2nd International Symposium on Magnetic Beaing
July 12-14, 1990, Tokyo, Japan

# DEVELOPMENT OF AN ACTUATOR FOR SUPER CLEAN ROOMS AND ULTRA HIGH VACUA

T.HIGUCHI* A.HORIKOSHI** T.KOMORI**

*Institute of Industrial Science, University of Tokyo, MInato-ku,Tokyo, Japan
**Nippon Seiko K.K., Maebashi-city, Gunma-pre, Japan

Abstract

The Magnetically Suspended stepping motor (MS-type stepping motor) is a new actuator that we are currentry developing. The MS-type motor has the function of both the attractive levitation and the precise positioning of a stepping motor in one construction. By making use of the MS-type stepping motor, a cotactless positioning actuator, which is smaller than one using a simple combination of a conventional magnetic bearing and the conventional positioning motor can be realized. Also, by building in a position sensor (a brushless multipolar resolver), it will be possible to drive the MS-type stepping motor as a servo mortor. That is to say, it will be possible for the contactless actuator to provide velocity control and high speed, precise positioning. Firstly, this paper describes the conception behind the MS-type stepping motor and its structure. Secondly, the structure and performance of the Super Clean Servo Actuator are presented. Further, the development of an actuator for ultra high vacua is explained.

## 1. Introduction

Since the magnetic bearing does not have any mechanical contact and requires no lubrication, it does not contaminate its environment with dusts or oil vapour. Using this merit of the magnetic bearing, an actuator that is completely free from dusts or oil vapour can be developed. However an actuator which combines a propelling mechanism with a magnetic bearing is apt to be large. Because of the cost of keeping a high degree of cleanliness or vacuity, a super clean environment or an ultra high vacuum environment is very expensive. So actuators that are used in such an environment are required to be as small as possible.

With this in mind, we have developed a new actuator, named the Magnetically Suspended stepping motor(MS-type stepping motor), which has the functions of both a magnetic bearing and a stepping motor. By using the MS-type stepping motor, we can build(or design) not only a more compact actuator for super clean room or ultra high vacuum chamber, but also precise positioning actuator making good use of the functions of a stepping motor.

This paper describes the principle and the structure of MS-type stepping motor and also introduces the structure and the performance of two types of actuators using the developed MS-type stepping motor. One of them is the super clean servo actuator, and the other is the actuator for ultra high vacua with the function of both rotary and thrust positioning in one body.

## 2. MS-type Stepping Motor Unit

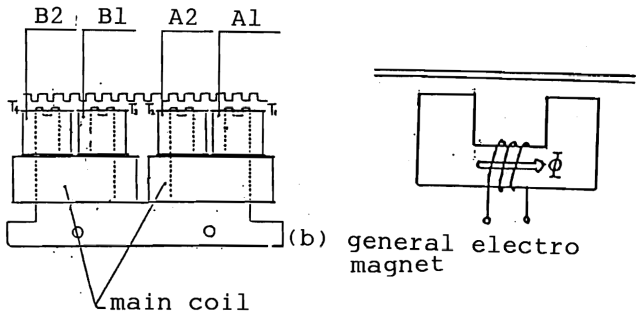
### 2.1 Structure of MS-type Stepping Motor Unit

Fig.1 (a) shows the structure of the MS-type stepping motor unit. The MS-type stepping motor unit is composed of the motor core and six coils that are wound around the motor core. The motor core is made from laminated silicon steel. Two larger coils(Main coils) are connected in series and produce magnetic flux (Main magnetic flux). Coil A1 and coil A2 are connected in series, but wound in opposite directions so generating opposing magnetmotive forces. The same applies for coils B1 and B2.

The MS-type stepping motor unit has four toothed poles T1,T2,T3,T4. The rack has the same teeth as those of the poles. Let one pitch of the rack be expressed as 2 pi rad., then the phase relationship between the toothed poles may be expressed as;(when the teeth of the toothed pole T1 are in phase with those of the rack) T1 0 rad.; T2 pi rad.; T3 pi/2 rad.; T4 -pi/2 rad..

