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# MAGNETICALLY SUSPENDED STEPPING MOTORS FOR CLEAN ROOM AND VACUUM ENVIRONMENTS

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## SUMMARY

To answer the growing needs for super-clean or contactfree actuators for uses in clean room, vacuum chamber and space, innovated actuators which have the functions of stepping motors and magnetic bearings in one body have been developed. The rotor of the magnetically suspended stepping motor is suspended exactly like a magnetic bearing and rotated and positioned exactly like a stepping motor. The important trait of the developed motor is that it is not a simple mixture or combination of a stepping motor and a conventional magnetic bearing, but an amalgam of a stepping motor and a magnetic bearing. Owing to optimal design and feed-back control, a toothed stator and rotor are all that are needed structurewise for stable suspension. More than ten types of motors such as linear type, high accurate rotary type, two-dimensional type and high vacuum type have been built and tested. This paper describes the structure and design of these motors and their performance for such applications as precise positioning rotary table, linear conveyor system and θ-Z positioner for clean room and high vacuum use.

## INTRODUCTION

The need for a super-clean environment is increasing in such areas as semiconductor processing, biotechnology experiments, in vacuo processing etc. Also, there is a need for an actuator that can operate without maintenance in these environments. However, conventional actuators are not always ideal from the view point of cleanliness. They are known to generate dust and oil vapor, and thus lower the yield rate and reliability of manufacturing processes and experiments. Types of contaminants and their sources are as follows. 1)oil vapor from lubricated parts (e.g. ball-bearings, linear guides, gears), 2)metal and oxide "flakes" from rubbing surface of metal-metal contact (e.g. ball-bearings), 3)carbon dust from brushes of DC motor, 4)evaporation of paint and insulation coating (e.g. coils), 5)gas evaporation from surfaces in vacuum. From the above examples, it can be concluded that an ideal actuator from the view point of cleanliness is the type where positioning, actuation, support of a moving object are carried out without mechanical contact.

Various contactless positioning tables, vehicles etc intended for use in clean-room have already been developed at research institutes, universities and companies. Such examples are: 1) linear induction motor and air bearing, 2) linear induction motor and magnetic levitation, 3) linear DC motor and air bearing, 4) rotary induction motor and magnetic bearing.

The above machines are a combination of a contactless (brushless) propelling/positioning motor and a contactless guiding/supporting mechanism. For use in vacuum and space, of course, an air bearing can not operate. And, the co-existence of magnetic bearing and motor tends to complicate and enlarge the whole structure. Thus, development of a totally new motor having the function of contactless motor and magnetic bearing/levitation at once was expected to enable the design of more compact and light machines which are especially demanded in vacuum and space use.

The research group led by the author has succeeded in developing such a motor by magnetically suspending a stepping motor rotor. The magnetically suspended stepping motor has the propelling and positioning abilities of an ordinary stepping motor and the contactless supporting function of a magnetic bearing at the same time in one construction. Owing to the characteristic toothed pole structure of the motor, its design and driving conditions were optimized to minimize the possible fluctuation of the attractive force acting between the stator and rotor. From experiments, gap fluctuation amplitude has been confirmed to be no greater than 1% of preset gap length.

Since the first prototype appeared in 1985, more than ten kinds of magnetically suspended stepping motors have been built. In this paper, the structure and design of the magnetically suspended stepping motor are described. And some actual examples of the developed motors are introduced about their construction, control method, and performance.

## IDEA AND STRUCTURE OF THE MAGNETICALLY SUSPENDED STEPPING MOTOR[1,2]

The basic idea of the magnetically suspended stepping motor (MS-type stepping motor) will be explained by comparing its structure and operating principles with conventional linear stepping motors and magnetic bearings. Figure 1 is a diagram of conventional Permanent Magnet (PM)-type linear stepping motor. The mover in the figure consists of a laminated silicon steel core, permanent magnets and coils. Propulsive force is gained by superposition of magnetic flux generated by the coils onto the magnetic flux of the permanent magnet. A strong attractive force, approximately ten times the propulsive force acts between the mover and the stator. Ball-bearings, which are the main source of dust and oil vapor are used to maintain a constant gap.

Figure 2 illustrates the idea of the MS-type stepping motor element. Its structure is quite similar to that of the PM-type stepping motor, but the permanent-magnets are replaced by electromagnets (Main Coils). It was expected that by controlling the magnetomotive force of the Main Coil according to the gap sensor signal, the gap between the mover and the stator will be controlled constant like an active magnetic bearing in spite of the toothed pole structure essential to a stepping motor. Thus, it can be said that the MS type stepping motor is an amalgam of a stepping motor and a magnetic bearing.

Figure 3 shows the structure of the MS-type stepping motor element. The mover is made of laminated silicon steel. Six coils are wound around it. Two larger coils (Main Coils) are connected in series and produce magnetic flux $\Phi m$. Coils a1 and a2 are connected in series and when one coil produces a magnetic flux in the same direction as Φm the other produces a magnetic flux counter-direction to Φm. The same applies for coils b1 and b2. The rotor has four toothed poles T1, T2, T3, T4. Let one pitch of stator be expressed as 2pi rad., then the phase relation of the toothed poles may be expressed as T1 0 rad. (i.e. teeth of toothed pole T1 in phase with that of stator); T2 pi rad. ; T3 -pi/2 rad. ; T4 pi/2 rad. As indicated in the figure, the X axis is defined as the direction of propulsion, and H as gap length. Figure 4 shows the equivalent circuit of the MS-type stepping motor element. 'U' stands for the magnetomotive force of the coils; 'R' stands for the reluctance values of the toothed poles. Magnetic reluctance and magnetic hysteresis of the iron core were assumed to be negligible.

