study the noise reduction of the hydraulic motors, it is necessary to accurately measure the noise of the motor (Brian et al., 2003; Johansson et al., 2007; Seeniraj et al., 2009). A complete noise test system is indispensable. The measurement of the noise level requires a semi-anechoic room, a matching hydraulic system and noise measurement equipment.

At present, during the hydraulic motor test (Liu et al., 2015; Li et al., 2012; Wen et al., 2017; Shi et al., 2014; Yan et al., 2005; Liu et al., 2019), the loading methods are mostly different. The common loading methods for hydraulic motor tests: (1) Mechanical loading, mechanical loading methods include friction dynamometer loading, torsion spring loading, and inertial disk loading. These methods are not suitable for high power situations; (2) Hydraulic loading, hydraulic
loading is to install a relief valve or a throttle valve on the hydraulic motor return line. The external leakage of this method is increased, the loading mode is unsafe, and the energy loss is large; (3) Electrical loading, electrical loading methods include electric dynamometer loading, DC excitation motor loading, and automatic load simulator. The method loading device is complicated and the test cost is high; (4) Hydraulic pump or motor loading, hydraulic pump and motor loading are the most common loading methods at present. However, the hydraulic system requires an additional hydraulic pump or motor. The hydraulic system is complicated, the interference is large, and the energy consumption is high.

From the research, there are many test platforms for the hydraulic motor’s performance, but few for noise test (Liang et al., 2016; Sun et al., 2016; Zhao et al., 2014). The traditional test platforms are not good for noise test because the load of the hydraulic motor will introduce noise interference.

The above technology cannot meet the requirements of the noise test for the hydraulic motor, so a new test system is designed to solve the above problems in this paper. First, the system and the layout are simple, which can eliminate noise interference from other hydraulic and mechanical systems when the noise test is conducted for the hydraulic motor in the semi-anechoic room. Second, the hydraulic motor is an actuator. It needs to add loads for the performance test of the hydraulic motor, especially in the laboratory, so a lot of energy consumed by the load will be a loss and noise interference from the load is introduced. Therefore, in the new system, the electrical motor and only one hydraulic pump are used to drive the hydraulic motor and as the load of the hydraulic motor, which will reduce the noise interference caused by loads and recover energy by the way of the tested hydraulic motor and electrical motor together driving the hydraulic pump.

In this paper, firstly the hydraulic system is designed and its principle is explained. Then the system is theoretically calculated and simulated with AMEsim. Finally, the effectiveness of the scheme for measuring the noise level of the hydraulic motor is verified by experiments.

2. Hydraulic system and principle

Hydraulic pump and hydraulic motor are connected to the electrical motor respectively. It meets the requirement of simplification and less interference in other parts of the noise test except for the test object and achieves the purpose of the energy saving and environmental protection.

2.1 System design

Figure 1 shows the hydraulic principle of the new system which is mainly composed of a hydraulic pump, an electrical motor, a hydraulic motor and several hydraulic components. The pressure control is shown in the left of Fig.1. It consists of a cartridge valve and two pilot relief valves. The middle part is an electrical motor and a hydraulic pump. The semi-anechoic room is in the right. The hydraulic system is simple in structure. The pressure control is simple, and the hydraulic motor loading is simple.
2.2 Working principle

The electrical motor 7 drives the hydraulic pump 9 to rotate, and the oil from the hydraulic pump 9 flows through the cartridge valve 19 to the hydraulic motor 1 and the cartridge valve 23. The output shaft of the hydraulic motor 1 and the other end of the motor 7 are connected by the universal joint 5. When the hydraulic motor is running, it drives the hydraulic pump together with the electrical motor. It solves the problem that the hydraulic motor will introduce extra loads in the tests. When the valve 25 works at the left position, the system pressure can be controlled by the relief valve 28 or 29. The pressure of the pilot oil of the cartridge valve 23 is controlled by the proportional relief valve 28 or the direct acting relief valve 29. The pressure gauge 2 is observed to determine whether the oil pressure supplied to the hydraulic motor 1 reaches the target value. When the valve 25 works at the right position and the valve 20 works at the right position, the system cannot be loaded and all the oil flows into the tank.