### 2.2 Magnetic Suspension Control

Fig.2 shows the equivalent circuit of the MS-type stepping motor unit. 'P1,P2,P3,P4' symbolize the permeance values of the toothed poles T1,T2,T3,T4, and Um symbolizes the magnetomotive force of the Main coils. The Magnetic reluctance and magnetic hysterisis of the motor core were assumed to be negligible. The magnetmotive forces of coils A1,A2,B1,B2 are not indicated in this figure.




(a) MS-type stepping motor

Fig.1 Structure of the MS-type stepping motor uinit

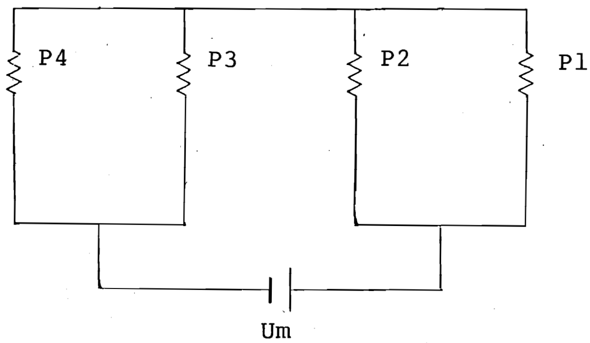
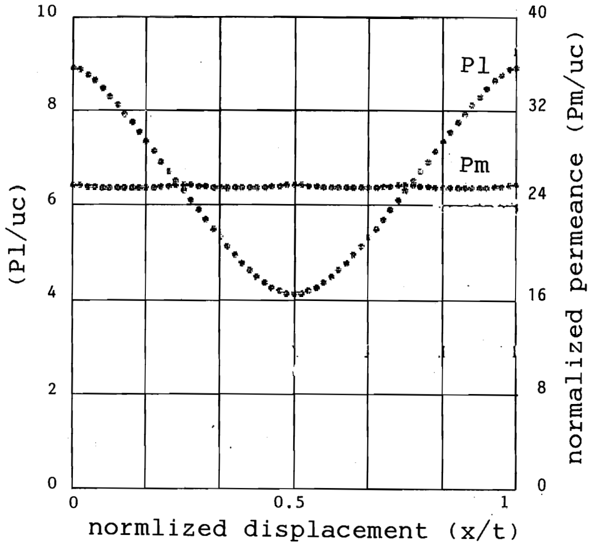



Fig.2 Equivalence circuit of the MS-type stepping motor unit

By using the assumed flux pattern method, permeance P1,P2,P3,P4 of toothed poles T1,T2,T3,T4 are given as functions of tooth width, valley width, gap length, x(the x axis was defined as the direction of propulsion). Due to the toothed pole structure of the motor, permeance P1,P2,P3,P4 fluctuates as the motor moves in the x direction. Fig.3 shows the fluctuation of permeance P1. However, total permeance is more or less constant and insensitive to change of x as shown in Fig.3. This is due to the phase relations of the toothed poles explained in chapter 3.1. The total permeance Pm is calculated using the following equation;

$$Pm = \frac{(P1+P2)*(P3+P4)}{P1+P2+P3+P4}$$

It should be noted that in spite of the toothed pole structure of the motor, the MS-type stepping motor shown in Fig.1.a is equivalent to the general electromagnet shown in Fig.1.b. So a magnetic suspension control circuit, independant of x, may achieve stable suspension.




c; thickness of the core
t; pitch of the teeth

Fig.3 Permeance P1 and Pm

## 2.3 Propulsion Method and Position Control

In the propulsion method of conventional stepping motors the magnetmotive force of coils A1,A2,B1,B2 is changed in a step form as shown in Fig.4. But we made use of another propulsion method, called 'micro step' drive, where the magnetmotive forces of coils A1,A2,B1,B2 take a sinusoidal form. This method was used because acute changes in the step form of Ua and Ub seemed to disturb stable suspension. Moreover, the 'micro step' drive provides smoother motion of the rotor and higher positioning resolution than the conventional method. It has been proved, by simulation and experiment(1),that suspension control and position control scarcely influence each other.