## ANALYTICAL PROOF OF STABLE SUSPENSION BY A STEPPING MOTOR

From the equivalent circuit of the SM-type stepping motor element (Figure 4), the magnetic co-energy may be expressed as a function with the following parameters as the following equation.

W =function (Um, Ua, Ub, p1, p2, p3, p4, X, tooth width, valley width, H)
Where W: magnetic co-energy of the system.
Um, Ua, Ub: magnetomotive force of coils.
p1, p2, p3, p4,: permeance of toothed poles T1, T2, T3, T4.
X: longitudinal displacement of rotor.
H: gap length.

Attractive force and propulsive force of the stepping motor element are given as the derivative of the magnetic co-energy by H and X as follows.
Attractive force = dW/dH, Propulsive force = dW/dX

By using the assumed flux pattern method, permeance p1, p2, p3, p4 of toothed poles T1, T2, T3, T4 are given as functions of X, tooth width, valley width, H. Figure 5 is the calculated value of the attractive force using the above equations. The horizontal axis is X/pitch, and the vertical axis normalized attractive force. F1, F2, F3, F4 are attractive force acting on toothed poles T1, T2, T3, T4 respectively. Due to the toothed pole structure of the motor, attractive force acting on each toothed pole fluctuates as the rotor moves in the X direction. Figure 5 shows the fluctuation of F1. However, summation of forces F1 to F4 is more or less constant and insensitive to change of X. This is due to the phase relations of the toothed poles mentioned before. It should be noted that the above calculation proves that an active magnetic suspension control can be achieved by only controlling the magnetomotive force ( that is current) of main coil independent of displacement X and the currents of the coils A and B.

The optimal structure and driving conditions of the motor were estimated. In designing the motor, the "optimal" design was set as such a design that the fluctuation of the attractive force acting between the stator and mover becomes minimum when the mover is driven in the X direction. In other words, parameters that define the shape and size of the toothed poles were chosen so that the attractive force becomes most insensitive to change of X. It was found from calculation that (attractive force fluctuation / average force) becomes minimum when the value of (tooth width / pitch) lies between 0.45 and 0.5.

Driving of the motor can be done in exactly the same manner as 2 phase PM stepping motor by using coil A (A1+A2) and coil B (B1+B2). The driving method commonly called mini-step drive or micro-step drive, where the currents are provided like sinusoidal forms, is preferable to MS stepping motor. Rapid change of the currents of coils A and B may disturb the calm suspension. And micro-drive method is also desirable for precise positioning and smooth movement.

## SUPER CLEAN ROTARY SERVO ACTUATOR[4]

Since the one MS stepping motor unit shown in Figure 3 does not have the function of attitude control in itself, totally contactless suspension of a rigid body requires several MS stepping motor units and electromagnets. Now our research group has made and tested more than 10 types of MS stepping motors applying the MS units. Three typical examples will be described in the following chapters.

In this chapter outer rotor type actuator shown in Figure 6 is explained. Its structure is illustrated in Figure 7. Inner surface of the rotor is toothed like an inner gear. Four MS stepping motor units installed as a stator rotate the rotor exactly like a stepping motor. For the magnetic levitation, in addition to the four MS stepping units, five eddy current type gap sensors and four electromagnets are placed as shown in Figure 7. Four MS stepping motor units and the gap sensors S1 and S2 compose a radial magnetic bearing by controlling the attractive forces of the MS units according to the sensor signals.

In order to keep the axial displacement and attitude of the rotor, the attractive forces of four electromagnets which pull up the rotor against the gravity are controlled by PD control circuit from the signals of sensors S3,S4, and S5.

Since a stepping motor has the ability of self positioning or open-loop drive, a developed actuator does not need any sensor for rotation and keeping an ordered position. However, when more accurate positioning is required, closed loop control with sensor feed back is effective in stepping motors. Moreover, to realize fine velocity control and torque control, sensor feed back is inevitable.

As shown in Figure 7, a resolver is installed in the actuator for precise position control. The resolver has a resolution of 1,536,600 pulses per revolution. Position control is done by using positional digital data and velocity digital data processed from resolver signal as shown in Figure 8 . Very precise positioning with 8.44 arc-sec step motion can be obtained as shown in Figure 9. For the measurement of the rotor position, a capacitor type gap sensor is used to detect the displacement between it and metal plate winged on the rotor. Even though the position controller does not imply integration in feed back loop, no difference is found between corresponding forward and backward steps. Because of no mechanical friction by means of magnetic suspension, steady state error and lost motion can not be observed. The specification of the actuator is listed in Table 1. By the aid of a precise positioning sensor,-an MS type stepping motor can display the ability of a very precise positioning actuator.

