A novel test rig development for experimental study of fluid mechanics of hydraulic orifice and/or gaps under high or low temperature conditions

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Abstract. To meet the demand of ever operating in extreme environments of modern high-end vehicles or machineries, it is meaningful to perform basic research on fluid mechanics of hydraulic orifices and/or gaps under high or low temperature conditions. In this study, a novel compact experimental module which integrates the oil, the oil supply mechanism, the testing damping valve with orifices and/or gaps and several sensors was proposed, the experimental module has avoided the bulky method of using a full hydraulic system for oil supply and can be wholly placed into a high/low temperature chamber to undertake experiments; Based on the integrated experimental module, a test rig employing a variable-frequency-motor-driven ball screw driver to excite the testing module was developed. By using the virtual instrument technology, the hardware and software of automatic measurement and control system was further developed, so the automatic control and data collection of the test rig was realized. Final results show that the test rig can conveniently perform fluid mechanics experiments for various hydraulic orifices and/or gaps under high or low temperature conditions with high efficiency, so the test rig can be a very good platform for pertinent basic research works.

1. Introduction

Modern high-end vehicles or machineries using fluid power technologies are more and more required to operate in extreme environments [1, 2], thus, it is significant to perform basic research on fluid mechanics of hydraulic orifices and/or gaps under high or low temperature conditions.

Previous works concerning fluid mechanics of hydraulic orifices were almost conducted under ambient temperature conditions. Ramamurthi et al. [3] studied the flow characteristics of sharp-edged orifices when using demineralized water as the fluids, Huang et al. [4] conducted research on the nature of discharge coefficients of perforated orifices as a new kind of flowmeter, Yu et al. [5] and Tharakan et al. [6] both investigated the effects of back pressure on orifice discharge coefficients. In addition, the existing experimental equipment testing the fluid mechanics of orifices almost use the same mechanism, which employs a full and bulky hydraulic system [7] including the pump, valves and even an accumulator to supply pressure oil to the orifices, and the experiments are also conducted under room temperature conditions.
Thus, in order to do experiments on hydraulic orifices under high or low temperature conditions and avoid the bulky method of using a full hydraulic oil-supply system, a novel compact experimental module which integrates the oil, the oil supply mechanism, the test valve with orifice, several sensors was proposed [8], the experimental module can be wholly placed into a high/low temperature chamber to undertake experiments; Based on the integrated experimental module, a test rig which uses a variable-frequency-motor-driven ball screw driver to excite the testing module was developed. By using the virtual instrument technology, the hardware and software of automatic measurement and control system was further developed, so the automatic control and data collection of the test rig was realized. Final results show that the test rig can conveniently perform fluid mechanics experiments for various hydraulic orifices and/or gaps under high or low temperature conditions with high efficiency, so the test rig can be a very good platform for pertinent basic research works.

2. A novel compact testing module
A novel compact experimental module, as shown in Figure 1, which borrows the idea of a railway hydraulic damper, was proposed [8]. The module integrates the oil, the oil supply mechanism, the testing damping valve with orifices and/or gaps and several sensors.

![Figure 1](image.png)

Figure 1. A novel compact module for testing the fluid mechanics of hydraulic orifices and/or gaps: (a) Cross-section of the module, (b) Damping valve with orifice flow, (c) Damping valve with parallel flat flow, (d) Damping valve with eccentric ring flow, (e) Damping valve with concentric ring flow, (f) Module samples.

In Figure 1(b), the orifice flow through the damping valve $Q_1$ can be formulated by

$$Q_1 = C_d \left( \frac{\pi}{4} d^2 \right) \sqrt{\frac{2}{\rho} \Delta p}$$  \hspace{1cm} (1)

where $C_d$ is discharge coefficient, $d$ is the orifice diameter, $\rho$ is the oil density and $\Delta p$ is the differential pressure of the orifice.

The parallel flat flow through the damping valve $Q_2$, as shown in Figure 1(c), can be formulated by
where $\mu$ is dynamic viscosity of the oil; $l$, $b$ and $h$ are length, width and height of the parallel flat, respectively.