## 3. Developing Super Clean Servo Actuator

As stated abave,the MS-type stepping motor has the function of positioning without a position detector. However, step out or ripple-full motion due to the resonance that is a characteristic of the stepping motor are apt to occur using open loop control. In the field of micro circuitry production, smooth motion (without speed ripple) is needed in order to provide a uniform chemical reaction on the surface of silicon wafers. Also, an

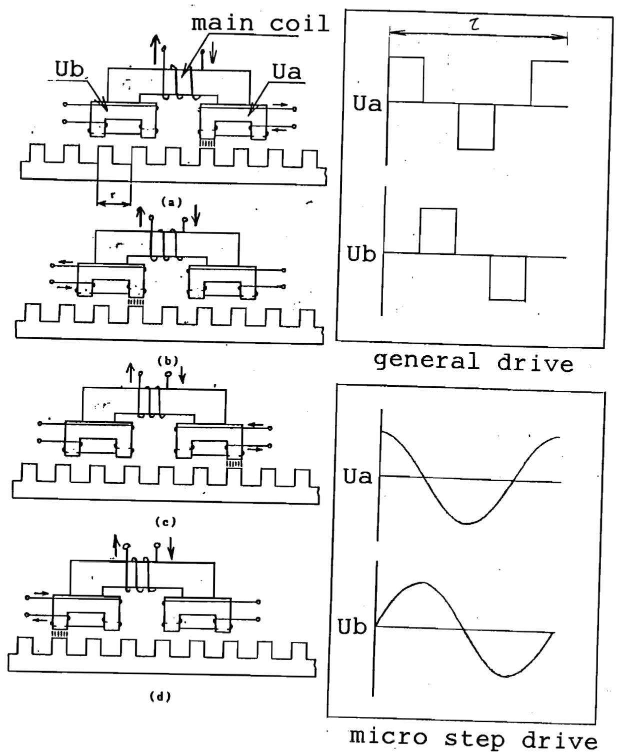



Fig.4 Propulsion method

actuator which has the ability to control speed, torque and position precisely is needed for industrial robots working in the vacuum chambers and the super clean rooms. Therefore, we have developed a servo actuator for super clean rooms by building in a position detector.

In this chapter, the structure and the principle of the built-in position detector are explained, and the developed super clean actuator and its performance are shown.

### 3.1 Built in Position Detector

The built-in position detector is a sort of brushless multi polar resolver. Fig.5 shows the structure of the built-in position detector. This position detector is part of both the rotor and stator.

The stator has many poles. The coils that are wound around the poles are connected in series. On the pole face and the rotor, the teeth are the same as those of a stepping motor. The gap length between a certain pole of the stator and the magnetically suspended rotor is not always constant. In order to cancel the influence of fluctation of the gap length, the poles are placed point symmetrically. By measuring the current of the coils excited by an A.C. constant voltage power supply, a signal, which is modulated by the variable permeance between the teeth of the rotor and stator can be obtained. Fig.6 (a) shows the carrier signal. Fig.6 (b) shows the modulated signal. Transforming this signal using a resolver to digital converter, we can get a resolution of 1,536,600 pulse per revolution.

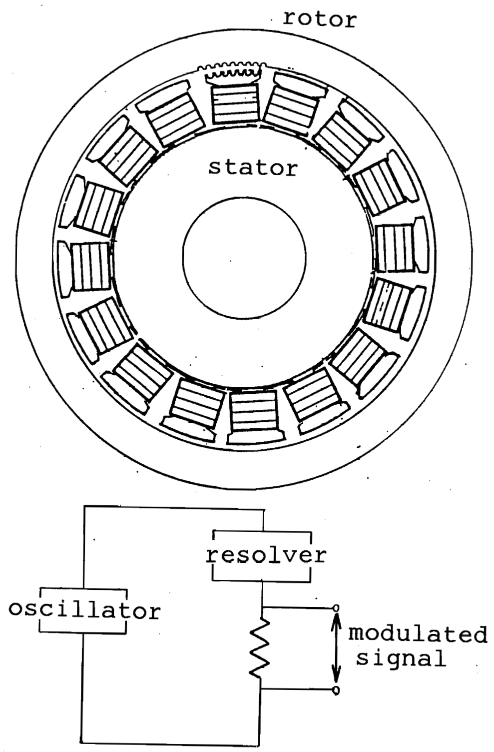



Fig.5 Structure of the built-in position detector(resolver)

