A Novel Flow Sensor in Hydraulic System

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Abstract This paper presents a built-in flow sensor for hydraulic system use. Unlike traditional counter parts, a MEMS (MicroElectroMechanical Systems) differential pressure-sensing element and a low cost throttle are integrated together in this sensor. It is of better spatial resolution and cause fewer losses than the widely used orifice flow meter. By theoretical analysis and experimental tests we have achieved an optimized design strategy.

Keywords: flow sensor; hydraulic system; MEMS

1. Introduction

Fault diagnosis and condition monitoring of hydraulic system are more difficult than those of mechanical or electric devices because hydraulic devices work in a closed system where the oil flow and elements movement are both invisible and untouchable. While oil pressure, flow quantity and flow direction realize the expected actions of hydraulic system, it is possible to find and handle the problems by them. Statistically, there are five dominant types of faults: low pressure, inadequate oil supply, too high temperature, leakage, vibration and noise [1]. So pressure, flow rate and temperature are the key parameters for monitoring. But in common hydraulic systems, take marine hydraulic system for example, there are few sensors inside, only several relatively unwieldy pressure and one or two temperature gauges are located, without any flow devices there. Besides high expenses, traditional flow meters such as orifice meters will bring substantial energy losses in pipe. Because of size of the sensing parts, pressure induce pipes connected by flanges are essential, which makes flow instrument large and heavy.

With the development of modern manufacturing technologies, various MEMS sensors are more and more commercially available, widely used in many fields, such as automobile, medical instruments and so on [2]. They have the features of small size, high performance, low power consumption and cheapness in large quantity. These advantages make it possible to replace common sensors in the near future, also in the field of flow measurement. Here we develop a built-in flow sensor for hydraulic system. This sensor consists of a nozzle and a MEMS sensor. They are fixed in a pipe. The nozzle inside has double effect on the fluid: contraction and expansion. It is easy to get low-loss pressure difference, which is measured by the MEMS sensor. Working principles and experimental results are shown.

2. Principles

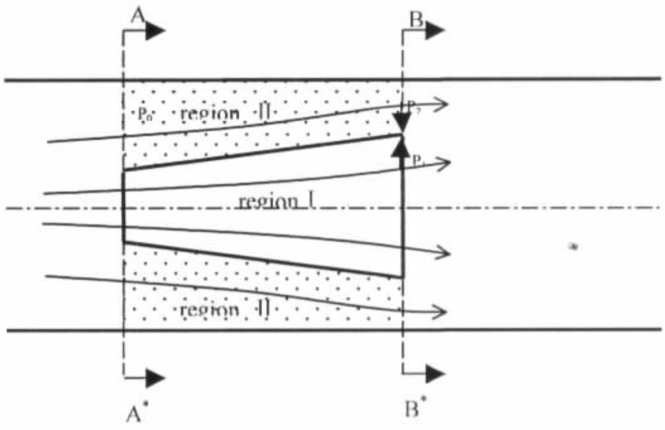

Fig.1a flow distribution in longitudinal cross section

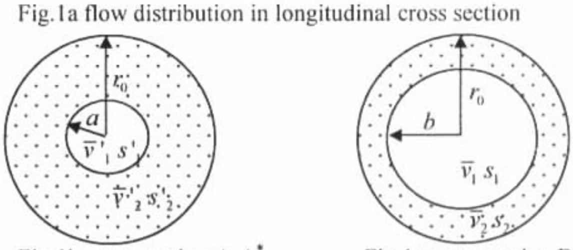

Fig.1b cross section A-A* Fig.1c cross section B-B*

Fig.1 flow field in pipe

As is shown in Fig.1a , oil flow in the pipe is separated into two parts: region Ⅰ and region Ⅱ.In region Ⅰ the oil is expanded so the oil pressure increases from A-A* to B-B*. On the contrary, by compression of the flow tunnel oil pressure decreases in region Ⅱ. Then pressure difference related to flow velocity is generated at cross section B-B*.