3. Theoretical analysis and simulation

3.1 Theoretical analysis

In the experiment, the input and output parameters need to be matched. The hydraulic pump and the hydraulic motor are connected by an electrical motor, so the rotational speed and torque have a certain relationship. The oil flows in two ways. One way leads to the hydraulic motor and the other way leads to the control part. There is a continuity relationship.

Hydraulic pump output flow:

\[ Q_p = V_p n_p \eta_pv / 60 \]  

Where, \( V_p \) is the displacement of the hydraulic pump, \( n_p \) is the rotational speed of the hydraulic pump, \( \eta_pv \) is the volumetric efficiency of the hydraulic pump.

Hydraulic motor inlet flow:

\[ Q_m = V_m n_m / 60 \eta_mv \]  

Where, \( V_m \) is the displacement of the hydraulic motor, \( n_m \) is the rotational speed of the hydraulic motor, \( \eta_mv \) is the volumetric efficiency of the hydraulic motor.

According to the principle of flow continuity:

\[ Q_p = Q_m + Q_r \]  

Where, \( Q_r \) is the flow through the cartridge valve 23.

Because the hydraulic pump and the hydraulic motor have the same rotational speed, \( n_m = n_p \), from the Eq. (1), (2), (3):

\[ V_p = V_m / \eta_mv + 60Q_r / n_p \eta_pv \]  

Therefore, the necessary condition for the hydraulic system to work normally is that the displacement of the hydraulic pump must be larger than the displacement of the hydraulic motor.

The pressure of the pilot chamber 23 is determined by the pressure of the relief valve 28 or valve 29. Usually, it is controlled by the relief valve 28.

The cartridge valve control port is X, the lateral port is A, the forward port is B. The pressure of the cartridge valve pilot chamber is assumed to be \( p_0 \). \( F_t \) is the cartridge valve return spring force, excluding the valve core weight and friction resistance. When the sum of the pressures of A and B is greater than the sum of the pilot X pressure and the spring preload:

\[ p_0 A_x + F_t \leq p_A A_A + p_B A_B \]  

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The valve element of the cartridge valve 23 is opened, and the oil flows from A to B and returns to the tank. The valve element is stable at a certain opening position to ensure that the pressure of the main oil circuit is stable to $p_A$:

$$
p_A = \frac{p_{eA} A_e + F_e - p_{eA} A_e}{A_e} \tag{6}
$$

In the Eq. (6), the oil pressure flowing to the hydraulic motor depends on the pressure of the relief valve 28 or the valve 29. The oil flows into the hydraulic motor through the cartridge valve 19. The valve 20 works in the left position. The oil can flow to the hydraulic motor only by overcoming the spring preload, and the pressure drop is negligible:

$$
p_m \approx p_A \tag{7}
$$

The pressure at the inlet of the hydraulic motor $p_m$ is determined by the pressure $p_D$. The hydraulic motor is connected to the other end of the motor. The electrical motor and the hydraulic motor together drive the hydraulic pump to work. The output power of the hydraulic motor is:

$$
N_m = \frac{p_m Q_m \eta_{mm}}{60} = \frac{p_m V_m n_m \eta_{mm}}{60} \tag{8}
$$

Where, $\eta_{mm}$ is the mechanical efficiency of the hydraulic motor, $V_m$ and $\eta_{mm}$ are certain parameters, the rotational speed of the hydraulic motor $n_m$ is determined by the electrical motor. Therefore, from the Eq. (8), the output power $N_m$ of the hydraulic motor depends on the pressure of the control portion.

The hydraulic pump converts the power of the electrical motor and the hydraulic motor into the hydraulic energy. The power of the hydraulic pump is:

$$
N_p = \frac{p_p Q_p}{\eta_{pm}} = \frac{p_p V_p n_p}{60 \eta_{pm}} \tag{9}
$$
Where, $\eta_{pm}$ is the mechanical efficiency of the hydraulic pump.