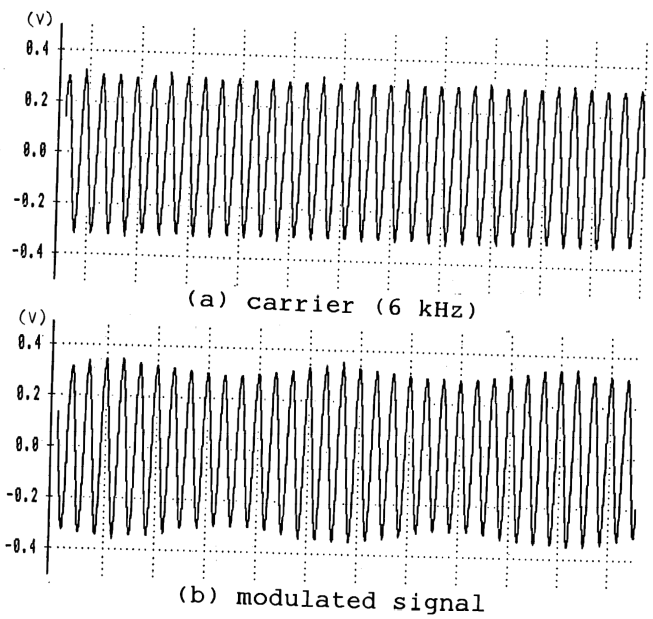



Fig.6 Signal of the resolver

A resolver has the following merits;

(1) A resolver can operate over a very wide temperature range.

(2) Because of its simple structure, a resolver can endure vibration and shocks

(3) Transmission over distance is possible.

## 3.2 Super Clean Servo Actuator

Phot.1 is the super clean servo actuator. This actuator is an outer rotor type, and it is possible to position the object attached to the rotor directly. Fig.7 shows the section view of the super clean servo actuator. Fig.8 shows MS-type stepping motor unit of this actuator. Four MS-type stepping motor units that are set at regular intervals carry out both the posture control and the position control. Also four electro magnets are set at regular intervals placed face down. They don't have teeth. The gap sensors to detect the motion of the rotor are eddy current-type.

The proportional-differential-feedback control circuit(P.D.control circuit) of Fig.9 is a circuit commonly used for magnetic suspension of conventional magnetic bearings. The magnetic suspension control is done using this P.D. control circuit at each degree of freedom according to the outputs of gap sensors. Four MS-type stepping motor units make up a radial magnetic bearing by their controlled attractive forces. Four electro magnets make up a thrust magnetic bearing.

Fig.10 shows the diagram of the position control circuit. The value of position and velocity of the rotor is given from the resolver to digital-convertor(R.D.C). The position control circuit consists of the position-feedback-loop and the velocity-feed-back-loop. The integrators are not included in this position control circuit.