In order to simplify the analysis, oil in pipe is assumed to be laminar flow. Unlike in common fluid transmission system, hydraulic oil is used to drive actuators. So flow rate inside the pipe is much lower and laminar flow is easy to occur [3]. For turbulent flow tremendous experiments should be carried out to amend coefficients.

Based on Bernoulli equation,

$$\frac{\rho v^2}{2} + p_0 + \gamma z = C$$

for height variation of flow is so small comparing to other items that γz can be took as constant, then we get

$$\frac{\rho \bar{v}'^2_1}{2} + p_0 = \frac{\rho \bar{v}_1^2}{2} + p_1 1 \tag{1}$$

$$\frac{\rho \bar{v}'^2_2}{2} + p_0 = \frac{\rho \bar{v}_2^2}{2} + p_2 \tag{2}$$

Where p_0 is pressure at cross section A-A*, p_1, p_2 are pressures inside and outside the nozzle at B-B*, $\bar{v}_1$, $\bar{v}'_1$, $\bar{v}_2$ and $\bar{v}'_2$ represent mean velocity at area s_1 , s'_1 , s_2 , s'_2 respectively (see Fig.1b, Fig .1c).

(1)-(2),

$$\Delta p = p_2 - p_1 = \frac{\rho}{2}\left[\left(\bar{v}_2^2 - \bar{v}'^2_2\right) - \left(\bar{v}_1^2 - \bar{v}'^2_1\right)\right] \tag{3}$$

From continuity equation, we can get

$$\bar{v}'^2_1 s'_1 = \bar{v}_1^2 s_1$$

While

$$\bar{v}'_1 = \frac{2Q}{\pi r_0^2}\left(1 - \frac{a^2}{2r_0^2}\right) ,$$

and

$$\bar{v}_1 = \frac{2Q}{\pi r_0^2}\left(1 - \frac{a^2}{2r_0^2}\right)\frac{a^2}{b^2} ,$$

then

$$\bar{v}_1^2 - \bar{v}'^2_1 = \frac{Q^2}{\pi^2 r_0^4}\left(1 - \frac{a^2}{2r_0^2}\right)\left(\frac{a^4}{b^4} - 1\right) \tag{4}$$

Here r_0, present radius of the pipe, a , b radius of the nozzle at A-A* and B-B*, respectively. Q is flow rate of the pipe.

Similarly,

$$\bar{v}_2^2 - \bar{v}'^2_2 = \frac{Q^2}{\pi^2 r_0^8}(r_0^2 - a^2)^2\left[\left(\frac{r_0^2 - a^2}{r_0^2 - b^2}\right)^2 - 1\right] \tag{5}$$

Take (4), (5) to (3),

$$\begin{aligned}\Delta p &= p_2 - p_1 \\ &= \frac{\rho}{2}\frac{Q^2}{\pi^2 r_0^8}\left\{(2r_0^2 - a^2)^2\left[\left(\frac{a}{b}\right)^4 - 1\right] - (r_0^2 - a^2)^2\left[\left(\frac{r_0^2 - a^2}{r_0^2 - b^2}\right)^2 - 1\right]\right\} \quad (6 \\ &= \frac{\rho}{2}\frac{Q^2}{\pi^2 r_0^4}\left\{\left(2 - \frac{a^2}{r_0^2}\right)^2\left[1 - \left(\frac{a}{b}\right)^4\right] + \frac{\left(1 - \frac{a^2}{r_0^2}\right)\left(1 - \frac{b^2}{r_0^2}\right) - \left(1 - \frac{a^2}{r_0^2}\right)^4}{\left(1 - \frac{b^2}{r_0^2}\right)^2}\right\} \\ &= \frac{\rho}{2}\frac{Q^2}{\pi^2 r_0^4}(\alpha + \beta),\end{aligned}$$

$$\alpha = \left(2 - \frac{a^2}{r_0^2}\right)^2\left[1 - \left(\frac{a}{b}\right)^4\right] \quad \beta = \frac{\left(1 - \frac{a^2}{r_0^2}\right)\left(1 - \frac{b^2}{r_0^2}\right) - \left(1 - \frac{a^2}{r_0^2}\right)^4}{\left(1 - \frac{b^2}{r_0^2}\right)^2}$$

Eq. (6) specifies that for a certain radius pipe when density of oil is constant, relationship between the measured differential pressure and flow quantity rests with parameters a and b , in other words, the geometrical shape of the nozzle. For Eq. (7) item α indicates the expansion effect caused by region Ⅰ, while β means the contraction effect caused by region II. This equation can be used to calculate the flow rate by the measured pressure difference.

