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[1.]Jyh-Chyang RENN, [2.]Wen-Jen HSU, [3.]Yun-Ruei LI

DEVELOPMENT OF HYDROSTATIC BEARING WITH SPOOL-TYPE RESTRICTOR FOR LARGE SINGLE COLUMN VERTICAL LATHE

[1-3.] National Yunlin University of Science and Technology, Faculty of Mechanical Engineering, 123 University Road, Section 3, Douliou, TAIWAN

Abstract: In this paper, a hydrostatic bearing with novel single-acting spool-type pressure feedback restrictor for large single column vertical lathe is developed. Due to the increasing demands of larger dimension, heavier load and higher precision for current and future machine tools, the development of hydrostatic bearing has become a more and more important issue over the past decades. Nowadays, the most commonly used pressure feedback restrictor for hydrostatic bearings installed in a large single column vertical lathe is membrane type, in which a thin and flexible metal sheet serves as the key component to meter the hydraulic oil flow precisely. However, the membrane-type restrictor is not quite suitable for extremely heavy load. Therefore, an alternative to design the hydrostatic bearing using spool-type restrictor is presented in this paper. Generally speaking, spool-type restrictor is easier to manufacture and has the advantage of lower cost than the membrane-type restrictor. It is thus expected that the developed spool-type restrictor can support much heavier load in machine tools than the membrane type. There are two significant features regarding this novel design. The first one is the introduced orifice restrictor which avoids effectively the influence of possible oil temperature variation. The second feature is the design of two adjustable hand wheels that are built into the valve body to widen the application range. Finally, a prototype of a single-unit hydrostatic bearing is successfully implemented and the experimental results prove the validity of the hydrostatic bearing with the proposed spool-type restrictor.
Keywords: hydrostatic bearing, pressure feedback restrictor, spool-type, single column vertical lathe

INTRODUCTION

Generally speaking, the trend of new generation machine tools is towards larger dimension, heavier load and higher precision. Among many different key components for current and future machine tools, the bearing is believed to play the most important role. Compared to traditional ball bearing, the advantages of aerostatic and hydrostatic bearing are non-contact, low friction and wear, low heat generation, etc. However, aerostatic bearing is only suitable for light load manufacturing.

For machine tools with large dimension and heavy load, like the large single column vertical lathe studied in this paper, the development of hydrostatic bearing becomes an inevitable task. Figure 1 shows the scheme of a large single column vertical lathe. The diameter of the rotary table may vary from 6 m to 10 m [1]. To support this very heavy rotary table, several hydrostatic bearings under the rotary table are utilized. In addition, these hydrostatic bearings are placed symmetrically about the center of rotation.

Nowadays, the most commonly used pressure feedback restrictor for hydrostatic bearings installed in a large single column vertical lathe is membrane type, in which a thin and flexible metal sheet serves as the key component to meter the hydraulic oil flow precisely as shown in Figure 2 [2-6, 11].

However, the membrane-type pressure feedback restrictor is not quite suitable for extremely heavy load. In addition, the membrane itself suffers from the fatigue problem [7, 10, 11]. Therefore, an alternative to design the pressure feedback restrictor for hydrostatic bearing using spool type is presented in this paper. Some previous reports [7, 8 and 10] indicated that disadvantages like the complex structure and difficult adjustment of the spool-type restrictor are inevitable. However, such a spool-type design is still believed to be a promising technique because the manufacturing of spool-type restrictor is basically easier than that of the above-mentioned membrane-type restrictor. In addition, there are many world-wide international or local famous companies that can manufacture different kinds of reliable spool-type hydraulic valves with excellent reputation.

Therefore, it is believed that the spool-type restrictor is a better choice when designing hydrostatic bearings for the large single column vertical lathe. In the following, the design concept of hydrostatic bearing with single-acting spool-type pressure feedback restrictor is illustrated.