Phot.1 Super clean servo actuator

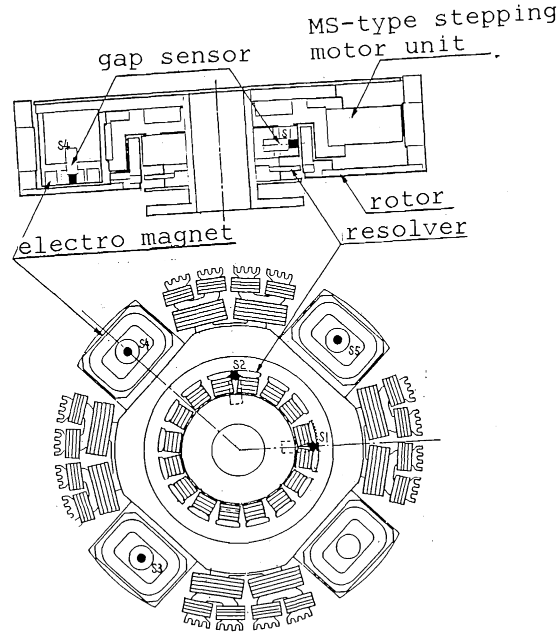



Fig.7 Structure of the super clean servo actuator

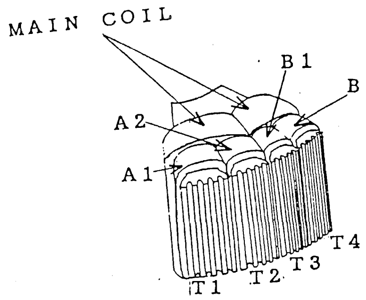
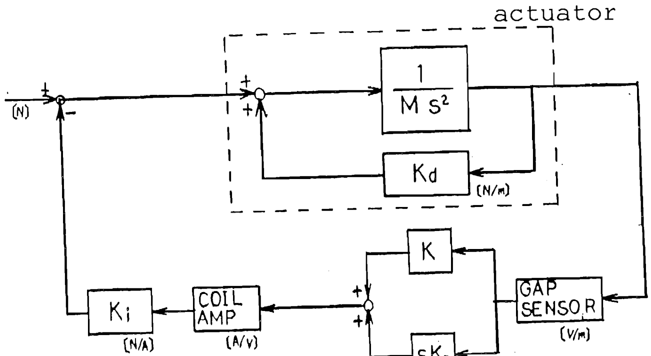



Fig.8 MS-type stepping motor unit of the super clean servo actuator




K ; proportional gain
KD; differential gain
Kd, Ki; coefficient of the magnet

Fig.9 Diagram of the P.D. controller

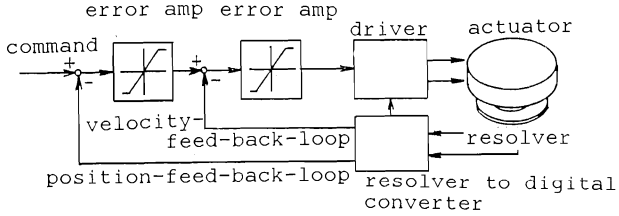



Fig.10 Diagram of the position controller

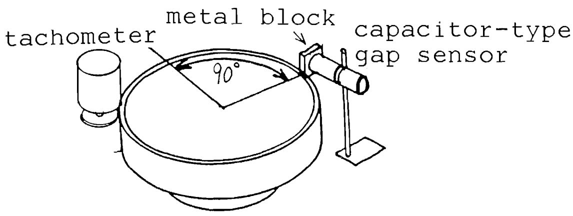



Fig.12 Experiment of high speed positioning

3.4 Performance of Super Clean Servo Actuator

Fig.11 shows the measured value of the velocity and the position of the rotor during high speed positioning(a rotation of 90 degrees in a counter-clockwise direction and 90 degrees clockwise in one second). The velocity was measured using a tachometer, and the position was measured by detecting the gap between the metal block attached to the rotor and a capacitor-type gap sensor. Fig.12 is the illustration of the actuator and the instruments set for this experiment. In Fig.11, the horizontal axis is time and vertical axis is position and velocity of the rotor. In this experiment, the velocity data which we inputted into the cntrol circuit was 0.52 [r.p.s], and the acceleration data was 2.6 [r.p.s2]. From Fig.11, it can be seen that the rotor followed, precisely, the command which we inputted into the control circuit.

Fig.13 shows the measured rotor position in steps using the minimum step size. (one step is 8.44[arc-sec]). The rotor position is detected by measuring the gap length between the metal block attached to the rotor and the capacitor-type gap sensor. Horizon tal axis is time, vertical axis is the rotated angle of rotor. However, even though the integrator was not included in the control circuit, the actuator stepped through the same value which was inputted the control circuit. The reason why steady-state error and lost motion are not found in Fig.13 seems to be that mechanical friction doesn't exist between the rotor and the stator.

Fig.14 is the measured velocity ripple of the actuator. This chart is the velocity ripple from the tachometer for the velocity commands 0.4, 0.9, 1.4, 1.9[r.p.s].

Table 1 shows the specification of the super clean servo actuator.