## ACTUATOR FOR HIGH VACUUM[4]

One of the most promising applications of magnetic bearings and magnetic levitation is application in vacuum. Since the developed motors do not need any lubricants like magnetic bearings, they are useful in vacuum environments. For the ultra high vacuum, however, careful attention should be paid to gases from the coils and resin of laminated cores of magnetic circuits which contaminate the vacuum environment. In order to prevent the gases in the vacuum environment, a thin non-magnetic metal sheet is used to seal the coils and laminated core in the actuator designed for ultra high vacuum shown in Figure 10.

Its construction is explained in Figure 11. It can rotate and move up and down by installing the linear MS units and rotary MS units to the inner stator shown in Figure 12. As presented in Figure 10 and Figure 11 the stator is completely capsulated and sealed by thin stainless steel. So the gas from coils is completely kept inside the actuator. The rotor, on the other hand, is made of iron and aluminum. On the central part of the inner surface of the rotor cylinder teeth are made so as to control the rotary motion. And on the upper and lower parts of it cylinder circular grooves are machined for up and down motion. To prevent the emission of the gas from iron, the surface of the iron part is masked by nickel.

While by means of the shelter, the gas from the actuator can be eliminated, several problems had to be solved for building up a magnetically suspended actuator. The major hurdle is to get good gap sensors to detect the position and attitude of the rotor for levitation control. Since there is a thin metal shield between the rotor and stator, it is impossible to use optical sensors and an eddy current type gap sensor. An inductance type gap sensor where position of a target is detected by sensing the change of permeance of a magnetic circuit shown in Figure 13 is newly developed. The frequency response of the sensor is up to 10 kHz and good enough for levitation control as a magnetic bearing. One gap sensor magnetic circuit can detect displacements of X and Y. Two sensor magnetic circuits are installed in upper and lower parts of the stator to detect four degrees of freedom of the rotor position and attitude for active magnetic levitation like a magnetic bearing.

As mentioned in the prior chapter, four MS stepping units make up a radial magnetic bearing. It is possible to compose a $\theta$-Z MS actuator by using a radial magnetic bearing with 4 rotary MS units and that with 4 linear MS units. Due to the gravity, moving the rotor upward is much harder than rotating it. So, another radial bearing with 4 linear MS units is added as shown in Figure 11 to produce enough propelling force to move up and hold the rotor.

Both the rotary and up and down motion are controlled independently and synchronously like a 2 degree of freedom robot by open loop and micro step driving method of a stepping motor. The specification of the developed actuator for the use in vacuum is shown in Table 2. It is expected that the developed actuator will be applied as a wafer handling robot in vacuum and clean room.

## VR type MS Stepping Motor Element

As there are two types in stepping motors: Permanent Magnet type and Variable Reluctance type, an MS stepping motor element originated from VR type can also be created. In Figure 14 structure and equivalent circuit of magnetic circuit of the VR type MS unit are shown. Comparing the MS unit based on PM type shown in Figure 3, a VR type MS unit does not need main coils but only four independent coils and amplifiers. However their operating principle is the same. As shown in Figure 15, by controlling the current of each coil so as to produce the same magnetomotive force to each pole gap as in a PM type MS unit, a VR type MS unit also obtains both the functions of attractive force control and positioning control.

## Prototype of Magnetically Suspended Linear Conveyer[3]

The linear unit shown in Figure 14 requires power supply wiring to the moving part. In actual applications, however, there seem to be many cases where the elimination of the wiring to the slider by locating the coils to the stator is preferred. Figure 16 is a schematic diagram showing the basic magnetic circuit of the Stator–Coil–VR type motor. The length of the laminated slider core is chosen so that the operating principles of the Stator–Coil–VR type and the formerly described VR type shown in Figure 14 are the same. How to choose the length is explained as listed below.

(1)In the equivalent circuit of the VR type shown in Figure 14, the resistors and batteries are connected in parallel. This means that the position of the toothed poles (T2 and T3 e.g.) are interchangeable.

(2)Toothed poles of the Stator–Coil type are situated in a cyclic array (i.e. T1–T3–T2–T4–T1–T3–....), therefore, if the slider core forms a closed magnetic circuit equivalently with four toothed poles, the equivalent circuit will be the same as the VR type shown in Figure 14.

(3)The length of the slider core is chosen to satisfy the equation: Length = 4 × (pitch between toothed poles). When this equation is satisfied , as is the case of Figure 16, the equivalent circuits of the Stator–Coil type and the Slider–Coil type are the same even if the slider core exists over five toothed poles.

In order to confirm the idea of the Stator–Coil VR type linear MS stepping motor, a magnetically suspended conveyer is constructed. In Figure 17 a simplified cross sectional diagram is shown. And Figure 18 is a photograph showing the lower stator cores and the slider ( upper stators are removed to show the internal structure). The slider has 4 laminated slider cores on each side. A pair of lower stator cores and a pair of upper stator cores are used to move and keep the longitudinal position and to control the horizontal position, rolling and pitching of the slider. Yawing and lateral motion of the slider are passively held by facing longitudinally grooved plates and permanent magnets.

32 eddy current type gap sensors are situated on the lower touch down surface. Control circuits are designed so that the gap sensor signals and energized magnet coils are switched according to the position of the slider. The slider could be magnetically suspended and propelled smoothly.