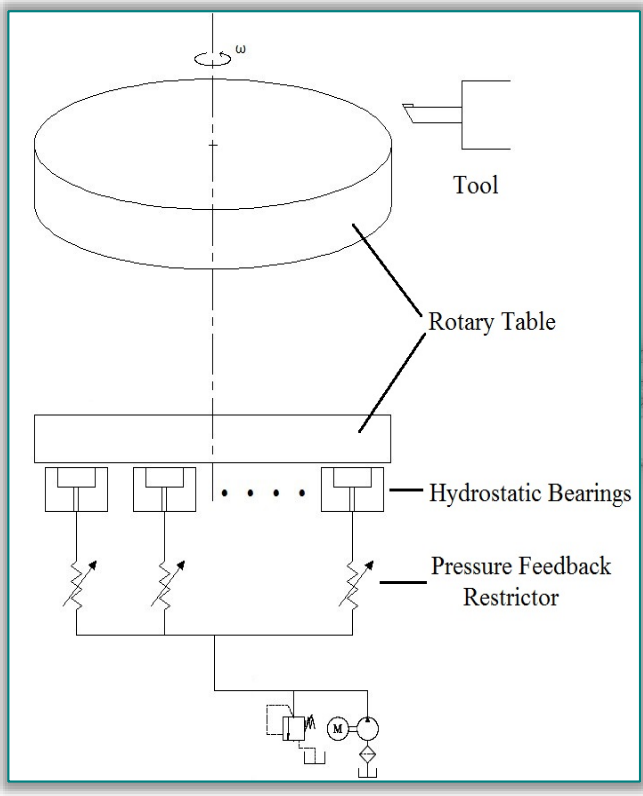


Figure 1 – Scheme of a large single column vertical lathe

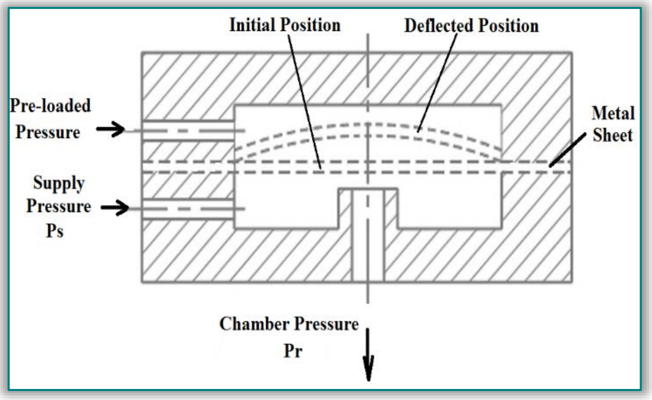


Figure 2 – Scheme of membrane-type pressure feedback restrictor

DESIGN OF HYDROSTATIC BEARING WITH SPOOL-TYPE PRESSURE FEEDBACK RESTRICTOR

Figure 3 shows the scheme of the developed hydrostatic bearing with novel spool-type pressure feedback restrictor. The operational principle is briefly described as follows. The initial opening allows basic flow rate of hydraulic oil through the orifice to the chamber to maintain a constant thickness of oil film between the circular pad and platform. It is worth mentioning that the circular pad is also called the hydrostatic bearing in some literatures. However, if some external disturbance load is imposed to the platform as shown in Figure 3, the thickness of oil film decreases and the chamber pressure, Pr, increases. In addition, if the chamber pressure exceeds some specific value defined by the spring, then the orifice opening will become larger due to the chamber pressure feedback. In details, the feedback chamber pressure acts on the right end of the spool and moves the spool to the left. This results in more hydraulic oil flowing to the chamber of the circular pad. Consequently, the chamber pressure increases trying to overcome the external disturbance load and enlarge the gap to maintain a constant thickness of oil film between the circular pad and platform.