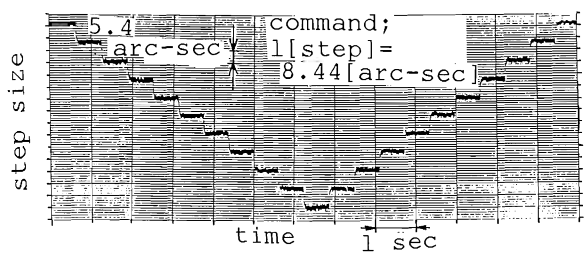



Fig.13 Minimum step size

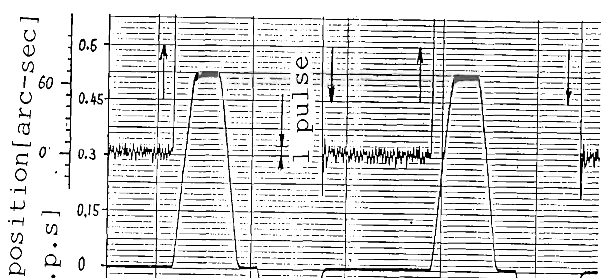



Fig.11 High speed positioning

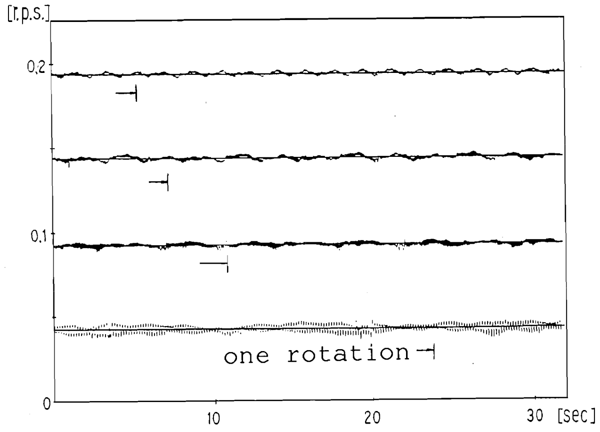



Fig.14 Velocity ripple

| | | |
|---|---|---|
| Levitation Control | Rotor Mass | 8 kg |
| | Axial Stiffness | 4 N/μ m |
| | Gap Fluctuation | 10 μ m |
| Position Control | Max. Speed | 3 r.p.s |
| | Max. Torque | 1 kgf m |
| | repeatability | ± 1.8 arc-sec |

Table 1 Specification of the super clean actuator

## 4. Development of an Actuator for Ultra High Vacua

It is possible to build a variety of contactless actuators by interconnecting MS-type motor units.

Because those actuators don't need any lubrication, it seems logical to adapt these actuators for vacuum environments in which it is impossible to use general lubrication. However, these actuators consist of materials which have high exhalation rates of gasses(for example coil wire and resin). So, it is difficult to use these actuators in vacuum chambers. It is nessecary to take measures to cope with this situation. Thus we have decided to seal the stator of the actuator with a sheet of non-magnetic metal. By this countermeasure, materials which exhale a lot of gas are isolated from the vacuum environment.

But there is a problem to solve in this countermeasure too. The problem is that an eddy current-type gap sensor can't detect the position of rotor beyond the sheet metal because of the eddy currents produced in it.Thus we have decided to develop a gap sensor that can detect the position of the rotor beyond the sheet metal.

### 4.1 Gap Sensor

The gap sensor which have been developed is a sort of inductance-type gap sensor.

An inductance-type gap sensor finds the position of an object by detecting the change of the permeance between the object and the gap sensor. And it is possible to detect the position of the object without using a high frequency carrier as with the eddy current-type. So, an inductance-type gap sensor candetect the position of the rotor beyond the sheet metal by tuning the frequency of carrier so that the influence of eddy currents is small.

Fig.15 shows the basic idea of the gap sensor which has been developed. This gap sensor is composed of a sensor rotor and sensor stator. Fig.15 shows the outer rotor-type. In Fig.15, the shaded area is the rotor. In this figure, there are two rotors, but really, one rotor is linked to another.

The sensor stator consists of a pair of poles which are placed in line with the poles facing outwards. The pole is made from laminated silicon steel and a coil which is wound around the pole core. Two coils(Cl,C2) are connected in series, and excited by V*sin wt and -V*sin wt(where w is frequency of the carrier). Then, the amplitude of a central point between Cl and C2 changes according to the position of the sensor rotor. When gap gl is equal to gap g2, the voltage is zero [v]. Therfore we can detect the position of the sensor rotor by measuring the voltage of the central point between Cl and C2.

