Internal Leakage Prediction of Hydraulic Spool valves Based on Acoustic Emission Technology

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Abstract. In order to realize the nondestructive testing (NDT) of the internal leakage fault of hydraulic spool valves, the internal leakage rate must be predicted by AE (acoustic emission) technology. An AE experimental platform of internal leakage of hydraulic spool valves is built to study the characteristics of AE signals of internal leakage and the relationship between AE signals and leakage rates. The research results show the AE signals present a wideband characteristic. The main frequencies are concentrated in 30~50 kHz and the peak frequency is around 40 kHz. When the leakage rate is large, there are significant signal characteristics appearing in the high frequency band of 75~100 kHz. The exponent of the root mean square(RMS) of AE signals is positively correlated with the exponent of the leakage rate only if the leakage rate is greater than 2~3 mL/min. This find could be used to predict the internal leakage rate of hydraulic spool valves.

1. Introduction
The hydraulic spool valve, with its numerous advantages, is widely applied in the hydraulic system. To ensure the good sealing and smooth action of the spool valve, the normal radial clearance between the valve core and the valve sleeve shall range from 3 to 8 μm [1-3]. With the radial clearance, it is inevitable for the internal leakage of the hydraulic spool valve. However, the leakage rate in the spool valve is very small under the normal clearance, and is usually smaller than 0.1% of the rated flow rate [4], which doesn’t affect the normal operation of the system. However, when there is any wear in the valve core and the valve sleeve, the leakage rate will be increased drastically due to overlarge radial clearance, which will affect the normal operation of the executing mechanism, resulting in excessive pressure loss and abnormal heating, and even cause the failure of the function of the spool valve in severe cases. Therefore, mastering the leakage in the spool valve will be of great significance to ensure the normal operation of the hydraulic system. However, the leakage fault is concealed, resulting in large diagnosis difficulty. With the traditional means, the valve shall be disassembled for pressurizing detection in the shutdown state in order not to affect the normal operation of the system, but the means requires a lot of labor and time; and in the case of numerous spool valves to be detected, such low-efficiency detection means will not be available.

Many studies indicate that with the AE testing technique, the real-time nondestructive testing of the internal leakage of valves can be achieved, without shutdown and the disassembly of valves. However, the study on the AE testing of the internal leakage of the valve focuses on valves in which gas is used as
the flowing medium, and especially ball valves, gate valves, and needle valves [5-7]; and there are a few studies on the AE testing of the internal leakage of the hydraulic spool valve in which hydraulic oil is used as the flowing medium. This article is intended to construct the AE experiment table for the internal leakage of the hydraulic spool valve, by which the internal leakage rate is predicted by analyzing the AE signals of the internal leakage of the spool valve, thereby providing basis for the nondestructive testing of the internal leakage fault of the hydraulic spool valve.

2. Internal leakage simulating experiment table for spool valve

The internal leakage simulating experiment table of the hydraulic spool valve, which is constructed, is shown in Figure 1. The experiment table is composed of two parts: A constant-pressure oil supply system and an internal leakage simulating device for the spool valve.

2.1 Constant-pressure oil supply system

The principle diagram of the constant-pressure oil supply system is shown in Figure 1. The system can provide 0 to 10 MPa of pressure oil for the internal leakage simulating device for the spool valve, and is connected with oil inlet/outlet of the leakage simulating device with the hydraulic hose (length ≥ 5m), which can avoid the interference of the vibration noise of the pump and valves on the collection of the AE signal of leakage. The accumulator arranged on the oil supply line can achieve two effects: One effect is to eliminate pressure pulsation generated during oil supply from the oil source so as to keep stable pressure; and the other effect is to achieve short-time oil supply for the leakage simulating device in extremely quiet environment as the auxiliary oil source upon the oil supply shutoff of the pump, thereby minimizing interference noise during AE testing. Since the internal leakage rate of the spool valve is small, it can be measured in the method of graduated cylinder + high-accuracy flow sensor, and switching between the volumetric cylinder and the high-accuracy flow sensor is achieved via the solenoid directional valve 19.