In order to balance the double action and reduce energy losses, by numerical simulation we acquire an optimized design strategy of the nozzle:

$$a = 0.4r_0,\ b = 0.8r_0,\ \alpha = 3.1740,\ \beta = 3.1360,$$

$$\alpha / \beta = 1.0121$$

3. Experimental

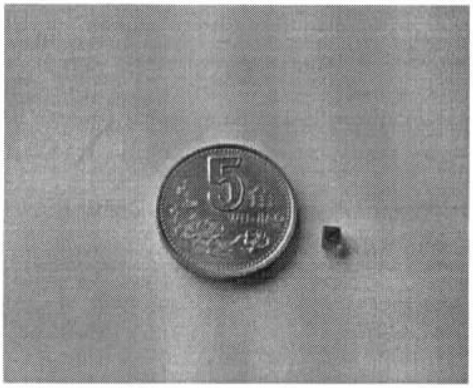

Fig.2 A MEMS sensor used in experiment (unsealed)

In the experiments we select a piezoresistive MEMS pressure sensor (Fig.2), which consists of a flexible diaphragm with diffused piezoresistors, connected to a Wheatstone bridge. The diaphragm is deflected by pressure difference, resulting in a mechanical stress on it. This stress changes the resistance of the piezoresistors. The bridge is unbalanced and output a voltage signal according to the pressure intensity.

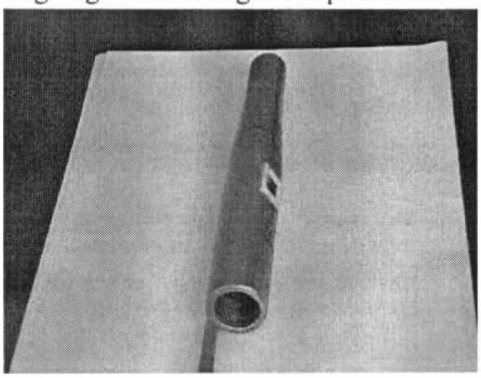

Fig.3 The nozzle used in experiment

Resistance fluctuation due to temperature changes is eliminated automatically because of the bridge. We fix this sensor on the nozzle (Fig.3) in the pipe. A hydraulic power station provides the 20# hydraulic oil flow from 0 to 50L/min at the pressure of 5Mpa. Output signals are got by WAVEBOO512 data acquisition system. Fig.4 shows the voltage signal versus different flow rates in the experiment. It is of good linearity and repeatability. The signal value is smaller than expected because the installation of the nozzle is not ideal. Influence of the incline should not be neglected.

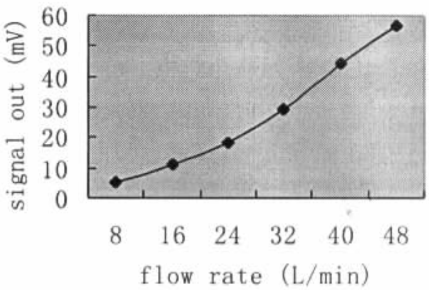

Fig.4 Testing results

4. Conclusion

This paper provides a novel flow sensor in hydraulic system with a MEMS sensor inside. It is cheaper and more energy efficient than common orifice flow meter. Without induce pipes, it responses faster and is much smaller. These advantages can make this sensor competitive in the future. The authors have done some primary works, while there is much space on it. Some are as following:

Sealing should be enhanced on the next step. In this experiment, only low-pressured oil is applied because of sealing problems of wire. Some wireless method can be hopeful [4].

More efforts need to be carried out on abundant experiments to know stability and reliability of this sensor, especially for turbulent flow.

Acknowledgment

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