THE BASIC RESEARCH ON K-TYPE FLUID FILTER^①

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ABSTRACT

In this paper a K — type fluid filter is theoretically studied. the impedance matching theorem and this filter model of hydraulic system are put forward. A lot of experimental work is done for finding out the optimal value of filter parameters. For a well designed filter, 85% pressure fluctuation after filter and its 60% before filter can be filtrated.

KEY WORDS

K — type fluid filter, Impedance matching

INTRODUCTION

The fluctuation of flow and pressure of pump is unavoidable, it causes vibration and noise of a hydraulic system. Nowadays, development of the hydraulic system is towards the high pressure, high speed and large horsepower, the vibration and noise of systems have become major problems which encompers its development. Using fluid filter is one of the most effective approaches. The K — type fluid filter (see Fig. 1) has a very simple structure, it can

be installed in system conveniently, but its research is very little, influences of the filter parameter on filterability are not clear.

THEORETICAL ANALYSIS

The model of K — type fluid filter

A K — type fluid filter is divided as Fig. 1.

When fluid flows from I — I to II — II, this process is not only a pressure loss process, but also an energy converting one and this part can not be

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Fig. 1 Sketch map of the division of K-type fluid filter.
replaced by a single impedance element. So a two

ports passive network A which stands for the transferring characteristics of this part is introduced. The whole model of the filter is shown as Fig. 2, from II — II to V — V, it may be approximately replaced by an electric equivalent circuit.

Fig. 2 Model of the K-type fluid filter
The relationship between k-type fluid filter and its equivalent circuit is listed in Table 1.

Table 1 The relationship between K-type fluid filter and its equivalent circuit

Equivalent circuit	K-type fluid filter
two ports passive network A	transferring characteristics of I — I to II — II
capacity C	the capacity produced by the whole cavity of the filter
resistance R_1	pressure loss as fluid flows from III — III to V — V
inductance L	the inductance caused by the long and thin inserted pipe
impedance Z	the impedance of the load

Theoretical analysis

Transfer function

(1) Transfer function of two ports passive network A

The transferring characteristics of two ports passive network A can be expressed by a four parameters matrix

$$A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \quad (1)$$

according to fluid mechanics, Equation (2) and (3) can be gotten

$$P_1(t) = P_2(t) - PQ^2 \frac{16(D^2 - d_1^2)}{\pi^2 D^4 d_1^2} \quad (2)$$

$$\begin{bmatrix} P_1(S) \\ Q_1(S) \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} P_2(S) \\ Q_2(S) \end{bmatrix} \quad (3)$$

Laplace transforming Eq. (2) and combining with the Eq. (3), then yields:

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} = \begin{bmatrix} 1 - PQ^2 \frac{16(D^2 - d_1^2)}{\pi^2 D^4 d_1^2} \frac{1}{S} & \\ 0 & 1 \end{bmatrix} \quad (4)$$

(2) Transfer function of two ports passive network B

① Calculation of R_1, L, C

The pressure loss as fluid flow from section III — III to section IV — IV can be expressed by resistance R_0 and it can be gotten from Bernoulian Equation, so

$$R_0 = \frac{\Delta P}{Q} = \frac{[P_3(t) - P_4(t)]}{Q} = PQ \frac{[11.76/d^4 - 8/D^4]}{\pi^2} \quad (5)$$

here R_0, R_2 represent the flow resistances of flow path from III — III to IV — IV and inserted pipe respectively, $R_1 = R_2 + R_0$. Capacity of the whole filter is

$$C = \frac{V}{\rho c^2} = \frac{\pi D^2 L_f}{4 \rho c^2} \quad (6)$$

Where:

c —Sound velocity in liquid, ρ —density of liquid, L_f —the length of the filter using the circuit imitation of hydraulic—electric method, the inductance of the filter is given as

$$L = \frac{\rho l}{a} \quad (7)$$

② Four parameters of transfer matrix B can be obtained from the equivalent electric circuit R_1-L-C

$$\begin{bmatrix} P_5(S) \\ Q_5(S) \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} \begin{bmatrix} P_2(S) \\ Q_2(S) \end{bmatrix} \quad (8)$$

then matrix B can be obtained as follows:

$$\begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} = \begin{bmatrix} 1 + SR_1 + S^2 LC & R_1 + SL \\ SC & 1 \end{bmatrix} \quad (9)$$