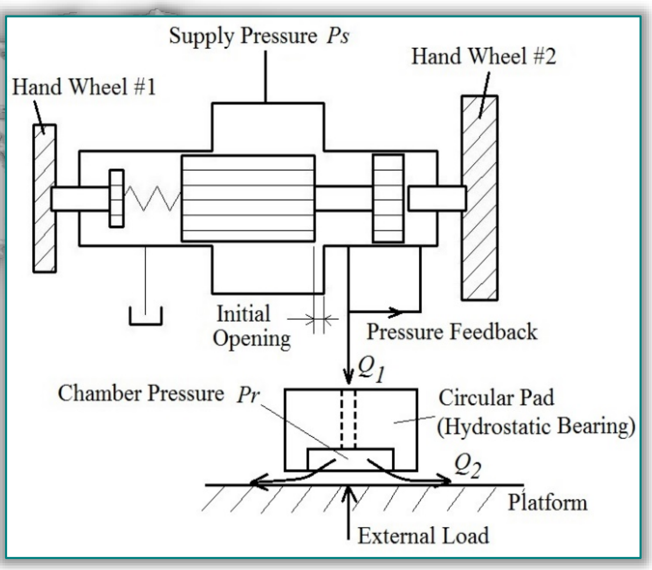


Figure 3 – Scheme of the hydrostatic bearing with novel spool-type pressure feedback restrictor

From Figure 3, it can also be observed that the proposed structure is active closed-loop pressure control scheme. However, no electric pressure sensor is necessary since the feedback pressure is directly connected to the right end of the spool. Hence, there are two significant features regarding this novel design. The first one is the introduced orifice-type restrictor which avoids effectively the influence of possible oil temperature variation. This can easily be proved by the following flow-rate equation through an orifice. Obviously, from Eq. 1, the flow-rate is independent of the oil viscosity and hence the temperature variation.

$$Q = C_f \cdot \pi \cdot d \cdot x\sqrt{\frac{2(Ps-Pr)}{\rho}} \quad (1)$$

where C_f - flow coefficient, d - diameter of the spool, x - opening of the orifice, Ps - upstream supply pressure, Pr - downstream chamber pressure.

The second feature is the design of two adjustable hand wheels that are built into the valve body to widen the application range. The handwheel#1 adjusts the pre-compression of the spring and set the effective working range of chamber pressure feedback. Since the chamber pressure is directly proportional to the external disturbance load, the handwheel#1 can then be adjusted to meet the actual external load condition accordingly. On the other hand, the handwheel#2 is used to regulate the initial opening of the orifice since the hydraulic oil must always flow into the chamber of the circular pad to set up the initial load capacity before the real operation. It is worth mentioning that circular pad is actually the hydrostatic bearing.

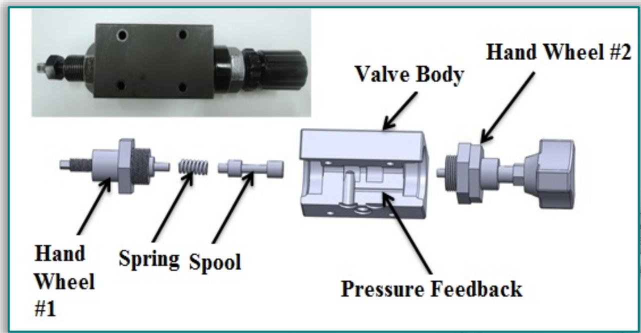


Figure 4 – Real picture and all parts of the restrictor

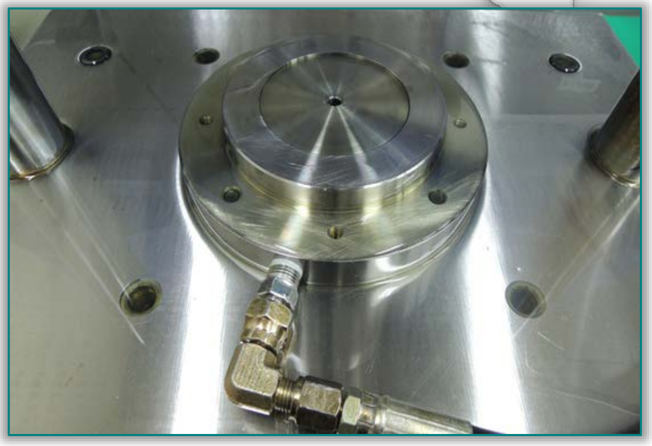


Figure 5 – Real picture of the circular pad (hydrostatic bearing)

