Seismic Test on Turbo-Molecular Pumps Levitated by Active Magnetic Bearing

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Summary
To evaluate the behavior of a rotating shaft undergoing seismic vibration, two types of turbo-molecular pumps were installed on a vibration table. One of the tested pumps has unique 4-axis control magnetic bearings that utilize both electromagnets and permanent magnets and features excellent zero power control, while the order has 5-axis control magnetic bearings that control all five degrees of freedom except for the rotating component around the shaft. Three types of seismic waves, El-centro, Taft, and Hachinohe and their time responses on a building floor were produced on the vibration table. The displacement of the shaft under vibrating conditions was less than 60 μmp-p in each test, thus it was confirmed that active magnetic bearings do actually possess sufficient bearing stiffness.

1. Introduction

A turbo-molecular pump (TMP) is an axial flow compressor which operates in high and ultra-high vacuum conditions. In recent years, the demand for oil contamination-free and vibration-free vacuum pumps has increased rapidly in the semiconductor industry in order to achieve high density integration of semiconductors. The TMPs levitated by active magnetic bearings (AMB) are attaching much attention as a new pump to meet these requirements. Because of their weakness in terms of bearing stiffness compared with ball bearings, it is very important that their stability be demonstrated with respect to external vibration forces such as seismic waves. To evaluate the behavior of the rotating shaft undergoing seismic vibration, two types of TMPs were installed and shaken on a vibration table. The followings are the results of the test and an introduction for the pump tested and their magnetic bearings.

2. Test pumps and their magnetic bearings

The following two pumps were tested;

Table 1

Pump model	KP18	KP13
Type of magnetic bearings	5-axis control	4-axis control
Operating Speed (mim^{-1})	45,000	32,000
Pumping Speed (ℓ/s)	310	620
Greatest Pressure (Torr)	10^{-10} order	10^{-10} order
Weight (kg)	10	27
Size (mm)	ϕ170 x ℓ272	ϕ250 x ℓ412

i) TMP with 5-axis control magnetic bearings

Fig. 1 shows the construction of a pump using 5-axis control magnetic bearings. The support system has the same construction as the conventional one with ball bearings used in the TMP. The two ball bearings which support the rotating shaft are replaced with two radial magnetic bearings and an axial magnetic bearing. By means of these magnetic bearings, all five degrees of freedom of shaft motion except for the rotating component around the shaft are actively controlled. The schematic construction of this bearing system is illustrated in Fig. 2.

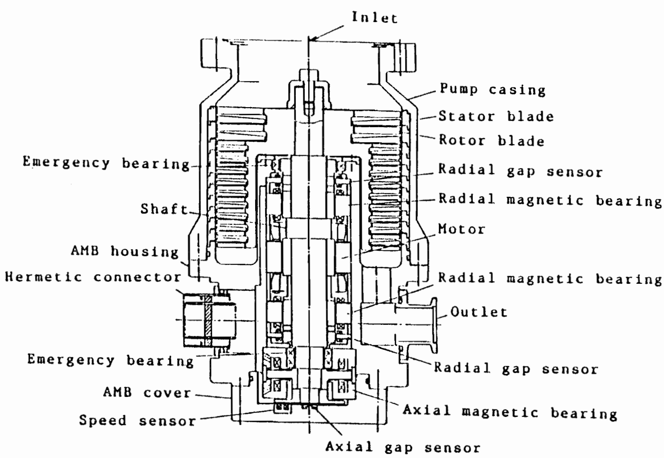


Fig. 1 Sectional drawing of TMP (KP18)

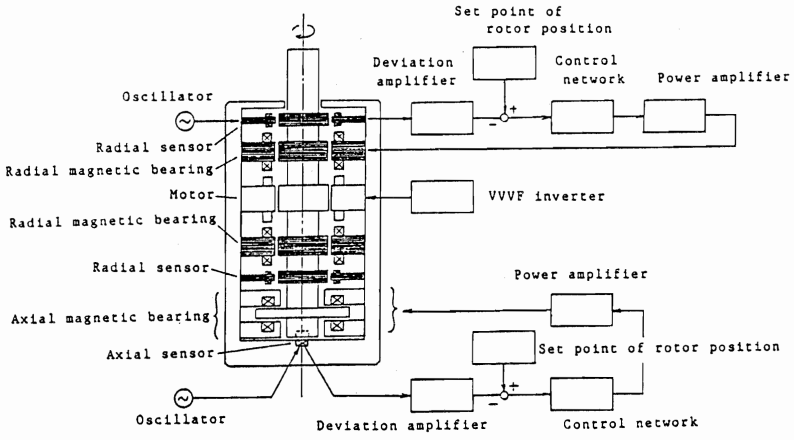


Fig. 2 Structure of 5-axis control AMB

As shown in Fig. 1 and 2, non-contacting inductive sensors that detect the rotor displacement are installed near each magnetic bearing. The rotor assembly is controlled to maintain its center position by regulating the attraction force of each magnetic bearing according to the rotor displacement signal from these sensors, and through the feed-back loop of the control circuit. The tested pump is designed so that the rated speed of the shaft is less than the bending mode frequency of the shaft.

