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Rotational feedthrough using an ultrasonic motor and its performance in ultra high vacuum conditions

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Abstract

Ultrasonic motor is one of the promising actuators that are utilized in ultra-high vacuum (UHV) conditions. The authors have proposed a rotational feedthrough for UHV using a mode-rotational type ultrasonic motor. This rotational feedthrough is distinguished by its arrangement of driving parts. The piezoelectric ceramics and wiring parts were arranged outside the vacuum chamber because they can be source of outgases.

Previously the authors have just proposed this idea and reported on the successful operation in vacuum, although the output torque and duration of operation were insufficient for such applications as positioning tables. In this study, the stator transducer was redesigned for larger output torque and stator–rotor interface materials were modified from combination of metal–ceramic to metal–plastic. As a result, output torque and duration of operation were improved by factors of 4 and 20, respectively; 22 mN m and 27 h. In addition, baking treatment was carried out and an UHV of 3×10^{-7} Pa was achieved.

Keywords: Rotational feedthrough; Ultrasonic motor; Ultra-high vacuum; Vacuum; Extreme condition; Actuator; Mechatronics; Baking

1. Introduction

In general, observation and handling of atomic or nanometer-sized structures are carried out in a high vacuum (HV) or an ultra-high vacuum (UHV) to avoid contamination of gas molecules. Since significance of such low pressure conditions is increasing, high performance mechatronics devices such as a positioning stage are required to support the operator's task. In addition, if these instruments are employed in production systems, these operations will become more complex in the near future.

In atmospheric condition, very sophisticated mechatronics, for example a positioning system with an accuracy of nanometer, is realized. However, when it comes to the operations in vacuum, the situation changes dramatically. For

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example, materials with high evaporating pressure such as liquid lubricant, plastics containing residual solvent or porous ceramic are not suitable for HV systems. Since achievement of UHV requires bake out treatment, UHV compatible mechatronics devices must withstand high temperature, greater than 200°C. Additionally, radiation and disturbance of magnetic field from mechatronics parts is strictly prohibited because control of electron beams is easily disturbed by unexpected emission of magnetic field or existence of magnetic materials. Therefore, electromagnetic motors, which are widely used as mechatronic actuators in atmospheric condition, cannot be utilized without very careful consideration about modification of magnetic field by installing the devices. Electromagnetic motor contains some plastics parts in their magnetic coils hence this type motor can be outgas source and limit the temperature of baking treatment.

On the other hand, ultrasonic motors are promising actuators for operation in vacuum [1,2] since they leak less magnetic field and are composed of less organic materials. Of course electric current to piezoelectric transducer might emit magnetic field, however, it is much weaker than that from electromagnetic motors. In terms of out-gassing and heat-resistance, ultrasonic motors are advantageous because they are not composed of organic materials except insulation of electric wires for power supply. The large torque with low speed property enables the direct drive, which means the operation without the reduction gears. Reduction gears can be outgas sources, hence this advantage is useful as an actuator driven in vacuum.

In the previous study [3], the authors introduced a rotational feedthrough utilizing an ultrasonic motor. This ultrasonic motor had its rotor inside a vacuum chamber and its piezoelectric elements outside. Owing to this arrangement, contaminations from piezoelectric elements and power supplying wires could be avoided. In addition, baking out treatment can be performed without damage of piezoelectric materials and these wirings because they are detachable during its treatment and are attached again to use the motor. With this feedthrough using an ultrasonic motor, operation was succeeded in the vacuum 10^{-6} Pa. However, the duration of operation was very short period of 70 min, and maximum torque in atmospheric condition was as small as 5 mN m. It surmised that these insufficient results were caused by unsuitable stator design and poor friction materials. Moreover, baking treatment was not carried out.