## CONCLUSIONS

Magnetic suspension of a rotor or slider of stepping motors is realized by developing an MS stepping motor element which can control the attractive force and the propelling force independently. By using a number of the elements, various kinds of contactless positioning mechanisms have been built and tested to confirm the effectiveness of the theoretical estimation about their design. The developed actuators, having the function of stepping motor and magnetic bearing at once, are expected to be applied as positioning mechanism, conveying system, and direct-drive actuators for robots, in clean room, vacuum chamber,space and hostile environments.

## ACKNOWLEDGMENTS

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3. Higuchi,Toshiro;and Kawakatsu, Hideki:Development of a Magnetically Stepping Motor for Clean-room Transportation and Sample Handling, Proceedings of International Conference of Maglev'89, July 1989, pp.363-368.
4. Higuchi,T.;Horikoshi,A.;and Komori,T.:Development of an Actuator for Clean Rooms and Ultra High Vacua, Proceedings of the Second International Symposium on Magnetic Bearings,July 1990, pp.115-122.

Table 1. Specification of the clean servo actuator.

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

Table 2. Specification of θ-Z actuator for ultra high vacuum.

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

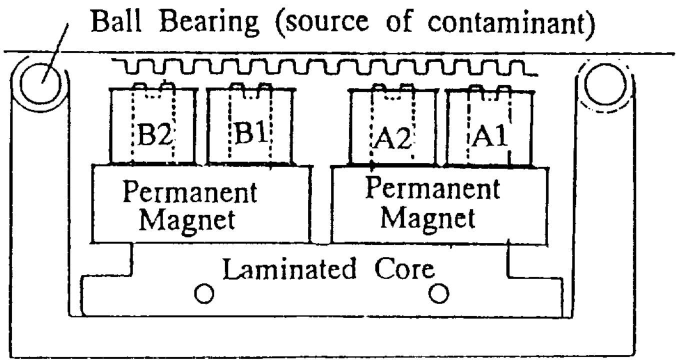


Figure 1. Conventional Permanent Magnet (PM)-type linear stepping motor.

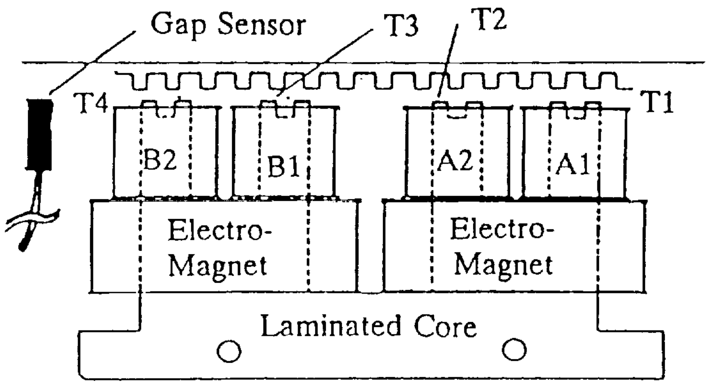


Figure 2. Idea of the MS-type linear stepping motor.

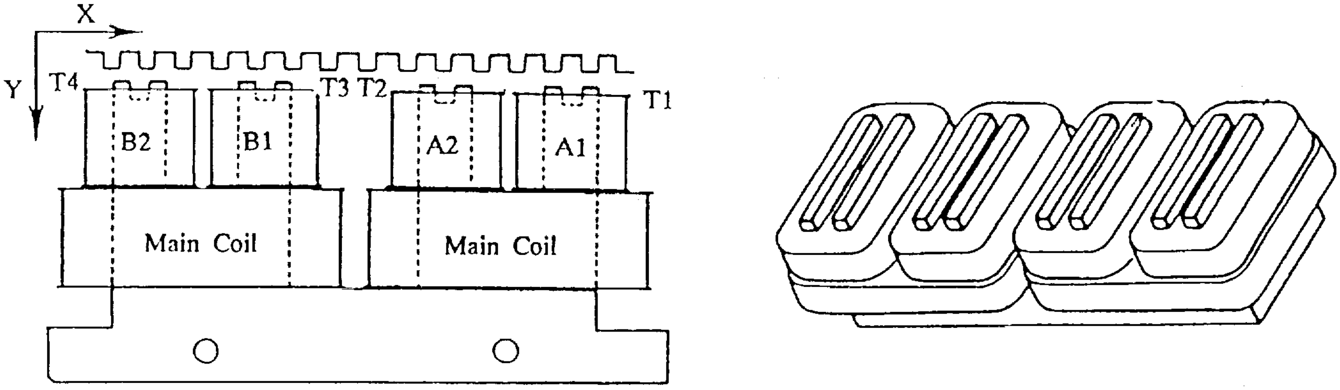


Figure 3. Structure of the MS-type stepping motor element.