In the system, the power recovered is the output power of the hydraulic motor. The efficiency of the energy recovery is:

$$\zeta = \frac{N_e}{N_p} = \frac{p_n V_n \eta_{inlet} \eta_{pm}}{p_r V_r} \approx \frac{V_m \eta_{inlet} \eta_{pm}}{V_p}$$

(10)

### 3.2 AMEsim simulation

The simulation model of the hydraulic system based on AMEsim is shown in Fig.2. The current of the proportional relief valve is adjusted to change the pressure of the system. The simulated image shows the relationship between the hydraulic motor inlet pressure and the relief valve pressure.

In the simulation, a valve is used to control whether the hydraulic system is in operation. It is equivalent to the function of the valve 25. Figure 3 shows the relief valve inlet pressure and hydraulic motor inlet pressure. The pressure drop at the valve is 1 MPa. And there is also a linear loss in the pipeline and pressure drop at the filter. Therefore, in the Fig.3, the inlet pressure of the hydraulic motor varies with the pressure of the relief valve. They are approximately coincident.

So, the relief valve controls the inlet pressure of the hydraulic motor. The double output shaft of the electrical motor is connected with the hydraulic pump and the hydraulic motor. The hydraulic motor drives the pump together with the motor, so the three have a certain matching relationship in torque. Figure 4 shows the torque relationship when the pressure of the relief valve is 15MPa. From Fig.4, the hydraulic motor and the motor jointly drive the pump to work. The torque of electrical motor and hydraulic motor is equal to the torque of hydraulic pump.

### 4. Experimental setup

#### 4.1 Mechanical design

Usually in the experiment, the hydraulic motor needs to be connected to an additional load. This introduces new noise sources and the energy consumption increases. This paper uses a double-shaft extension motor to connect with a hydraulic pump and a hydraulic motor. In Fig.5, the positions of the hydraulic pump and hydraulic motor are marked. The structure meets the load requirements of the noise test without introducing a new noise source.

The specification of the main equipment used in the hydraulic system are listed in table 1. The type of hydraulic motor selected in the experiment is L2FM80/61W-VAB020. Its displacement is 80cm$^3$/r, rated speed is 4000r/min and rated inlet pressure is 35MPa. This motor is a kind of hydraulic motor commonly used nowadays, so the noise test platform designed according to the parameters of the hydraulic motor is suitable for most motors. The suitable electrical motor and the hydraulic pump are selected through the parameters of the hydraulic motor. According to Eq. (4), the displacement of the hydraulic pump should be larger than that of the hydraulic motor. Different working conditions need
to be considered, so the parameters of the hydraulic pump need to be greater than the parameters of the hydraulic motor. This can ensure that the experiment can be carried out under different working conditions. In the experiment, the pressure in the hydraulic system will not exceed 40MPa, and the relief valve is used as the pilot chamber pressure control of the cartridge valve. The pressure sensor is selected because it is suitable for 0–40MPa measurement.

| Equipment                  | Type                      | Important parameter |
|----------------------------|---------------------------|---------------------|
| Hydraulic motor tested     | L2FM80/61W-VAB020         | 80cm³/r             |
| Electrical motor           | Y315L2-2                  | 200kw               |
| Hydraulic pump             | SY-160SCY14-1EL           | 160cm³/r            |
| Relief valve               | DBET-6X420G24K4           | 0–35MPa             |
| Frequency converter        | FRN200P11S-4CX            | 0.1–120Hz           |
| Torque meter               | JC2C                      | 0–1000N.m           |
| Pressure sensor            | NS-II                     | 0–40MPa             |

### 4.2 Laboratory layout

Figure 6 shows a view of the noise test laboratory. It is divided into two rooms. The electrical motor, the hydraulic pump, the monitoring platform and some hydraulic components are placed in one room, and the noise test platform is placed in the semi-anechoic room. Since the electrical motor is placed outside the semi-anechoic room, when the electrical motor is used as a load of electrical motor, no new noise source will appear in the semi-anechoic room under normal operating conditions.
Figure 7 shows the picture of the two rooms in Fig.6 and the mechanical structural part shown in Fig.5. Figure 7(a) shows the position of the hydraulic motor. The oil inlet is on the left of the hydraulic motor, the oil outlet is on the right, and both ends are equipped with pressure sensors.

