Design of High-speed Wear Lifetime Tester of the Instrument Ball Bearings

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Abstract. The instrument ball bearings are the key components of movable components for various kinds of measuring and control instruments; they often operate in the environmental condition of high-speed and light preload. In general, the non metal, disposable oil-impregnated retainer material has been used for these kinds of high precision miniature bearing. The engineering practice shows that the common failure mode of them is the wear which appears under the condition of insufficient lubrication condition. As the results, the vibration and noise will be enlarged, so does the frictional torque, which makes the ball bearings to lose its original working accuracy. It is the lifetime test of bearings that can enable the designers and manufacturers to chose the material of the bearing properly, optimize the product structure, mend the manufacturing technique process, and to enhance the technical level of the bearing products significantly. In this paper, the wear lifetime tester has been designed according to the requirements of the life test for the instrument ball bearings, which consists of the main body of tester, electric system, drive unit and computer measure and control system, etc. The motor spindle has been selected to drive the device which is supported by the aerostatic bearing; frequency conversion speed adjustment mode, its scope of rotating speed is between 0 and 10,000 rpm. A pair of bearings can be tested under the pure axial preload condition, the maximum load is up to 50N, the control accuracy is ±2%; the scope of temperature control is up to 200°C. The variation of frictional torque on the bearing couple will be measured by an on-line torque transducer. The variation of power dissipation can be monitored under arbitrary speed by use of an on-line high-precision power meter. The wear and quality situation of the contact surface of the bearings will be reflected on these two parameters. Meanwhile, the values of temperature and vibration will also be monitored respectively as the accessoril parameters to assess the real quality of the bearings. Experimental results show that this tester has the capable of presetting load, rotating speed and temperature; monitoring the raise of the temperature and vibration of each bearing, frictional torque and the power variation of the apparatus automatically, these parameters can also be saved as a datum file into the computer at the same time. The developed tester can be used to carry on wear lifetime test, it is suitable for various kinds of instrument ball bearings with different structure and dimension which have been applied for different working conditions, it realized the self-service, intelligent management of the test, and provided a basis for the implement of the lifetime and reliability test to the instrument ball bearings.

1. Introduction
The instrument ball bearings are the key supporting components in instruments. A large number of them have been applying for various kinds of adjustment instruments, measuring and control...
The lifetime experiment is the most important approach to evaluate performance of bearing during the phase after the bearings are finished to manufacture, before giving to the customers to verify. It is the lifetime test, which is of full scales by simulating the real working condition, can enable the designers and manufacturers to fully understand the reliability and lifetime of bearing and, consequently, to choose bearing material properly, optimize product structure, mend manufacturing technique process, and enhance the technical level significantly [2].

There are lacks of test means of lifetime and reliability tests for the instrument ball bearings currently. Only the static parameters are measured for the bearings, then they will be dispatched to the customers. The customers installed these bearing on their own equipments to evaluate and screen them. The manufactures have to waiting for the results from the customers. This process makes the manufactures difficult to improve their R&D levels. As a result, it’s necessary to design and develop the lifetime testers to meet the demands of engineering practice.

2. Requirements for the tester and tester design

The instrument ball bearings are different from the common bearings in usage. Most of them have special performance and higher precision while they often operate in the working conditions of high-speed (the range of rotating speed is between 12,000 and 60,000 r/min) and comparably lighter applied load (weight of rotor itself and applied axial preload after installing the bearings into instruments) [3]. The higher and lower temperature demands are needed in some circumstance. In such working condition, the failure mode of bearings is also different from the common ones—it is the wear out, not the fatigue crack to make them lose their regular performances. Under the good condition of lubrication, the main failure mode is that, due to the shear effect of lubricant under contact stress, the oxidation and polymerization reactions will occur to make the lubricant thicken and harden with the raise of surface temperature, then its lubricating ability will be damaged. In the poor lubricating condition, the interaction of metal surface and oxygen will form a thicker layer of mechanical mixture which is also very fragile and easy to crack down, then the remnant will be taken and mix with the lubricant. This process will deteriorate the lubricant performance and make it degrade. The former failure mode may change into the latter one. The repeat progress of the process will cause the bearing to seizure or overly wear, following the elevated frictional torque of bearing or loss in its precision performance, with a louder noise or a higher vibration value at same time, the bearing can not keep on its regular operating ability. According to the analysis above, the tester to be developed must has the ability of step-less speed regulating, changeable load and temperature freely; further more, it must monitor the variation of wear rate on line.