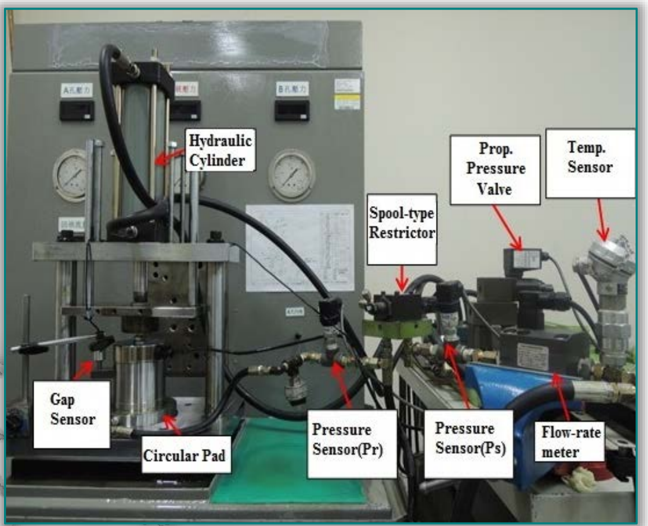
Thus, the chamber pressure gradient formula can be described by Eq. 2. Obviously, from Eq. 2, the initial flow-rate through the orifice, Q_1, is necessary for the build-up of the chamber pressure and maintaining a definite oil-film thickness between the circular pad and platform. Finally, the real picture together with all parts of the developed spool-type pressure feedback restrictor is depicted in Figure 4. In addition, the real picture of the circular pad (hydrostatic bearing) is shown in Figure 5.

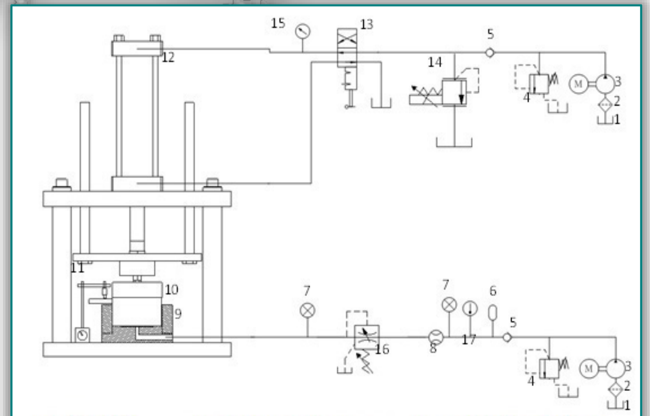
$$\frac{dP_r}{dt} = \frac{\beta_e}{V_e}\sum(Q_1 - Q_2) \quad (2)$$

where Pr - chamber pressure, β_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.

EXPERIMENTAL TEST RIG

To evaluate the performance of the developed single-unit hydrostatic bearing with spool-type pressure feedback restrictor, a test bench is designed and constructed. Figure 6 shows the circuit diagram and real picture of the test bench. There are two power units in this test bench. The upper power unit is utilized to produce various external disturbance loads.





1. Oil Tank
2. Filter
3. Pump
4. Relief Valve
5. Check Valve
6. Accumulator
7. Pressure Gauge
8. Flow-rate Meter
9. Circular Pad
10. Load Cell
11. Gap Sensor
12. Cylinder
13. Switching Valve
14. Proportional Pressure Valve
15. Pressure Gauge
16. Tested Restrictor
17. Temp. Gauge

Figure 6 – Circuit diagram and real picture of the test bench

The key component is the proportional pressure valve (#14) which controls the load pressure precisely and is used to simulate various external disturbance loads acting on the circular pad (#9) through the hydraulic cylinder (#12). The adjustable range for the external disturbance load from 0 to 2000 Kgf or 20000 N is available in this test bench. On the other hand, the lower power unit is specifically used for the hydrostatic bearing.

To compensate the oil film variation caused by the external disturbance load, the developed spool-type pressure feedback restrictor (#16) is connected to the circular pad. The pressurized hydraulic oil supplied by the pump (#1) flows through the restrictor and enters the circular pad. It establishes a thin oil film between the circular pad and load cell (#10). Consequently, the load cell and cylinder rod (#12) are lifted up and floats above the circular pad.

By applying different external disturbance loads through the hydraulic cylinder, the oil-film thickness changes accordingly. In this case, the proposed spool-type pressure feedback restrictor is expected to play an important role to maintain a constant thickness of oil film. The relief valve (#4) is set at 30 bar and the maximal flow-rate output of the pump (#1) is 10 L/min.