Figure 7(b) shows another room, where there is an electrical motor, a hydraulic pump, control parts, a tank, etc. The operation is also carried out in this room. Semi-anechoic room is an important part of the test system, which can affect the accuracy of test data. Background noise of the semi-anechoic room is 13dB(A) and the cut-off frequency is 25~10000Hz. The semi-anechoic room is used to reduce interference.

4.3 Experimental method
Firstly, the background noise is tested. This noise level is measured when the hydraulic pump and motor are working normally at 1000rpm and the hydraulic motor is not working. Then the hydraulic motor is tested under specific working conditions. Different speeds and different system pressure will influence the noise level in tests. So in this experiment, the system pressure is maintained at 10MPa, and the electrical motor rotational speed is changed to achieve different working conditions. The noise level of the hydraulic motor is tested at 800rpm, 1000rpm and 1200rpm.

In the process of noise data acquisition, the 4189-A-021 microphone from Denmark B&K, the 4-channel data acquisition hardware of LAN-XI3050 and the post-processing software of LabShop are used. The arrangement of the microphone in the free sound field is based on hemispherical measurements. The center should be at the projection point of the sounding center of the hydraulic motor on the reflecting surface. In this experiment, the geometric center of the hydraulic motor is used as the center of the hemispherical measurement surface, and the microphone is arranged on the hemi-spherical surface with a radius of 1m. The position of the microphone is shown in Fig.8. The noise level can be tested in all directions by the method. In the experiment, the power of the electrical motor is obtained from the frequency converter, the power of the hydraulic pump is calculated by torque from the torque meter and the flow rate is from the flow meter.

5. Results and discussion
5.1 Background noise test
By using the hydraulic motor noise level test platform and the semi-anechoic room, the noise sound pressure level of the bent-axis type axial piston motor is tested under different working conditions (Zhang et al., 2017). The noise level spectrum under different working conditions (BAHR et al., 2002; Li et al., 2016; Xu et al., 2016) is analyzed to determine the noise source inside the hydraulic motor. To ensure that the experimental results are effective, it is necessary to test the background noise. The background noise and the noise generated by the hydraulic motor must meet specialized requirements (Ye et al., 2017). According to the following Eq. (11):

$$\bar{L}_{pA} = 10 \log \left[ \frac{1}{N} \sum_{i=1}^{N} 10^{0.1 L_{pA,i} - K_{1,i}} \right] - K_{3}$$

Where: $\bar{L}_{pA}$ is the A-weighted average sound pressure level, dB(A); $L_{pA,i}$ is the i-th point A-weighted sound pressure level, dB(A); $K_{1,i}$ is the correction value of the background noise level of the i-th point, dB; $K_{3}$ is the temperature and air pressure correction value, dB; $N$ is the number of points.

The measured values of each point are about 46dB(A). One point of the CPB diagram is shown in Fig.9.
This will compare with the noise level when the hydraulic motor is working. According to the standard, the sound pressure level data measured in the hydraulic motor noise experiment needs to be 12dB higher than the background noise. This is the data that can be directly used without correction.

### Table 2 Sound pressure levels of each point

| Rotating speed (rpm) | Pressure (MPa) | No. 10 (dB(A)) | No. 5 (dB(A)) | No. 7 (dB(A)) | No. 1 (dB(A)) |
|----------------------|----------------|----------------|---------------|---------------|---------------|
| 800                  | 10             | 68.6           | 64.3          | 68.6          | 66.7          |
| 1000                 | 10             | 69.9           | 68.5          | 71.1          | 69.8          |
| 1200                 | 10             | 72.5           | 71.2          | 75.3          | 72            |