2.1. The structure of tester

On the basis of working condition and failure mode, the tester developed consists of the main body, lubricating system, electric system, drive unit, load applying system, heating and computer measure and control system. The main body of the tester is showed as Figure 1. The “bridge type” of mechanical structure is inside it. When the pure radial load was applied, four sets of bearing would be tested once. If both radial and axial load were applied, two sets of bearing would be tested at one time, while the other two sets of bearing would be used as the accompanied testing bearings. The foundation of tester connects the main body, the drive unit, frictional torque transducer in series. When the test starts out, the main body will connect with the drive unit through a precision coattail-groove to position them. When measuring the frictional torque, the main body will connect with the torque transducer through a precision cross-coattail-groove to carry on the measurement.
2.2. The driving unit
The AC frequency conversion speed adjustment mode is adopted and the rotating speed of main spindle is controlled by the computer automatically with its 3% control accuracy and being capable of step-less speed adjustment. The aerostatic spindle is selected as driving unit which has the advantage of higher speed, higher precision, lower power dissipation, longer lifetime, and constant stiffness as well, comparing with the spindle supporting by the rolling bearings and the oil lubricated journal bearings [4,5].

2.1.1. Lubrication mechanism of aerostatic bearing, performance calculation and comparison. Under the conditions of isothermal and steady state, the general Reynolds equation is defined as follows:

\[
\frac{\partial}{\partial X} \left( H^3 p \frac{\partial p}{\partial X} \right) + \frac{\partial}{\partial Y} \left( H^3 p \frac{\partial p}{\partial Y} \right) = \Lambda \frac{\partial}{\partial X} \left( \rho H \right)
\]

(1)

Where \( X = x/R, \ Y = y/R, \ H = h/c, \ \Lambda = 6 \mu \omega / Pa(R/c)^2, \ \sigma = 12 \nu \omega / Pa(R/c)^2 \)

With \( R \)- radius of bearings,
\( c \)- average clearness of radius,
\( \omega \)- angular velocity of shaft,
\( \nu \)- frequency of whirl/squeeze.

According to the practical structure of bearing and applied condition, combining with the given boundary condition, the results can be got by solving the equation (1). Then, the load capability, stiffness and power dissipation etc. can be calculated.

While taking the structure into account, the design of throttle is the key point of the whole design for aerostatic bearing. It’s the basis for determining the function of bearing. While thinking of the performance analysis, it’s the primary to ascertain the appropriate throttle rate \( K_g \) (or the rate of surface pressure).

The basic form of structure of aerostatic bearing designed here adopted the single-row hole to supply air for it. The simple calculating formulas of performance are illustrated as follow.

Load capability \( W_j = C_j LD(p_s - p_a) \quad C_j = 0.2 \) for single-row hole (2)

Stiffness capability \( K_j = 2W_j / c \) (3)

Frictional torque \( T_j = \frac{\pi \mu D^3 L}{4c} \omega \) (4)
Power dissipation \[ P_w = T \omega \] (5)

Where: \( P_s \) - pressure of supplied and ambient air; \( \mu \) - viscosity of gas

2.2.2. The calculation of frictional torque for ball bearing couple. Generally, the frictional torque of a bearing (\( M \)) consists of a load factor (\( M_L \)) and velocity factor (\( M_v \)), which is illustrated by the following equation:

\[ M = M_v + M_L \quad (N \cdot mm) \] (6)

While

\[
\begin{align*}
if \quad v \cdot n \geq 2000, \quad M_v &= 10^{-7} f_o \left( vn \right)^{2/3} d_m^2 \\
if \quad v \cdot n < 2000, \quad M_v &= 160 \times 10^{-7} f_o d_m^2
\end{align*}
\] (7) (8)

where

- \( d_m \) - pitch diameter of bearing, mm,
- \( f \) - coefficient about bearing type and the lubricating manner,
- \( n \) - bearing rotational speed, r/min,
- \( \nu \) - kinematic viscosity, mm\(^2\)/s.

\( M_L \) reflects the frictional dissipation of elastic hysteresis and local differential slip, which can be calculated by using the following equation:

\[ M_L = f_1 P_r d_m \] (9)

Where

- \( f_1 \) - coefficient related to the bearing type and the applied load,
- \( P_r \) - the equivalent load to determine frictional torque of bearing, N.