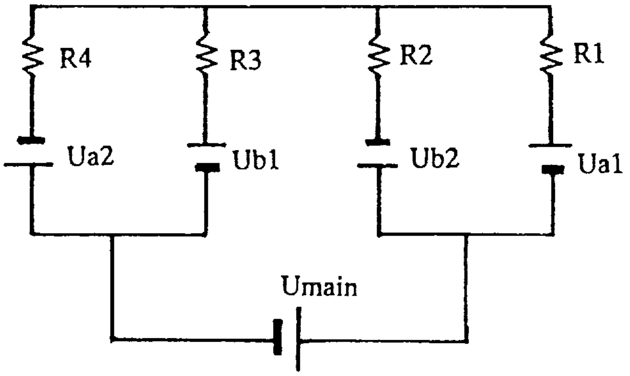


Figure 4. Equivalent circuit of the MS-type stepping motor element.

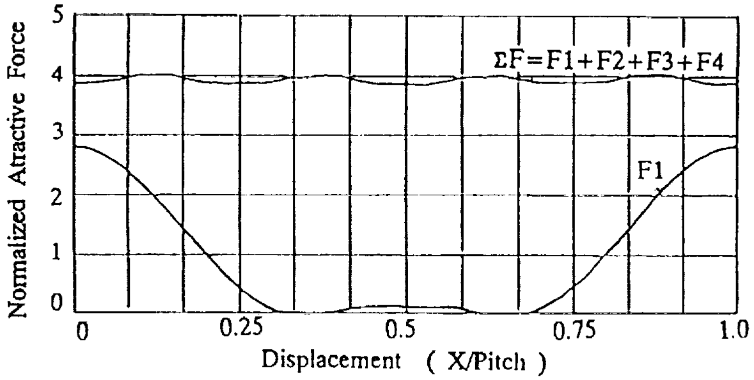


Figure 5. Calculated value of attractive force of a pole and poles.

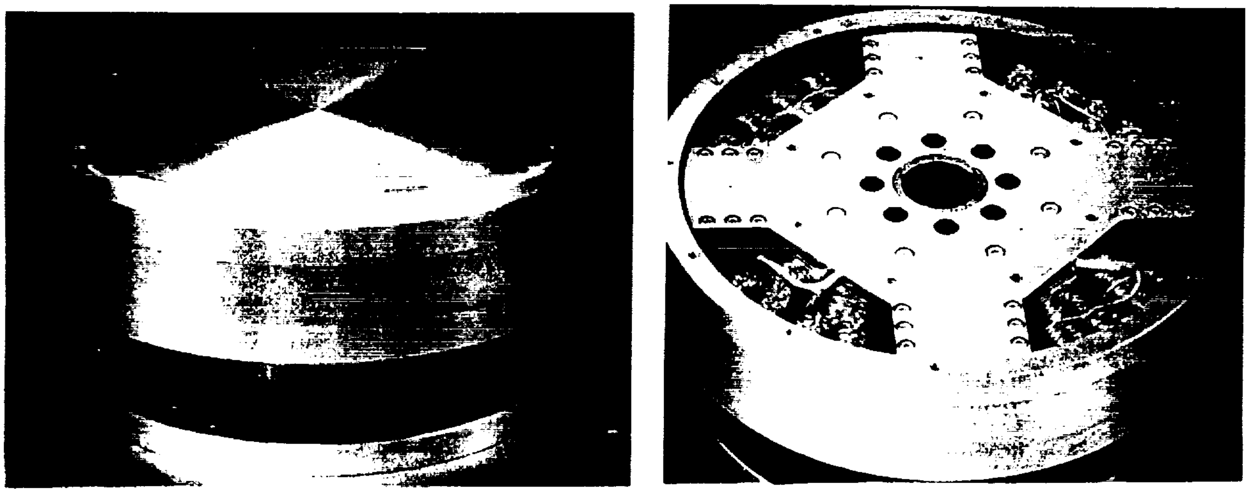


Figure 6. Photos of outer rotor rotary servo actuator.

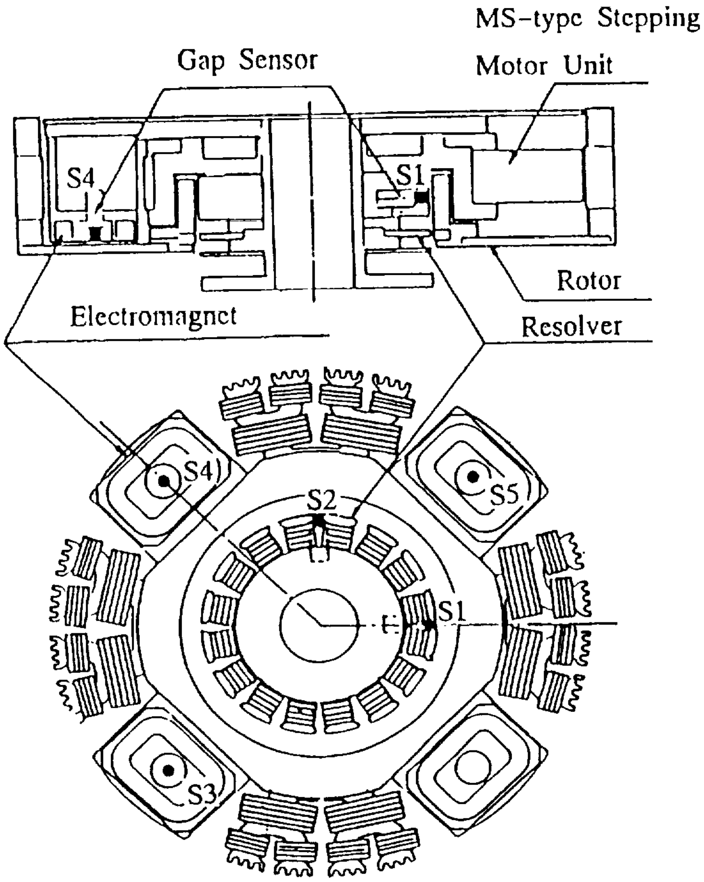


Figure 7. Structure of clean rotary servo actuator.