Energy transfer coefficient α

In this paper, energy transfer coefficient α is defined as the ratio of the hydraulic energy at the input of the filter to output of it. According to Eq. (3) and Eq. (4) α_a of two ports passive network A is

$$\alpha_a = \frac{|P_2 Q_2|}{|P_1 Q_1|} = 1 / \left[1 - \frac{1 - 16p Q_2 (D^2 - d_1^2)}{Z \pi^2 D^4 d_1^2 S} \right] \quad (10)$$

In general condition, the value of α_a is between 1.0005~1.001, so it may be neglected.

Fig. 3 Bode diagram of filter

According to Eq. (8) and Eq. (9), α_b of two ports passive network B is

$$\alpha_b = \frac{|P_5 Q_5|}{|P_2 Q_2|} =$$

$$\frac{1}{(1 + (R_1 + SL)/Z)(SCZ + 1 + SR_1 C + S^2 LC)} \quad (11)$$

Energy transfer coefficient α of whole filter is

$$\alpha = \frac{|P_5 Q_5|}{|P_1 Q_1|} \approx \alpha_b \quad (12)$$

The model of the K-type fluid filter

As analysed above, the model of the K-type fluid filter can be simplified and imitated by a R_1-L-C electric network as the right part of Fig. 2, so the K-type fluid filter is a low-pass filter.

Bandwidth of the frequency of filter ω_b and its coefficient k

Fig. 4 Relationship between ω_b and

structure parameters of the filter

According to Eq. (11), the Bode diagram of filter and its bandwidth ω_b of the frequency may be represented in Fig. 3. The bandwidth ω_b ($\alpha=0.707$) is an important index of filter performance for evaluating its filterability, theoretically, the less the ω_b is, the bigger frequency band range of pressure fluctuation may be filtered, but from this Fig. it is also obvious that for certain pressure fluctuation, there must have an optimal filter impedance by which the main frequency band range (200~1000 rad/s in Fig. 13) of this flow fluctuation may be attenuated best. Let $\alpha=0.707$, from Eq. (11) by simulation

on computer, the formula of ω_b can be derived. Fig. 4 illustrates the simulation results of Eq. (11) for $\omega_b(d, l, V)$, analysing these curves, we know that $\omega_b \propto d/\sqrt{Vl}$, so the formula of ω_b may be written as follows:

$$\omega_b = \frac{kcd}{\sqrt{Vl}} \quad (13)$$

where the k is a coefficient and can be obtained by simulating of filter. Let $|a| = 0.707$ and substituting Eq. (13) into Eq. (11), by simulating results, it can be seen that the coefficient k in Eq. (13) is kept constant with value of 0.31, it does not change with changing the value of filter parameters.

System impedance

Fig. 5 Relationship between Z_0 , Z_1 and inputting frequency ω

The impedance of hydraulic pump is regard as the internal impedance, and the impedance outside the pump is considered to be system impedance. Supposing the impedance of none filter installed system is Z_0 and the impedance of system with filter is Z_1 , then

$$Z_1 = \frac{(R_1 + Z_0) + j\omega[L - \omega^2 L^2 C - C(R_1 + Z_0)^2]}{(1 - \omega^2 LC^2) + \omega^2 C^2(R_1 + Z_0)^2} \quad (14)$$

its module is

$$|Z_1| =$$

$$\frac{\sqrt{(R_1 + Z_0)^2 + [\omega L - \omega^3 L^2 C - \omega C(R_1 + Z_0)^2]^2}}{(1 - \omega^2 LC^2)^2 + \omega^2 C^2(R_1 + Z_0)^2} \quad (15)$$

The frequency response of $|Z_1|$ to ω is shown in Fig. 5.