EXPERIMENTAL RESULTS AND DISCUSSION

The performances of the developed single-unit hydrostatic bearing with spool-type pressure feedback restrictor can be evaluated in two ways. The first way is the static performance test. The external disturbance load acting on the load cell is increased slowly from 350 to 1850 Kgf by electrically controlling the proportional pressure valve.

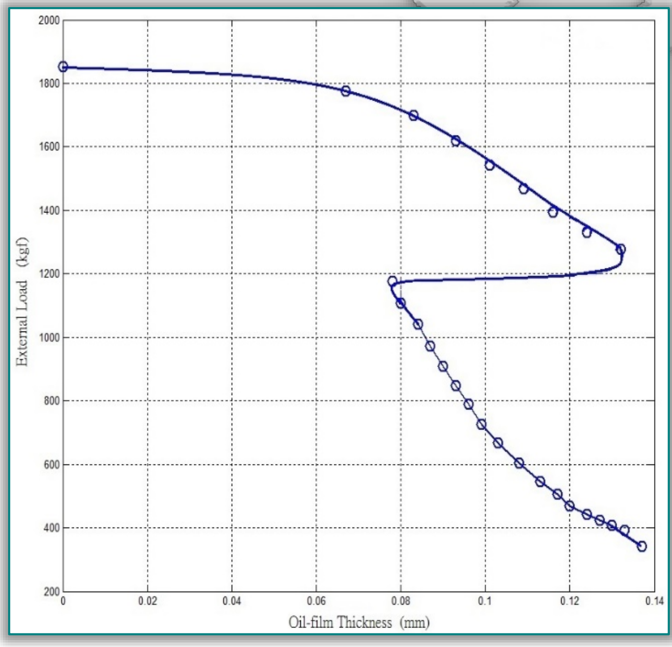


Figure 7 – Static performance test results of developed hydrostatic bearing with spool-type pressure feedback restrictor

At the beginning operating point of 350 Kgf, the external load is smallest which results in a largest oil-film thickness of 0.137 mm as shown in Figure 7. However, the oil-film thickness will decrease when the external load is further increased. In addition, if the external load exceeds a specific limit of 1200 Kgf, the oil-film thickness increases rapidly due to the operation of the spool-type pressure feedback restrictor. This increased oil-film thickness prevents the real contact between the load cell and circular pad. It is worth mentioning that this limit depends actually on the pre-compression of the spring, the spring constant as well as the friction force between the spool and valve body.

In other words, this limit can be adjusted according to the real operation condition. Figure 8 shows the static performance comparisons between the hydrostatic bearing with and without spool-type pressure feedback restrictor. It is clear that the static performance of hydrostatic bearing without any restrictor is worse than that with restrictor. Its oil-film thickness decreases monotonically as the external load is increased continuously.

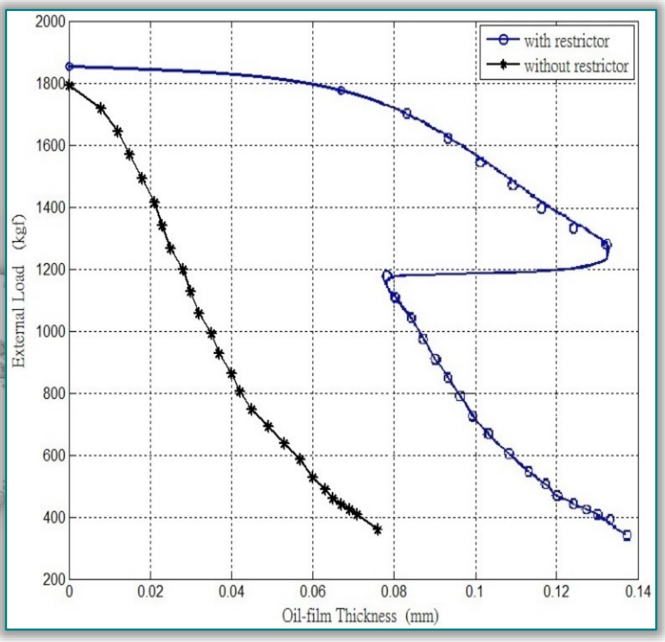


Figure 8 – Static performance comparisons between hydrostatic bearing with and without restrictor

The second means to evaluate the performance of the developed single-unit hydrostatic bearing with spool-type pressure feedback restrictor is the dynamic test. In the dynamic test, a square wave representing the external disturbance load from 350 to 1400 Kgf is produced by sending an equivalent electric signal to the proportional pressure valve. The frequency of the square wave is set to be 0.1 Hz. The experimental result of oil-film thickness for hydrostatic bearing without any restrictor is shown in Figure 9.