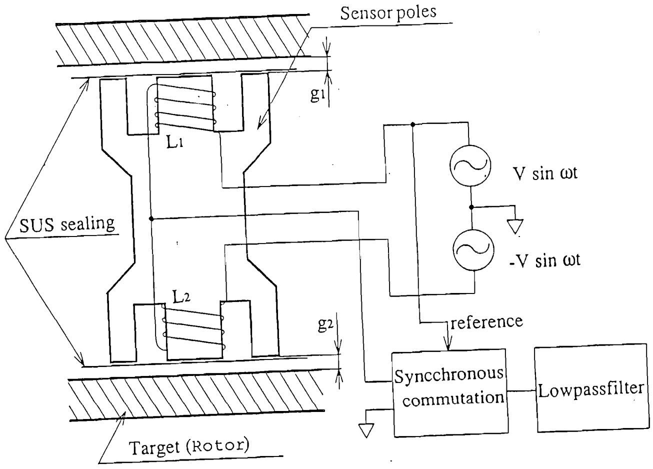



Fig.15 Basic idea of the developed gap sensor

Fig.16 shows the frequency response of developed gap sensor. From fig.16, it can be seen that the gap sensor was able to detect the vibration of 10kHz of rotor beyond the sheet metal, and this gap sensor has enough performance to be used for the magnetic levitation control.

This gap sensor has the following merits

1. It's possible to detect the position of an object beyond the sheet non-magnetic metal.
2. It's hard to be influenced by changes of dimension (caused by fluctuations in temperature), because of the way of detecting the position of an object from the difference between inductance L1 and inductance L2.
3. Because its structure is simple, this gap sensor can endure vibration or shock.

4. This gap sensor can operate over a wide range of temperatures.

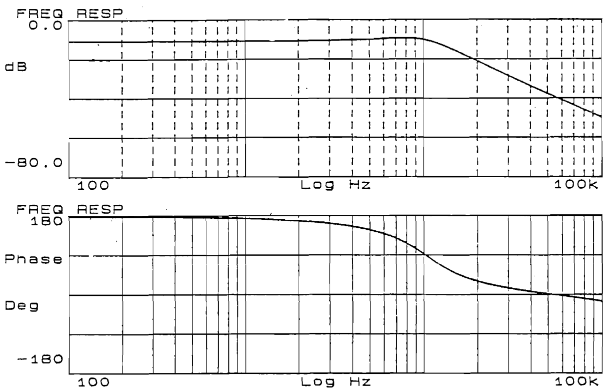



Fig.16 Frequency response of the developed gap sensor

4.2 Actuator for Ultra High Vacua

Phot.2 is the actuator for ultra high vacua which has been developed. The stator is sealed by the sheet stainless steel(which is non-magnetic). The sheet stainless steel is welded to the stator using the electron beam welding. And a metal seal flange which is made of stainless steel is attached to the stator. With this flange, the inside of the vacuum chamber is isolated from the atmosphere. On one side, the rotor is made of magnetic iron and alminium. The magnetic iron is plated with nickel. Therfore, there are not any materials which exhale gas.

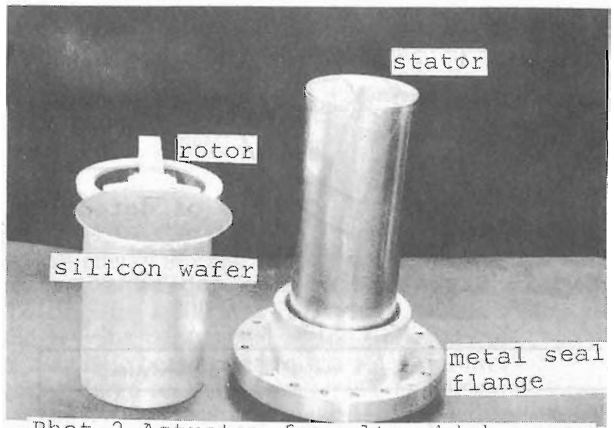
This actuator has been built with a view to displacing a silicon wafer in a vacuum environment. For this, we have made this actuator to have the function of two axial positionings. One of them is rotational positioning, and the other is linear positioning.(up & down motion)

Fig.17 shows the section view of this actuator. The use of both a linear unit and a rotary unit enables this actuator to do both the rotational positioning and the linear positioning without mechanical contact at any one point. Fig.18 shows the linear unit and the rotary unit.

Fig.19 shows the structure of the gap sensor. This gap sensor can detect the position of the rotor in two axes at once. Two of these gap sensors are built into this actuator. Therefore, we can detect four degrees of freedum of the rotor.