EXPERIMENTAL RESEARCH

Experimental equipment

Fig. 6 Experimental system

The system for experimental research is shown in Fig. 6. The pressure fluctuation of hydraulic system is measured by a pressure transducer, hose between pump and it should be avoided. In the measuring process the relief valve acts as safe valve, throttle valve 1 is used to adjust the flow rate crossing the filter and 2 is used to change the pressure of the system.

As the predominant frequencies pressure fluctuation is under 800Hz in hydraulic system, so the frequency of oscillator of SC-16 oscilloscope is chosen to be 1200Hz. The tape recorder is utilized to get the frequency spectrum of pressure fluctuation.

Experimental results

(1) Pressure fluctuation of system with no filter:

The records of pressure fluctuation ΔP caused by different pump pressure P , are shown as Fig. 7, the $\Delta P - P$, curve is given as Fig. 8.

Fig. 7 Waves of pressure fluctuation

Fig. 8 ΔP — P curve

(2) The relationship between the pressure fluctuation ΔP of the filter—installed system and the filter parameters.

The experimental results are demonstrated in Fig. 9 to Fig. 13, the test conditions:

□ — $D=6.0\text{mm}$ ○ — $d=8.0$
 ● — $d=7.0$ △ — $d=9.0$
 $V_0=1.61$ $l=110\text{mm}$

Fig. 9 Relationship between pressure fluctuation and volume of the filter

Oil temperature $T=40^\circ\text{C} \pm 2$, $P_2=5.0\text{MPa}$, $Q=$

80L/min, ΔP with no filter is 1.8MPa. Solid lines denote the ΔP at the inlet and dashed lines denote ΔP at the outlet of filter

① The relationships between the ΔP and the volume of the filter V are demonstrated in Fig. 9, it shows that ΔP decrease with increasing V .

② The relationships between the ΔP and the inside diameter of inserted pipe d are demonstrated in Fig. 10

Fig. 10 Relationship between pressure fluctuation and the inside diameter of the inserted pipe

③ The relationships between ΔP and the length of inserted pipe l are demonstrated in Fig. 11.

From above Fig. 9 and Fig. 10 it can be observed that corresponding to every l there is the best matching value of d by which ΔP is maximum reduced, moreover the l is shorter the corresponding d is smaller, obviously, it is in accordance with the impedance matching theorem.

④ The relationship between ΔP and the flow rate crossing the filter Q is demonstrated in Fig. 12. The experimental results show that with increasing Q , ΔP increase slightly.

(3) Frequency spectrum of pressure fluctuation is shown in Fig. 13, the main frequency band range is $\omega=200\sim 1000\text{rad/s}$ which must be considered while designing filter, besides, from this Fig., obviously, the pressure fluctuation ΔP has been highly filtered.

Fig. 11 Relationship between pressure fluctuation and length of the long and thin inserted pipe

Fig. 12 Relationship between pressure fluctuation and flow rate crossing the filter

CONCLUSIONS

1. The filtrating performance of K-type fluid filter is determined by the impedance caused by K-type fluid filter. The model of this filter in principle is a R-L-C network, besides, it is a low-pass filter.
2. The bandwidth of the frequency of the filter α_b is an important index of filter performance, approximately $\alpha_b = 0.31 \text{ cd}/\sqrt{Vl}$.
3. Theoretical and experimental studies show that for a certain hydraulic system and pressure fluctuation there is a corresponding matching impedance of filter by which pressure fluctuation of pump may be attenuated best. By a well designed filter, not only after filter (85% out), but also before filter (60% out), system ΔP can be significantly decreased.
4. According to theoretical and experimental studies, for certain ΔP there is a set of optimal value of inserted pipe diameter d and length l , but ΔP decrease with increasing filter volume V and decreasing flow rate crossing filter Q monotonously.

Fig. 13 Frequency spectrum of pressure fluctuation

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