2.2 Internal leakage simulating device for spool valve

The internal leakage simulating device for the spool valve attains the function of simulating the actual condition of the internal leakage of the spool valve under each operating condition to make a study on the influence rule of each factor on the internal leakage rate of the spool valve. The internal structure of the device is shown in Figure 2. The variable parameters of the device include valve core diameter, clearance height, and sealing length; the valve core diameter and the clearance height can be changed by replacing a combination of the valve body 4 and the valve core 3; and the sealing length can be changed by adjusting the spiral micrometer head 1 on the leakage simulating device. The locking mechanism is arranged; and upon adjustment in the sealing length, the valve core can be fastened via...
the locking nut to prevent the position of the valve core from being changed under the action of hydraulic power.

Figure 2. Internal leakage simulating device for spool valve
1-Spiral micrometer head; 2-Check block; 3-Valve core; 4-Valve body; 5-Oil inlet; 6-Sleeve; 7-Return spring; 8. Locking nut; 9-Oil outlet

3. Theoretical basis

3.1 Calculation of leakage rate of spool valve

As hydraulic oil is large in viscosity of hydraulic oil, the leakage gap of the spool valve is micron-sized, and the viscous drag of the wall achieves the principal effect in the oil flowing process, the leakage of the spool valve is, generally, in the laminar flow state. Without the relative movement, the formula of the laminar flow in the concentric annular slot in terms of the internal leakage of the spool valve is [8, 9]:

\[ Q_0 = \frac{\pi dh^3}{12\mu} \Delta p \]  

(1)

Where, \( Q_0 \) is the leakage rate (L/min) of the concentric annular slot under the laminar flow, and \( d \) is valve core diameter (m); \( h \) is clearance height (m); \( \Delta p \) is differential pressure (Pa) between upstream and downstream; \( l \) is sealing length (m); \( \rho \) is oil density (kg/m\(^3\)); and \( \mu \) is dynamic viscosity (Pa·s) of oil.

The valve core of the spool valve is parallel to the valve sleeve. However, in the case of eccentricity, the calculation formula of the leakage rate is [8, 9]:

\[ Q_e = (1+1.5\varepsilon^2)Q_0, \quad 0 \leq \varepsilon \leq 1 \]  

(2)

Where, \( Q_e \) is the leakage rate (L/min) in the case of the eccentricity of the valve core, and \( \varepsilon \) is the eccentricity ratio of the valve core. The internal leakage rate in the case of parallel eccentricity is \((1-2.5)Q_0\). In addition to eccentricity, there is also an inclination case in the valve core, and the angle of inclination will affect the leakage rate of the spool valve. It can be known from the study of the pertinent literature that the leakage rate is \(0.5Q_0\) in the case of complete inclination [9], and thus, with the overall consideration of the influence on the eccentricity and inclination of the spool valve, the leakage rate under the laminar flow shall be:

\[ Q = (0.5-2.5)Q_0 \]  

(3)

3.2 Relationship between leakage rate and AE signal

The study of the pertinent literature [5-7] indicates the index of the acoustical power of the AE signal of leakage is in positive proportion with the index of the leakage rate, and acoustical power is \( P_a \propto AE_{\text{rms}}^2 \). Therefore, the index of the RMS of the AE signal is also in positive proportion with the index of the internal leakage.

\[ \log Q = k_{\text{RMS}} \log AE_{\text{rms}} + k_e \]  

(4)
Where, $Q$ is the leakage rate (L/min); $AE_{\text{RMS}}$ is RMS (mV) of the leakage AE signal; $k_{\text{RMS}}$ and $k_c$ are coefficients.

4. Analysis on test results

In the test, three valve core diameters are 10 mm, 16 mm, and 20 mm, the AE signal of leakage and the internal leakage rate are collected under normal clearance (5 μm) and excessive clearance (40 μm). In the test, variable parameters include sealing length (0.25 mm, 0.5 mm, 1.0 mm, 1.5 mm and 2.0 mm), and differential pressure (2 MPa, 4 MPa, 6 MPa, 8 MPa and 10 MPa). In the test, 46# antiwar hydraulic oil is used, oil density is 850 kg/m$^3$, and kinematic viscosity is $4.5 \times 10^{-5}$ m$^2$/s. To reduce the influence of oil temperature on the test, the test shall be started after the system is started up until it reaches the thermal equilibrium state.