In this study, we tried to obtain larger output torque with redesigning the stator transducer and selecting better friction materials. With this improvement, speed–torque characteristics were measured again in atmospheric condition and in vacuum condition. Baking treatment was applied on a vacuum chamber with this ultrasonic motor installed. Operation time and out-gas measurements were also discussed.

2. Structure of the feedthrough

Fig. 1 is a schematic cross-sectional view of the feedthrough utilizing an ultrasonic motor. All parts except stator–rotor interface materials, the piezoelectric ceramic and electrodes were made of stainless steel. It is well known that adhesive wear between metal parts rubbing to each other in vacuum is rapid. To avoid this phenomenon, in

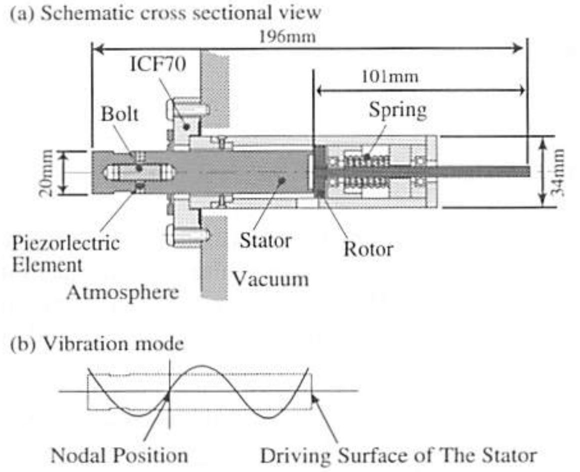

Fig. 1. A structure of a rotational feedthrough using an ultrasonic motor.

this study, rotor and stator surfaces were coated with tungsten carbide and vacuum-compatible adhesive (Torr Seal®), respectively. In the previous study [3], stator surface was made of stainless steel without coating and the rotor was alumina. Since both surface of the rotor and stator were coated with very hard material, the rotor bounced on the stator and they hit each other. As a result, the driving force was not transmitted efficiently. This time, softer vacuum-compatible adhesive made of epoxy resin was selected so as to absorb the stator driving vibration.

To prevent contamination inside vacuum chamber, the feedthrough was designed to have its piezoelectric transducers outside the chamber and its rotor inside. For complete sealing, a stator transducer was welded to a standardized flange of ICF-70, and its flange was rigidly attached to vacuum chamber. Inside the chamber, a rotor was pressed to the end surface of the stator with a spring. The two bending vibration modes were degenerated to excite traveling wave at the driving surface. Fig. 2 shows a structure of the bolted Langevin-type transducer for bending vibration. The bending vibration mode has two-wave length. This kind of operation principle is called as a "mode rotational type".

3. Experiments and results

3.1. Redesign of a stator transducer

In the previous study [3], maximum torque was as small as 5.5 mN m. First reason for this small torque was hard rotor material (alumina) and the second one was insufficiently optimized design of the stator transducer. Ultrasonic motor utilizes the resonance vibration; hence the mechanical energy depends on a quality factor of the stator transducer. For the rotational feedthrough application, the mismatch between nodal positions of vibration mode and a holding position, that corresponding to the flange position, results in a low mechanical quality factor. To increase this factor, the holding position must be optimized.

Ideally, the holding position should be shifted with the same stator transducer, although it is impossible because the stator transducer was welded strongly to the flange. Instead of this method, a short cylindrical block, which fastens the piezoelectric rings, was modified, since this part can be screwed to the stator transducer. Changing the length of this cylindrical block part, total length of the stator transducer can be modified to adjust the resonance conditions resultantly. Various short cylindrical blocks with different length were fabricated and total length of the stator transducer was changed from 92 to 105 mm. Fig. 3 shows the relationship between the conductance of the stator transducer and total length of the stator. From this result, the length of the stator transducer was decided to be 97 mm.

