An Innovative Spool-Type Pressure Feedback Restrictor for Hydrostatic Bearings

Jyh-Chyang Renn, Wen-Jen Hsu and Yun-Ruei Li

Department of Mechanical Engineering, National Yunlin University of Science and Technology, Douliou, Taiwan, ROC

ABSTRACT

This study presents the design of a novel single-acting spool-type pressure feedback restrictor for hydrostatic bearings. The increasing demand for larger machine tools that will handle heavy loads with precision has resulted in much attention being directed toward the development of hydrostatic bearings. At present, the most commonly used pressure feedback restrictor for hydrostatic bearings employs a membrane. In the membrane device, a flexible metal diaphragm is the key component and this kind of restrictor can provide precise metering of hydraulic oil flow. However, the membrane device is not suitable for extremely heavy loads and we present a spool type of pressure feedback restrictor as an alternative. This type of restrictor can support much heavier loads than the membrane type and is suitable for the bearings in large machine tools. The novel design has two significant features: the first is the orifice restrictor which effectively circumvents the influence of fluctuating oil temperature. The second feature is the introduction of adjustment screws at each end of the valve body which widen the range of operation. A prototype was successfully fabricated and the experimental results validate the design of this new and innovative pressure feedback restrictor.

1. Introduction

The new generation of machine tools leans toward bigger machines that can handle heavier loads with higher precision. Amongst the many different components in these machines the most important role is played by the bearings. The advantages of aerostatic and hydrostatic bearings, when compared to traditional ball bearings, are no-contact, low friction and wear, and low heat generation. However, aerostatic bearings are only suitable for light loads. For big machine tools and heavy loads such as those encountered in surface grinders and similar machines, hydrostatic bearings become necessary. Presently, the most commonly used pressure feedback restrictor used for hydrostatic bearings is the membrane type. In this device a flexible metal diaphragm is the key component serving to precisely meter the flow of hydraulic oil, see Figure 1. [1–5, 9]. However, the membrane-type pressure feedback restrictor is not suitable for extremely heavy loads and the...
and the chamber pressure, $P_r$, will rise. If the chamber pressure exceeds a specific value, preset by the spring, the pressure feedback will cause the orifice to widen as the pressure causes the spool to move to the left against the force of the spring, and more oil will flow. The chamber pressure rises and falls in response to changes of load to maintain a constant oil film thickness between the pad and the platform. Figure 2 also shows that the pressure control system is an active closed loop. No electrical pressure sensor is necessary since feedback is directly connected to the right hand end of the spool. The first of the two significant features of this design is the orifice restriction which effectively circumvents the influence of oil temperature fluctuation. This can be explained by the orifice flow-rate equation shown below. It can be seen that the flow rate is independent of oil viscosity and temperature changes.

$$Q = C_f \cdot \pi \cdot d \cdot \sqrt{\frac{2(P_s - P_r)}{\rho}}$$

membrane is also subject to fatigue.[6, 8, 9] Therefore, an alternative pressure feedback restrictor of the spool type is presented here. Earlier reports [6–8] have discussed some disadvantages of spool-type restrictors, such as the complex structure and adjustment difficulties. As a response we offer a novel design for a spool-type pressure feedback restrictor for hydrostatic bearings. The static and dynamic performance of this valve has been evaluated and the design concept of new single-acting spool-type pressure feedback restrictor for hydrostatic bearings is described.

### 2. Design of a new Spool-type Pressure Feedback Restrictor

Figure 2 is a schematic of the novel spool-type pressure feedback restrictor. The operational principle is briefly described as follows. The initial opening allows hydraulic oil to flow through the orifice at a predetermined rate which is enough to maintain a constant oil film thickness between the circular pad and platform. This pad is also referred to as a hydrostatic bearing. However, in operation an external disturbance of the load on the platform (see Figure 2) will cause the thickness of the oil film to decrease and the chamber pressure, $P_r$, will rise. If the chamber pressure exceeds a specific value, preset by the spring, the pressure feedback will cause the orifice to widen as the pressure causes the spool to move to the left against the force of the spring, and more oil will flow. The chamber pressure rises and falls in response to changes of load to maintain a constant oil film thickness between the pad and the platform. Figure 2 also shows that the pressure control system is an active closed loop. No electrical pressure sensor is necessary since feedback is directly connected to the right hand end of the spool. The first of the two significant features of this design is the orifice restriction which effectively circumvents the influence of oil temperature fluctuation. This can be explained by the orifice flow-rate equation shown below. It can be seen that the flow rate is independent of oil viscosity and temperature changes.

$$Q = C_f \cdot \pi \cdot d \cdot \sqrt{\frac{2(P_s - P_r)}{\rho}}$$

### Table 1: Specification of pressure feedback restrictor.

| Specification                          | Value   |
|----------------------------------------|---------|
| Dimension of valve body ($L \times W \times H$) (mm) | 80 × 46.1 × 40.3 |
| Mass of spool (g)                      | 16      |
| Diameter of spool (mm)                 | 10      |
| Spring constant (Kgf/mm²)              | 3.002   |
| Maximum supply pressure (bar)          | 30      |
where \( C_f \): flow coefficient, \( d \): diameter of the spool, \( x \): opening of the orifice, \( P_s \): upstream supply pressure, \( P_r \): downstream chamber pressure.