5.2 Noise test under loading

A certain bent-axis type axial piston motor is tested under different conditions. The PULSE LabShop is used to collect and analyze the sound pressure level data of the hydraulic motor noise. The CPB analysis method is used to obtain...
the wide-band and narrow-band information of the noise sound pressure level. In the Fig.10, as the electrical motor rotational speed increases, the peak value of the noise sound pressure level tends to expand. Figure 10(a) shows different sound pressure level peaks of each measurement point. The sound pressure level peaks of point 1 and point 7 appear at 128Hz, and the sound pressure level peak of point 10 appears at 448Hz. The peak frequency is compared with the theoretically calculated frequency of the internal excitation source (Xu et al., 2010; Ye et al., 2019) of the bent-axis axial piston motor. According to the data, the noise of these three points is caused by the eccentricity and imbalance of the hydraulic motor rotating body. The peak of the sound pressure level at the point 5 appears near 832Hz. Similarly, the noise is generated by the distribution impact. For noise sound pressure level analysis at 1000rpm and 1200rpm, the noise source at different points can also be analyzed. Based on the analysis of noise sources, optimization can be performed to reduce noise.

Table 2 lists the numerical statistics summarized from Fig. 10. It shows the A-weighted average equivalent sound pressure level of each measuring point under different working conditions.

This experiment requires a certain stability of the hydraulic motor inlet pressure. So, the pressure sensor is placed at the inlet of the hydraulic motor to monitor the pressure in real time. In the experiment, the pressure of the relief valve is controlled to 5MPa, 10MPa, 15MPa, and the pressure at the inlet of the hydraulic motor is compared. The comparison results are shown in the Fig. 11.

From the Fig. 11, when the pressure of the relief valve is 15MPa, the pressure value at the inlet of the hydraulic motor fluctuates the most. The pressure at the inlet of the hydraulic motor always fluctuates within 2% of the relative error at 15MPa. At 10MPa and 5MPa, the fluctuation is relatively small. Therefore, the pressure of the relief valve controls the pressure at the inlet of the hydraulic motor and the pressure at the inlet of the hydraulic motor is relatively stable.

5.3 Verification of energy recovery

In the experiment, the displacement of the hydraulic pump is 160cm³/r and the displacement of the hydraulic motor
is 80cm³/r.

In Fig. (12), $N_p$ is the power of the hydraulic pump and $N_{em}$ is the power of the electrical motor. When the system pressure is at 10MPa, the power of the hydraulic pump and the electrical motor increases linearly with the electrical motor’s speed increasing, and the efficiency of energy recovery is almost the same. From the Fig. (12), it can be seen that the efficiency of the energy recovery will be lower than that of the theory, because it does not take into account the mechanical friction of the system in the theoretical calculation.

In Fig. (13), the rotational speed is at 1000rpm. Increased pressure can lead to larger pump leakage, so the efficiency of the energy recovery declines slightly when the pressure is higher.

According to Eq. (10), take $\eta_{mm}=0.92$ and $\eta_{pm}=0.92$, and the efficiency of the power recovery is 42.32%. From the theoretical analysis, it can be seen that the efficiency of the power recovery is related to the displacement of hydraulic motor, the larger the displacement of the hydraulic motor is, the greater the power recovery is.

6. Conclusions

In this paper, taking the hydraulic motor as the research background, it proposes a new noise test platform for the hydraulic motor, and its properties are tested. The main conclusions are as follows:

1. In the experiment, the measured hydraulic motor noise sound pressure level is 75.7dB(A), far exceeding the background noise. According to the regulations, the background noise level should be 12dB(A) lower than the sound pressure level when the noise source is operated. It proves that the noise test platform is valid, and the data measured can be accurate.

2. The system uses an electrical motor and only one hydraulic pump to drive the hydraulic motor and as the load of the hydraulic motor. The power of the hydraulic motor is recycled into the system and the efficiency of theoretical energy recovery is about 40%.

3. The specific noise source can be analyzed from the sound pressure level spectrum and some damage of the hydraulic motor can be found out. On this basis, structural optimization can be done to optimize the noise level of the hydraulic motor, which can improve the service life and promote the development of hydraulic components.

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