Vibration velocity as a function of frequency is depicted in Fig. 4. In the previous study [3], the holding position was not suitable, so that similar graph has several peaks. On the other hand, the

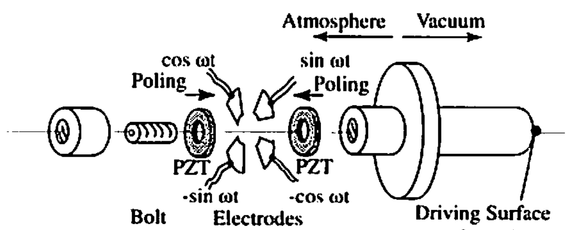

Fig. 2. Langevin type stator transducer for generating a bending vibration.

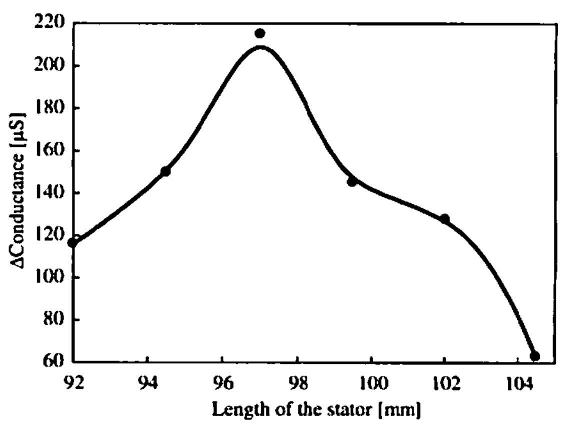

Fig. 3. Relationship between conductance and stator transducer length.

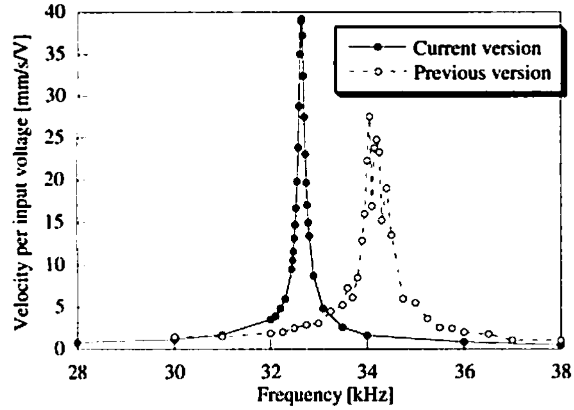

Fig. 4. Vibration velocity as a function of a driving frequency.

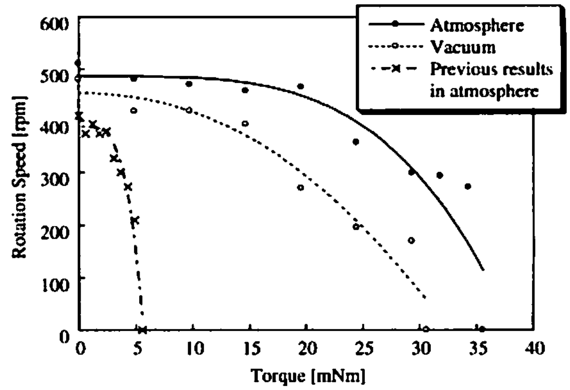

Fig. 5. Load-revolution speed characteristics of the rotational feedthrough in vacuum condition and atmosphere.

present study showed a single peak that means higher mechanical quality has been realized. Measured mechanical quality factor of 290 was reasonable as an ultrasonic motor.

3.2. *Measurement of speed–torque characteristics*

Revolution speed as a function of a mechanical load was measured in atmosphere and vacuum. The results are shown in Fig. 5. Input voltage, driving frequency and pre-load were 800 V_{p-p}, 32.4 kHz and 11.7 N, respectively. Vacuum level was $7(\pm 2) \times 10^{-5}$ Pa. Various weights were pulled up as loads with a thread. The results are shown in Fig. 5 together with the previous one. In vacuum condition, maximum torque and revolution speed were 22 mN m and 265 rpm. These two values in vacuum condition were slightly smaller than those in atmosphere.