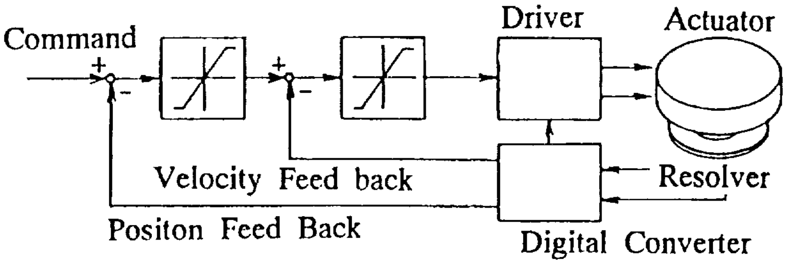


Figure 8. Diagram of position controller for the servo actuator.

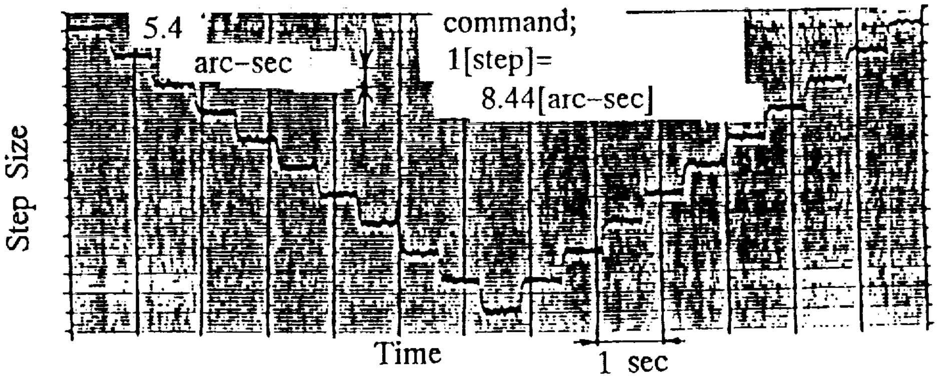


Figure 9. Minimum stepwise movement of forward and backward rotation.

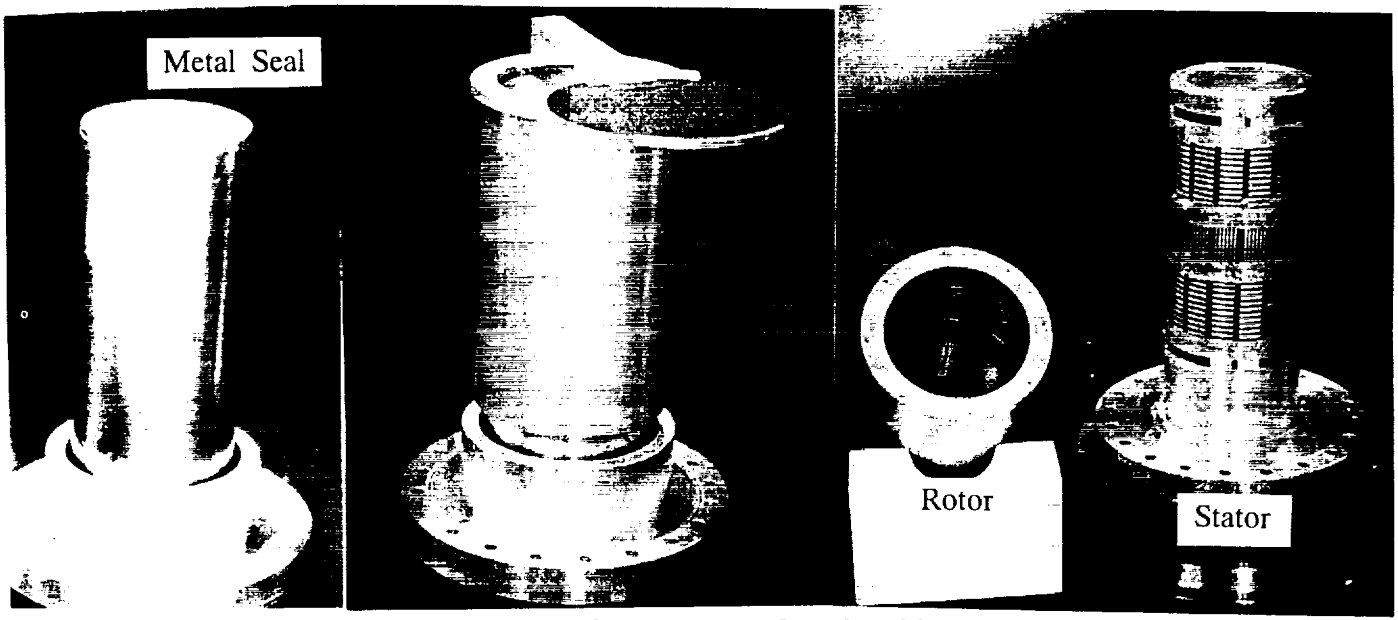


Figure 10. Photos of θ-Z actuator for ultra high vacuum.