4.1 Frequency spectrum analysis on AE signal of leakage

When the sealing length measured under normal clearance (5 μm) and excessive clearance (40 μm) in the test is 0.25 mm, the frequency spectrum of the AE signal of leakage of each valve under differential pressure of 2 to 10 MPa is shown in Figure 3 and 4.

It can be known from Figures 3 and 4 that in the case of large internal leakage rate, the AE signal of leakage shows the broadband characteristic, which also proves that the AE signal of leakage is caused by turbulent jet flow at the outlet of the spool valve slot. Sealing length and differential pressure hardly affect the frequency spectrum component of the AE signal of leakage, but affect the amplitude of each frequency; and with increase in differential pressure, and reduction in sealing length, the amplitude shows an increase trend. Change in clearance height is significant to the influence on the frequency spectrum, i.e., exerting influence on the frequency spectrum component and the amplitude; and with increase in clearance height and frequency spectrum component, the amplitude is increased significantly.

Regardless of normal clearance or excessive clearance, the primary frequency component of the AE signal of leakage is concentrated within the range of 30 to 50 kHz, with the peak frequency of approx. 40 kHz. Compared with the AE signal of leakage under the normal clearance, the AE signal under the excessive clearance shows the significant signal characteristic at the high-frequency section of 75 to 100 kHz.

![Figure 3. Spectrogram of AE signal (clearance 5 μm, sealing length 0.25 mm)](image-url)
4.2 Prediction of leakage rate

It can be known from the formula (4) that the index of the leakage rate is in direct proportion with the index of the RMS of the AE signal, and correlation coefficients between $\log Q$ and $\log AE_{RMS}$ are calculated by data measured from the test, which are shown in Table 1.

| Clearance height of 5 μm | Clearance height of 40 μm |
|-------------------------|--------------------------|
|                         | 10 mm  | 16 mm  | 20 mm  | 10 mm  | 16 mm  | 20 mm  |
| 0.25 mm                 | 0.79   | 0.83   | -0.18  | -      | -      | -      |
| 0.5 mm                  | 0.99   | -0.02  | 0.97   | 0.88   | 0.97   | 0.96   |
| 1.0 mm                  | -0.39  | -0.91  | 0.99   | 0.97   | 0.98   | 0.88   |
| 1.5 mm                  | -0.19  | -0.74  | 0.94   | 0.98   | 0.99   | 0.91   |
| 2.0 mm                  | -0.75  | -0.89  | -0.76  | 0.76   | 0.93   | 0.89   |

It can be known from Table 1 that in the case of small internal leakage, the indexes of the internal leakage rate of the spool valve and the RMS of the AE signal of leakage are poor in correlation, and even, are negatively correlated with each other; and in the case of large leakage rate, the correlation between both is good, and in most cases, the correlation coefficient is larger than 0.9. Therefore, in the case of large leakage rate, it is feasible to predict the internal leakage rate via the RMS of the AE signal. The fitting parameters are obtained by performing fitting on the formula (4) with leakage rate measured in the test and AE data, which are shown in Tables 2 and 3. The actually measured leakage rate and fit internal leakage rate under each pressure in terms of each valve core diameter are shown in Figure 5.
It can be known from Figures 5 and 6 that with rise in pressure, reduction in sealing length, and increase in valve core diameter and clearance height, the internal leakage rate of the spool valve exhibits a rising trend, and the leakage rate is the most sensitive to increase in clearance height; and the internal leakage rates of normal clearance and excessive clearance differ by approx. 3 orders of magnitude. The above-mentioned rule is consistent with the formula (1).