Ishii et al. [2] installed an ultrasonic motor into the vacuum chamber; hence UHV conditions might not be realized because of outgas from the motor, although their paper provides advanced insights about the ultrasonic motor driven in vacuum condition. They used various frictional materials, for example CFRP, carbon metal and Si_3N_4, and the ultrasonic motor's characteristics had similar tendency except with CFRP frictional material. They mentioned that the reason of these phenomena came from the frictional condition change, wear and heat generation. Similar to their research, we should try to investigate various frictional materials and measured the frictional coefficient and wear conditions in the next step. Our rotational feedthrough is affected by the holding condition as mentioned above. To realize stiff holding condition, mechanical properties of the vacuum chamber should be taken into account.

3.3. *Baking characteristics*

The target of this feedthrough is operation in the vacuum level of 10^{-8} Pa. Baking treatment is indispensable to achieve such UHV condition. In this study, the rotational feedthrough was attached to the vacuum chamber whose capacity was 35 l. The chamber was evacuated with dual turbo molecule pumps at evacuation rate of 400 and 70 l/s. Under this condition, a baking treatment was carried out for 48 h at 100°C. This baking temperature was limited because the frictional material on the rotor cannot withstand. After 12 h of cooling, gas pressure has reached 3.3×10^{-7} Pa. Then the motor was operated without a load. The revolution speed of the rotational feedthrough and outgas pressure were measured during operation. As shown in Fig. 6, the operation lasted over 24 h. When the rotor was stopped the intermittent noise was generated and very quick increase of gas pressure in the chamber was observed. Before stoppage, abnormal wear and adhere were not occurred. The operation continued much longer than previous version [3] and rotation speed was

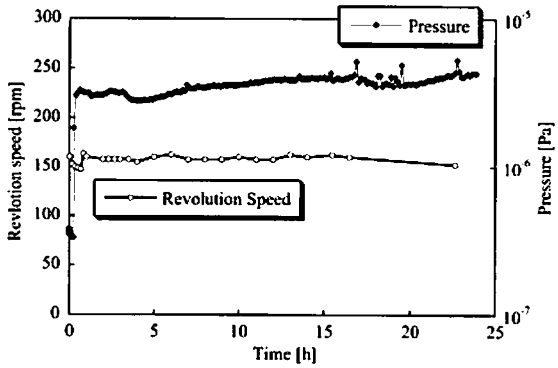

Fig. 6. Vacuum pressure change due to the rotational feedthrough operation.

maintained almost constant. At the starting duration, the gas pressure was increased to 10^{-6} Pa level, although was also almost constant during operation between from 4×10^{-6} to 5×10^{-6} Pa.

According to partial gas pressure measurement during feedthrough operation, pressure of nitrogen gas occupied the largest part of 70% of total pressure. This observation supports that the outgas source was air that had been captured as bubbles in the rotor and been released.

4. Conclusion

In this paper, we reported an improvement of the maximum torque with optimization of the stator design. And the maximum torque and rotation speed were measured in the vacuum level of $7(\pm2)\times10^{-5}$ Pa. Compared to the motor's properties in the atmosphere and the vacuum, those in the vacuum were poorer. The reasons are driving performance was effected by change of friction condition in vacuum. During motor operation, the surface of the ultrasonic motor was rubbed with high pressure condition. By using various kinds of frictional material, this phenomenon should be verified in the next step.

Owing to baking treatment, vacuum level of 10^{-7} Pa was achieved. This vacuum level is one of the superior ones in which an ultrasonic motor was operated. Operation time in this UHV condition, achieved by baking treatment, was over 24 h that was much longer than that in previous study. The gas pressure rose up to order of 10^{-6} Pa during operation. It is considered that revise of the coating material or material of the rotor itself is desirable to achieve superior vacuum and prevent the increase of gas pressure during operation.

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