The second significant feature is the design of the two adjusting screws built into the valve body. Adjustment screw #1 sets the pre-compression of the spring and controls the effective working range of chamber pressure feedback. Since the chamber pressure is directly proportional to the external load, adjustment screw #1 can be set to meet the actual external load conditions. On the other hand, adjustment screw #2 is used to regulate the initial opening of the orifice, because hydraulic oil must always flow to the circular pad to set up an initial load capacity before operation begins. The chamber pressure gradient

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**Figure 5.** Circuit diagram of the test bench.

**Figure 6.** The test bench setup.
Equation (2) is shown below. From Equation (2) it can be seen that the initial flow-rate through the orifice, $Q_1$, is necessary to build-up pressure and maintain an oil film between the circular pad and platform. The assembled valve and an exploded view of all the parts is shown in Figure 3. Figure 4 shows the circular pad (hydrostatic bearing) (Table 1).

$$\frac{dP_r}{dt} = \frac{\beta_e V_e}{Q_1 - Q_2} (Q_1 - Q_2)$$

where $P_r$: chamber pressure, $\beta_e$: bulk modulus of hydraulic oil, $V_e$: effective chamber volume, $Q_1$: in-flow rate into the chamber, $Q_2$: out-flow rate from the chamber.

3. Experimental Test RIG

A test bench was designed and built to evaluate the performance of the new feedback restrictor. Figure 5 is a circuit diagram of the test bench setup. There are two power units and the upper one is used to produce different external disturbance loads. The key component is a precision proportional pressure valve (#14) which controls the load pressure used to simulate various external loads delivered to the circular pad (#9) by the hydraulic cylinder (#12). The range of adjustment is 0–2000 Kgf or 20000 N. The lower power unit is used exclusively for the hydrostatic bearing. The pressure feedback restrictor (#16) is connected to the circular pad and changes the oil flow to regulate the thickness of the oil film to balance the variation caused by differences in external load. The pressurized hydraulic oil supplied by the pump (#1) flows through the restrictor and enters the circular pad to establish a thin oil film between the circular pad and the load cell (#10). The load cell and cylinder rod (#12) are lifted and float on the oil film above the circular pad. The application of different external load from the hydraulic cylinder results in changes of oil film thickness. The new spool-type pressure feedback restrictor plays an important role in maintaining a constant thickness of oil film. The relief valve (#4) is set to 30 bar and the maximal flow-rate output of the pump (#1) is 10 L/min. Figure 6 shows the layout of the test bench.

4. Experimental Results and Discussion

Performance of the new spool-type pressure feedback restrictor can be evaluated in two ways, the first being a static performance test. The external load acting on the load cell is increased slowly from 350 to 1850 Kgf by the proportional pressure valve. At the starting point of 350 Kgf, the external load is small and the resulting oil film is 0.137 mm thick as shown in Figure 7. However,
contact and undesirable wear between the load cell and the circular pad. However, the experimental results when the new spool-type pressure feedback restrictor is used are shown in Figure 10. It can be seen that the thickness of the oil-film is nearly a constant irrespective of the square wave input simulating external disturbance loads ranging from 350 to 1400 Kgf. Real contact and undesirable wear between the load cell and circular pad can be avoided and this is the exact function of a hydrostatic bearing. The dynamic performance of bearing system with and without resistor is shown in Table 2.

5. Conclusions

A spool-type pressure feedback restrictor has been developed and implemented. Performance evaluations were made and discussed. Three conclusions may be drawn from this research.

1. The successful development of the spool-type pressure feedback restrictor has been verified by both static and dynamic tests and the results were satisfactory.
2. The spool-type pressure feedback restrictor together with a properly designed circular pad (hydrostatic bearing) is suitable for heavy duty machine-tools such as surface grinding machines and other heavy duty equipment.
3. The most innovative aspect of this design is the inclusion of the two adjustment screws built into the valve body. These widen the application range and this is especially important with fluctuating external disturbance loads.
4. Compared to traditional spool-type pressure feedback restrictor, the flow rate of the new spool-type pressure feedback restrictor is controlled by metering orifice which has the advantage of independent of oil viscosity and temperature changes.

Table 2. Dynamic performance of bearing system.

| Without resistor | With resistor |
|------------------|--------------|
| Percentage of overshoot (%) | – | 36.3 |
| Settling time (sec) | – | 0.58 |
| Average gap deviation (mm) | 0.064 | 0.002 |

Nomenclature

- \( C_f \): flow coefficient
- \( D \): diameter of the spool
- \( X \): opening of the orifice
- \( P_s \): upstream supply pressure
- \( P_r \): chamber pressure
- \( \beta_e \): bulk modulus of hydraulic oil
- \( V_e \): effective chamber volume
- \( Q_1 \): in-flow rate into the chamber
- \( Q_2 \): out-flow rate from the chamber
Disclosure Statement

No potential conflict of interest was reported by the authors.

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