A radial magnetic bearing is made from the controlled attractive forces of eight linear units. And at once, by the propulsive forces of these eight linear units, the linear positioning is done.

The position control of rotary and linear motion is the micro step driving, explained in chapter 2.3. Table 1 shows the specification of this actuator.




Phot.2 Actuator for ultra high vacua

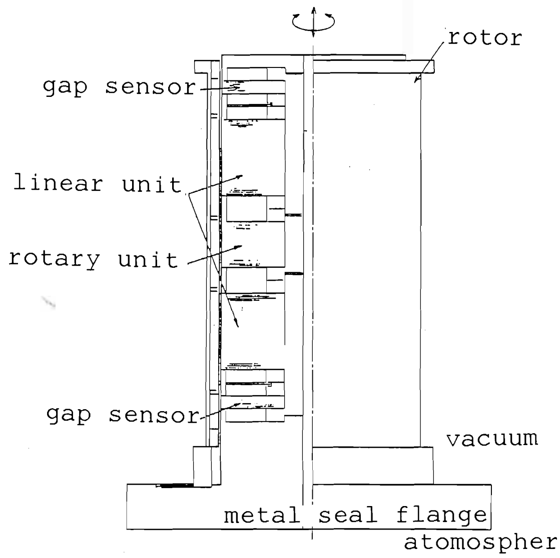



Fig.17 Section view of the actuator for ultra high vacua

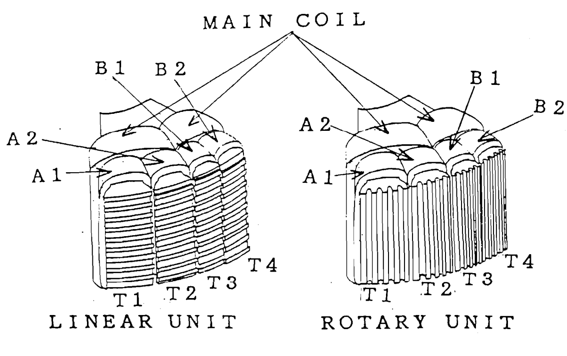



Fig.18 MS-type stepping motor units

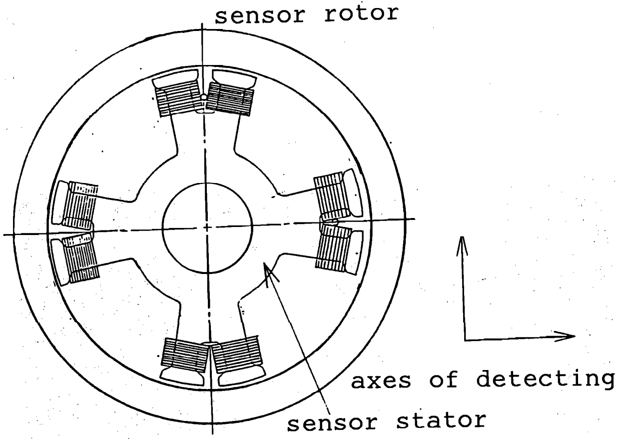



Fig.19 Structure of the gap sensor.

| | Up & Down | Revolution |
|---|---|---|
| Repeatability | ±5 μ | ±10 sec |
| Max.Propulsive Force | 4.5 kgf | 5 kgf·cm |
| Positioning Resolution | 2.9 μm/pulse | 10.5 sec/pulse |
| Stroke (up & down) | 10mm | |
| Radial Stiffness | 2.0N/μm | |
| Rotor Weight | 2.7kg | |

Table 2 **Specificasion of Cylindrical Positioning Actuator for Ultra High Vacua**

## 5.Conclusion

By using the MS-type stepping motor which we are currentry developing, we have built the super clean servo actuator and an actuator for ultra high vacua. Also, in order to build the super clean servo actuator, we have developed the position detector which can cancel the influence of fluctuation of the gap length between a rotor and a stator. And, in order to build an actuator for ultra high vacua, we have develpoed the gap sensor which can detect the motion of rotor beyond the sheet metal.

## Reference

1. Higuchi, T.; Kawakatu, H.: Super-clean actuator for machines and robots.Proc of IECON'87 (1987) 303-310.