The calculating results have showed that the frictional torque of the aerostatic journal bearing is less two to three orders of magnitude than the tested bearing couple. While taking the respect of design into account, the variation of power loss which can be measured by using a milli-power meter will be mainly the variation of frictional torque of bearing couple. Hence, indirect measurement and control can be realized for the wear of tested instrument ball bearings.

2.3. Computer measure and control system

For the purposes of realizing the measure and control automatically, and to make the operation of test process reliable and accurate, the computer measure and control system with industry level has been developed. The system can carry out the real time and multi-tasks management. The system parameters are preset on the computer screen, which include rotational speed, ambient temperature, applied load, loop time of variants, the storage time of data and automatic printing time of data, etc. Some parameters can be set to an alarm limit, in order to stop the tester when the defined alarm thresholds have been exceeded. The unusual signal which occurs in the electric motor of spindle during the test process can also be displayed on the computer screen. The vibration, temperature of bearings and load loop curve (air pressure) are also displayed synchronously. The window of the software is showed as figure 3.

2.4. The measurement of frictional torque and milli-power

With the extension of test time, the premature wear will occur in the bearing components. The progress of wear will enlarge the clearance of ball bearing. As a result, the operational and supporting accuracy of bearing turn to bad, following the enhancement of operational noise and frictional torque. A torque transducer and a milli-power meter have been designed to monitor the variation of frictional torque and power dissipation. These values are seen as indicators for the wear variation inside the bearing components.

When torque measurement is needed for the bearing couple, the first step is to take apart the core shaft and coupling, then to connect core shaft and main body of tester together on the two sides of the
torque transducer. After the measuring process is finished, taking core shaft and main body apart, quitting the torque transducer to its original position. The measurement scope of torque transducer is between 0 and 0.001 N·m, the maximum speed is up to 30,000 r/min and the measuring accuracy is 5μN•m.

The milli-power meter connects the circuit in series; it can monitor the variation of power without the limits of speed. From the former analysis, we know that the variation of power reflects the wear situation of tested bearing couple, so the on-line monitoring of wear variation has been realized.

3. Lifetime experiment and monitoring results
In order to verify the overall performance and the performance of every subsystem, the operational examining experiment has been carried out for 200 hours by using a pair of precision angular-contact ball bearings, C6084. The bearings were selected from the products to supply for the customers. The experimental conditions and bearing’s parameters are showed in Table 1.

3.1. The feasibility verification of measurement for torque transducer
Under the conditions of changing rotational speed and applied axial load, the frictional torque of system has been measured to verify the sensitivity of torque transducer. The result is illustrated in Figure 4, with five kinds of axial loads and three kinds of rotational speeds. It confirmed that the torque transducer has enough sensitivity to the torque variation of the bearing couple.

3.2. Monitoring results of other test parameters
The life experiment which lasted for 200 hours has been finished under the conditions of table 1. The computer system has been used to monitor the parameters of bearing’s temperature, vibration and milli-power and so forth. The figure 5 and figure 6 are the overall illustration during the whole experimental period. We can know from them that the whole tester and every subsystem have been operating regularly; the tested bearings are in good conditions.

4. Conclusion
The newly developed tester has the capable of presetting load, rotating speed and temperature; defining alarm limits and monitoring the raise of temperature and vibration of each bearing, frictional torque and the power variation of the apparatus automatically, these parameters can also be saved as a datum file into the computer at the same time. The developed tester can be used to carry on wear lifetime test, it is suitable for various kinds of instrument ball bearings with different structure and dimension which have been applied for different working conditions, and it realized the self-service, intelligent management of the test process.

The operational experiment which lasted for 200 hours proved that every subsystem of the tester operates regularly and meets the requirements of design and development. It provides a basis for the implement of the lifetime and reliability test to the instrument ball bearings.
Figure 4. The measuring results of torque.

| speed n/(r/min) | 60,000 |
|----------------|--------|
| axial load Fa/(N) | 5 |
| ambient temperature t/(°C) | 10 |
| lubrication approach | disposable oil lubricating |
| bearing number | C6084 |
| bearing type | angular contact ball bearing |
| precision grade | P4 |
| contact angle | 20° |
| size d×D×B/(mm) | φ4×φ9×3 |

Figure 5. Temperature trend for bearings.

Figure 6. Vibration and power trend for bearings.

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