Fig. 3 shows the result of a natural frequency analysis of the shaft. The bending mode frequency is denoted as "order 6".

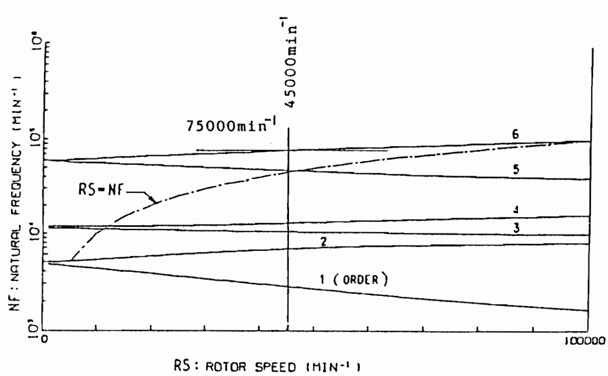


Fig. 3 Natural frequency analysis

ii) TMP with 4-axis control magnetic bearings

Fig. 4 shows the construction of a pump with 4-axis control magnetic bearings. The arrangement of the magnetic bearings is similar to the 5-axis type except that the axial magnetic bearing is not employed here. A schematic drawing of a bearing unit is shown in Fig. 5.

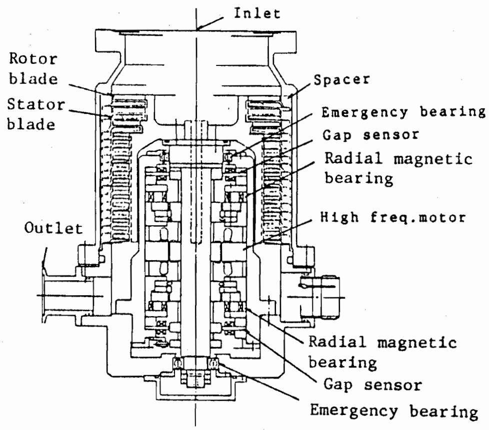


Fig. 4 Sectional drawing of TMP (KP13)

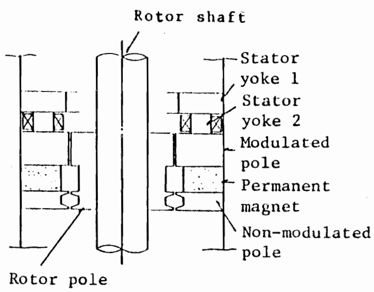


Fig. 5 Schematic of AMB Unit

This bearing unit is a radial control magnetic bearing in which passive stability is provided in the axial direction by the use of permanent magnets and electromagnets. No active control is needed in the axial direction, because axial stability is obtained by the use of bias flux through the tooth profile in the non-modulated magnetic pole. This type of bearing unit requires less electric power than the other bearing which use continuous current through a coil to establish bias flux, because bias flux is supplied from the permanent magnet.

Fig. 6 shows the construction of the entire bearing system.

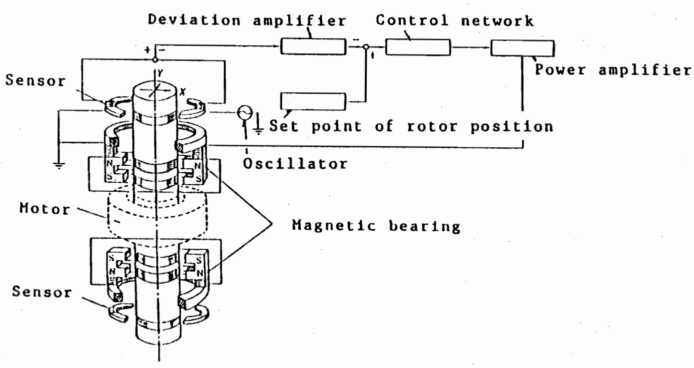


Fig. 6 Schematic of an active magnetic bearing

3. Seismic tests

1) Testing arrangement

Fig. 7 is a schematic diagram of the testing equipment. Two pumps were mounted together on a vibration table, and vibrated both horizontally and vertically in each test by changing their mounting positions. Accelerometers were set on the pump casing and on the vibration table as illustrated in the figure. The displacement of the rotating shaft was measured by the sensors of the magnetic bearings. All data recorded were converted, to digital form and analyzed by a computer. Table 2 describes the test items and the methods used.

Table 2

Test item	Testing method
1. Seismic response test	Pumps were vibrated directly with three different seismic waves (El-centro, Taft and Hachinohe), and the acceleration at the pump casing and the displacement of shaft were measured.
2. Test with seismic response of a model building	Pumps were vibrated with response waves of a model building under seismic vibration. El-centro, Taft and Hachinohe were used as seismic waves. The natural frequency of the model building was 2.5 Hz. The acceleration at the pump casing and the displacement of the shaft were measured.