Because the eccentric ring flow through the damping valve $Q_4$ as shown in Figure 1(d), can be formulated by

$$Q_4 = \frac{\pi d_1^3 h_0}{12 \mu l_1} \left(1 + 1.5 \varepsilon^2\right) \Delta p$$

where $d_1$ and $l_1$ are inner diameter and length of the ring, respectively; $h_0$ is the difference of the inner radius and outer radius of the ring when the ring is concentric; $\varepsilon$ is the eccentric rate of the ring, and given by $\varepsilon = e/h_0$, where $e$ is the eccentric value of the ring.

Thus, if make $\varepsilon=0$ in Equation (3), the concentric ring flow through the damping valve $Q_3$, as shown in Figure 1(e), can be obtained by Equation (3):

$$Q_3 = \frac{\pi d_1^3 h_0^3}{12 \mu l_1} \Delta p$$

For the experimental module is as the size as a damper, it can be readily placed into a high/low temperature chamber to undertake experiments.

3. Test rig development

3.1 The mechanical and drive system

Based on the proposed compact experimental module, the mechanical system has been designed, as shown by Figure 2(a). Basically, the mechanical system includes a stand, a cryostat, a testing module which is placed into the cryostat and a ball screw driver, the ball screw driver is connected with the testing module by a connector with a load sensor.

Figure 2(b) demonstrates the mechanism of the ball screw driver. The worm is driven by an electric motor which is controlled by a frequency changer, so the worm wheel will be driven by the worm, because the worm wheel is fixed with the nut, the nut will be simultaneously driven by the worm wheel, so the lead screw will be driven by the nut. For the lead screw is connected with the testing module, the module will be finally excited.
When controlling the motor by the frequency changer, different driving laws would be obtained, so the testing module would be excited with different velocities, the constant velocity and accelerated velocity are common driving laws adopted.

3.2 The automatic measurement system
An automatic measurement system is developed for automatic experiment control, data acquisition and data post processing, the developed hardware and software are partly shown in Figure 3. The hardware includes the industrial control computer, the data acquisition unit, the filter circuit, the main control circuit, the frequency changer for electric motor control and the control panel.

The software is developed using the LABVIEW platform, Figure 3(b) shows the page for parameter setting, in this page, the law of driving velocity, the temperature for experiment and data acquisition setting can all be set before any experiment.

3.3 System integration
By integrating the proposed testing module, the mechanical system and the automatic measurement system, a test rig for experimental study of fluid mechanics of hydraulic orifice and/or gaps under high or low temperature conditions is finally obtained, the apparatus is shown in Figure 4(a) and its main technical parameters and values are given by Table.1.

As an example, Figure 4(b) shows the tested flow characteristics of a sharped-edged hydraulic orifice under -50℃ temperature conditions, by using the developed test rig.
| Parameter                        | Value       | Parameter                        | Value       |
|---------------------------------|-------------|----------------------------------|-------------|
| Maximum displacement (m)        | 0.5         | Temperature range for testing (℃)| -50→+100    |
| Maximum height for fixing (m)   | 1.2         | Maximum temperature range (℃)    | -70→+120    |
| Maximum testing load (kN)       | 15          | Full extension of the module (m) | 0.32        |
| Maximum testing speed (m/s)     | 0.1         | Extension for experiment of the module (m) | 0.2 |

4. Conclusions
(1) The proposed novel experimental module compactly integrates the oil, the oil supply mechanism, the testing damping valve with orifices and/or gaps and sensors, so it has avoided the traditional bulky method of using a full hydraulic system for oil supply and can be wholly placed into a high/low temperature chamber to undertake experiments.

(2) By using the virtual instrument technology, the hardware and software of automatic measurement and control system was developed, so the automatic measurement system makes experiments be conducted with high efficiency.

(3) Because various orifices and gaps with different geometric parameters can be designed and conveniently in-bedded in the module, so the test rig developed is actually a versatile and powerful platform for fluid mechanics research.

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