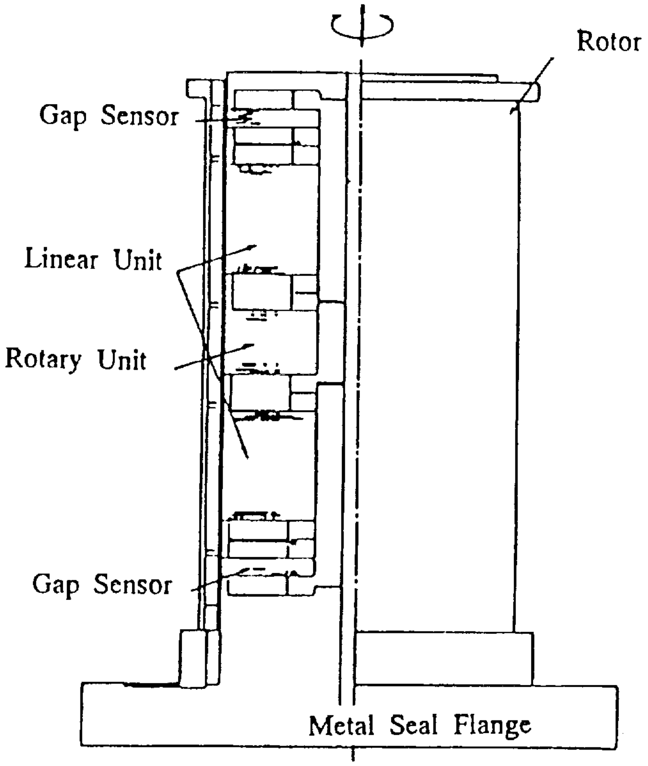


Figure 11. Section view of the actuator for high vacuum.

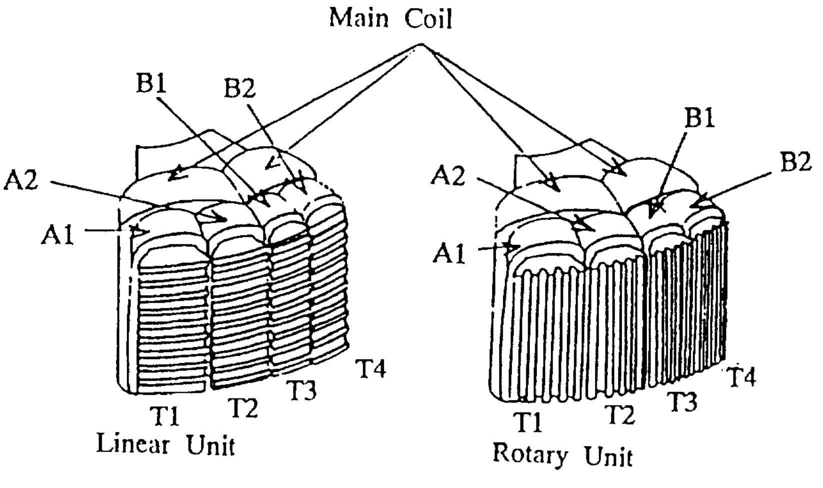


Figure 12. MS-type linear and rotary stepping motor units.

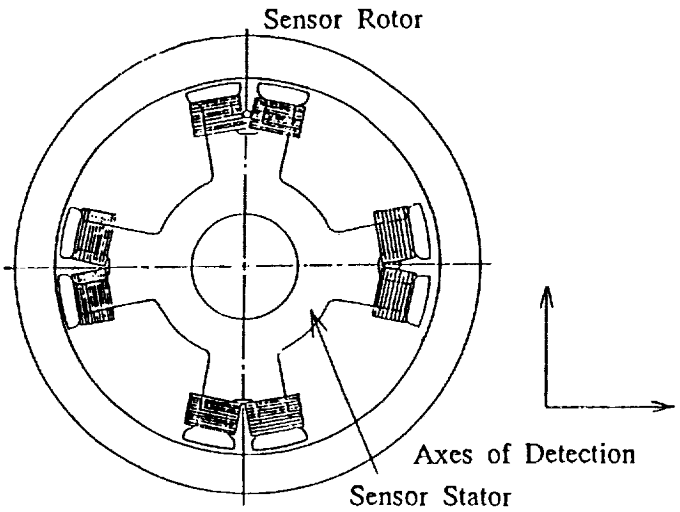


Figure 13. Inductance type gap sensor.