Obviously, the oil-film thickness seems to be an inverse square wave approximately in response to the square wave input of external load. In other words, the oil-film thickness cannot be kept a constant and the smallest thickness is around 0.07 mm which may cause the real contact and undesirable wear between the load cell and circular pad. On the other hand, the experimental result of oil-film thickness for hydrostatic bearing with the developed spool-type pressure feedback restrictor is shown in Figure 10.

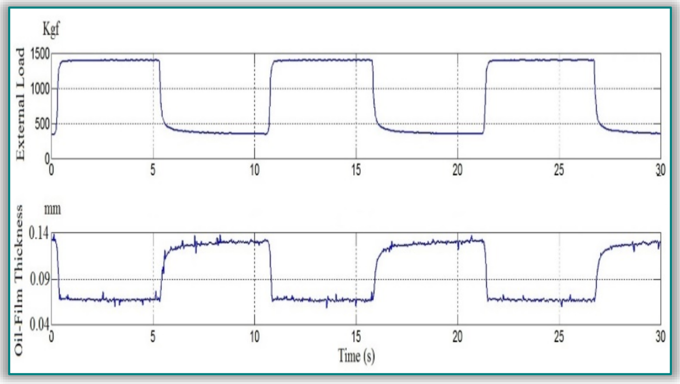


Figure 9 – Experimental results of hydrostatic bearing without restrictor

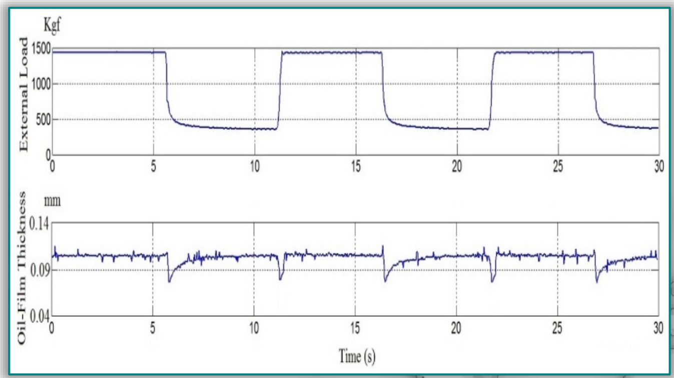


Figure 10 – Experimental results of hydrostatic bearing with restrictor

It can be observed that the oil-film thickness is nearly a constant valve regardless of the square wave input of external disturbance load from 350 to 1400 Kgf. Therefore, the real contact and undesirable wear between the load cell and circular pad can be avoided. This is exactly the principle function for a hydrostatic bearing.

CONCLUSIONS

In this paper, a single-unit hydrostatic bearing with spool-type pressure feedback restrictor for a large single column vertical lathe is successfully developed and implemented. Besides, four conclusions may be drawn from this research.

1. The successful development of hydrostatic bearing with spool-type restrictor is verified by both the static and dynamic tests. And the results are satisfactory.
2. In addition to the large single column vertical lathe, the proposed hydrostatic bearing together with spool-type restrictor is also suitable for other machine-tool applications with heavier load, like the surface grinding machine, etc.
3. One most innovative design revealed in this paper is the design of two built-in hand wheels to adjust the application range. In addition, such a design also overcomes the fault of difficult adjustment in some conventional spool-type restrictors mentioned in previous reports [7, 8 and 10].
4. The range of applied external disturbance load for the developed prototype is recommended to be from 1300 to 1500 Kgf. Within this range, the hydrostatic bearing possesses highest stiffness and the corresponding oil film thickness can be maintained at a nearly constant value. On the other hand, this operational range can also be adjusted by the hand wheel #1 shown in Fig. 3.

Acknowledgment

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Note

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