| Table 2. Fitting parameters of normal clearance |
|-----------------------------------------------|
| 10 mm | 16 mm | 20 mm |
| \(k_{RMS}\) | \(k\) | \(k_{RMS}\) | \(k\) | \(k_{RMS}\) | \(k\) |
| 0.25 mm | 0.69 | -0.62 | 0.89 | 0.22 | -0.04 | -1.74 |
| 0.5 mm | 4.67 | 10.57 | -0.1 | -2.92 | 1.01 | 0.51 |
| 1.0 mm | -8.72 | -29.34 | -16 | -51.51 | 1.33 | 1.29 |
| 1.5 mm | -5.29 | -19.55 | -9.23 | -31.44 | 2.37 | 4.51 |
| 2.0 mm | -2.85 | -12.17 | -13.45 | -42.54 | -2.97 | -11.71 |

| Table 3. Fitting parameters of excessive clearance |
|-----------------------------------------------|
| 10 mm | 16 mm | 20 mm |
| \(k_{RMS}\) | \(k\) | \(k_{RMS}\) | \(k\) | \(k_{RMS}\) | \(k\) |
| 0.5 mm | 0.09 | 0.73 | 0.77 | 2.09 | 0.27 | 1.24 |
| 1.0 mm | 0.34 | 1.12 | 0.6 | 1.71 | 0.52 | 1.92 |
| 1.5 mm | 0.94 | 2.38 | 0.63 | 1.78 | 1.01 | 3.16 |
| 2.0 mm | 0.28 | 0.73 | 0.58 | 1.71 | 1.22 | 3.69 |

It can be known from Tables 2 and 3 that in the case of excessive clearance (40 μm), the fitting parameters \(k_{RMS}\) of the diameters of three valve cores under the sealing length ranging from 0.5 to 2.0 mm are larger than zero, indicating that the internal leakage rate of the spool valve is positively correlated with the RMS of the AE signal of leakage. In the case of the normal clearance (5 μm) of the spool valve, the fitting parameters are \(k_{RMS} > 0\) under the sealing length ranging from 0.25 to 0.5 mm in terms of the valve core diameter of 10 mm; the fitting parameter is \(k_{RMS} > 0\) under the sealing length of 0.25 mm in terms of the valve core diameter of 16 mm; the fitting parameters are \(k_{RMS} > 0\) under the sealing length ranging from 0.5 to 1.5 mm in terms of the valve core diameter of 20 mm; and the leakage rate curve under the sealing length of 0.25 mm exhibits a declining trend after 4 MPa, resulting in the fitting parameter of \(k_{RMS} < 0\), but the value is very small. In conjunction with the formula (3), it is speculated that with rise in pressure, the stress of the valve core is changed, while its eccentricity and inclination degree are also changed, which causes reduction in the leakage rate, resulting in \(k_{RMS} < 0\).
The fitting parameters are \( k_{\text{RMS}} < 0 \) under the sealing length ranging from 1.0 to 2.0 mm in terms of the valve core diameter of 10 mm; the fitting parameters are \( k_{\text{RMS}} < 0 \) under the sealing length ranging from 0.5 mm to 2.0 mm in terms of the valve core diameter of 16 mm; and the fitting parameter is \( k_{\text{RMS}} < 0 \) under the sealing length of 2.0 mm in terms of the valve core diameter of 20 mm. In the above-mentioned operating conditions, \( k_{\text{RMS}} < 0 \) indicates that the RMS of the AE signal isn’t positively correlated with the internal leakage rate, which means that the AE signal can’t effectively predict the internal leakage rate of the spool valve. The leakage rates in such operating conditions are small, and the maximum leakage rate is approx. 2 to 3 mL/min. In view of the above, the minimum internal leakage of the spool valve, which is detected via the RMS of the AE signal, is approx. 2 to 3 mL/min.

5. Conclusions
In the experimental study on the internal leakage of spool valves with three valve core diameters under the normal clearance and excessive clearance through the constructed internal leakage simulating experiment table, the following conclusions can be drawn:

- The AE signal of leakage is caused by turbulent jet flow at the outlet of the spool valve slot, which shows the broadband characteristic.
- The primary frequency component of the AE signal of leakage is concentrated within the range of 30 to 50 kHz, with the peak frequency of approx. 40 kHz.
- Compared with the AE signal of leakage under the normal clearance, the AE signal under the excessive clearance shows the significant signal characteristic at the high-frequency section of 75 to 100 kHz.
- The minimum internal leakage of the spool valve can be detected via the RMS of the AE signal, which is approx. 2 to 3 mL/min.

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