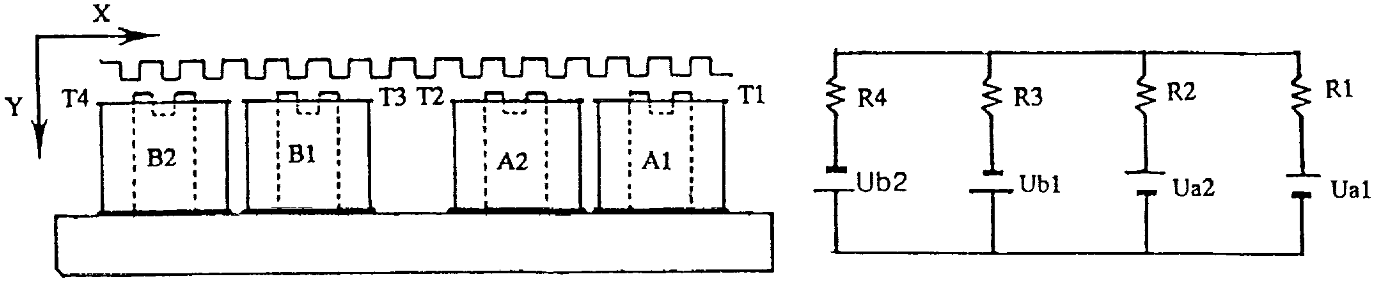
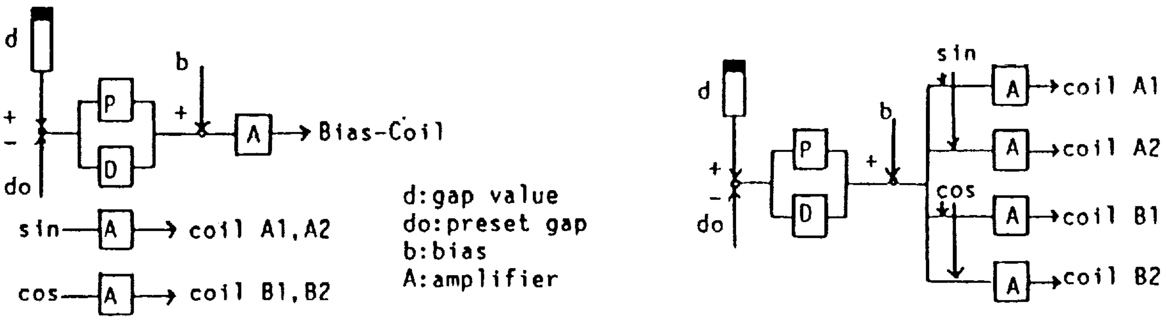


Figure 14. Structure and equivalent circuit of magnetic circuit of the VR type MS unit.



(a) PM type

(b) VR type

Figure 15. Control circuits for PM and VR MS stepping motor elements.

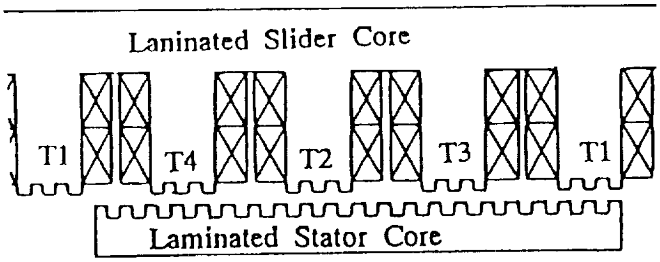


Figure 16. Schematic diagram of Stator-Coil-VR type motor.

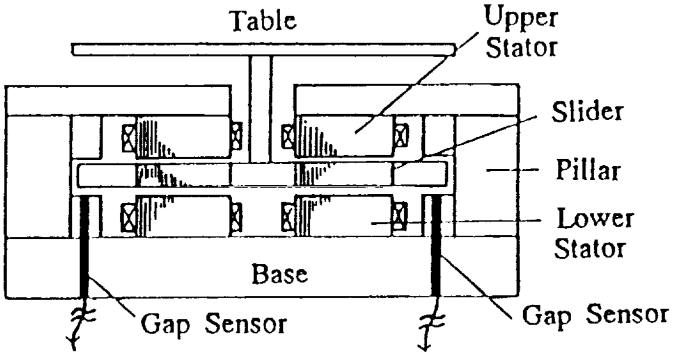


Figure 17. Cross sectional diagram of MS stepping conveyer.

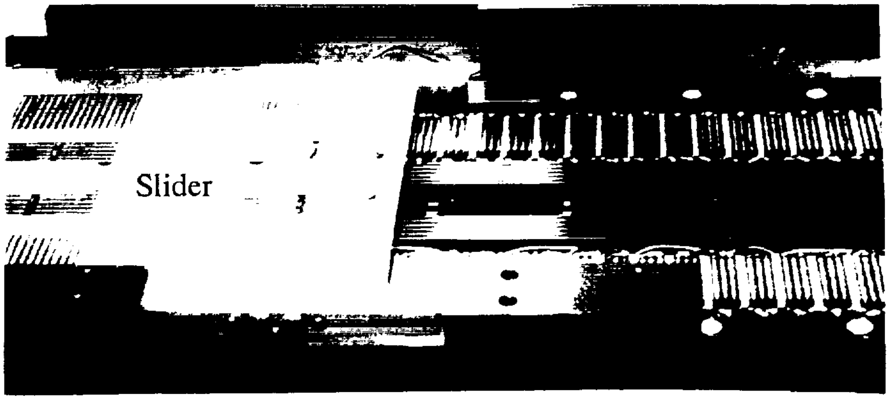


Figure 18. Photograph showing the lower stator cores and the slider.