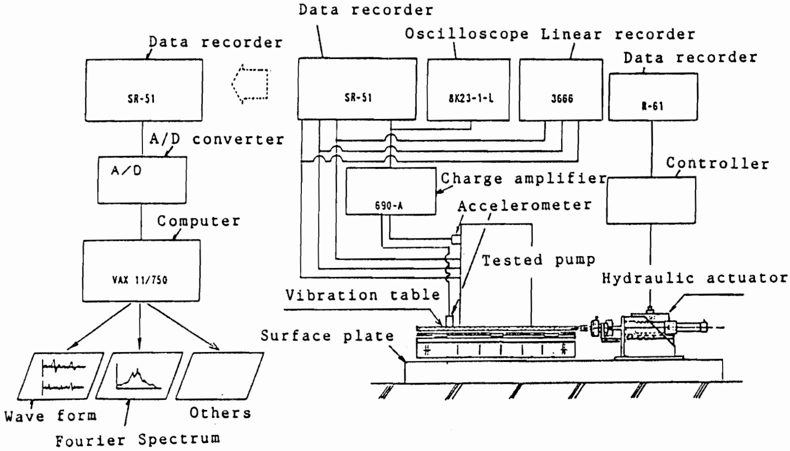


Fig. 7 Block diagram for measurement and analysis

2) Test results

i) Seismic response of the pumps

a. Radial direction

Pump model	Acceleration at pump casing	Displacement of shaft
KP18	187 - 385 gal	0.0084 - 0.0500 mm
KP13	200 - 457 gal	0.0036 - 0.0448 mm

b. Axial direction

Pump model	Acceleration at pump casing	Displacement of shaft
KP18	235 - 378 gal	0.0184 - 0.0260 mm
KP13	199 - 407 gal	No axial gap sensor

ii) Test with seismic response of a model building

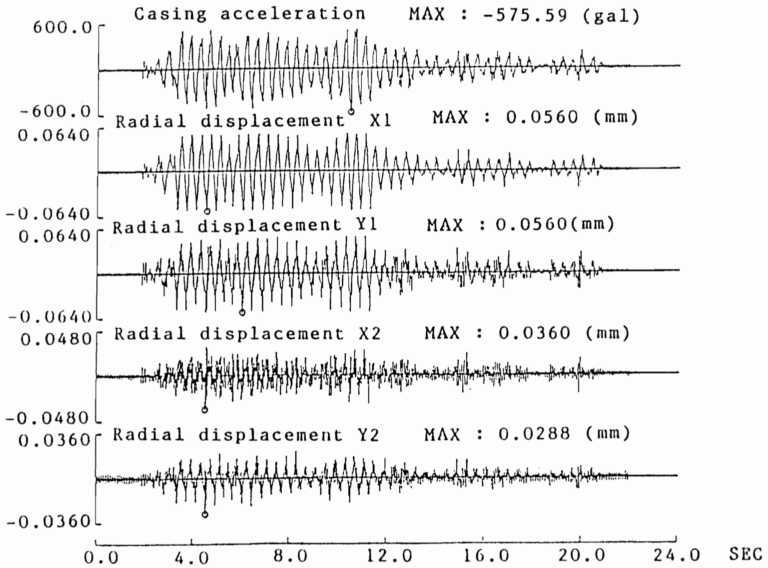
a. Radial direction

Pump model	Acceleration at pump casing	Displacement of shaft
KP18	467 - 1052 gal	0.0200 - 0.0568 mm
KP13	516 - 1027 gal	0.0048 - 0.0236 mm

b. Axial direction

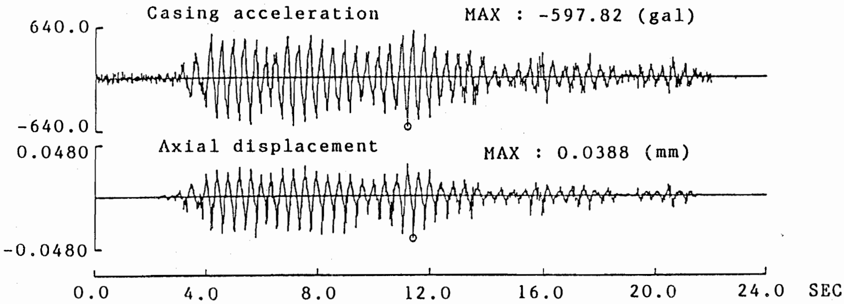
Pump model	Acceleration at pump casing	Displacement of shaft
KP18	235 - 378 gal	0.0196 - 0.0476 mm
KP13	199 - 407 gal	No axial gap sensor

Tested pumps operated in each test without touching the emergency bearings. Figs. 8 and 9 show examples of shaft displacement during this test.



Seismic wave : El-centro NS, response of a model building
Pump : KP18

Fig. 8 Radial displacement of shaft under seismic vibration



Seismic wave : El-centro NS, response of a model building
Pump : KP18

Fig. 9 Axial displacement of shaft under vibration

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