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Rotational feedthrough using ultrasonic motor for high vacuum condition

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Abstract

A vacuum environment is indispensable for various measurement devices. To make the use of these devices easy, the mechatronics systems for vacuum conditions, for example, a sample stage, should be advanced. In this paper, we propose a rotational feedthrough using an ultrasonic motor. An ultrasonic motor has many advantages, and is suitable for achieving vacuum conditions. However, the piezoelectric material might be a source of outgas and may hinder the baking treatment. Therefore, the piezoelectric part is arranged outside the vacuum chamber. The driving mechanism is a mode-rotation motor. The stator transducer was a bolted Langevin vibrator for generating bending vibration. This motor was successfully operated under a vacuum condition of 2×10^{-6} Pa. The endurance of the motor and the change of the vacuum level were measured and discussed. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Ultrasonic motor; Rotational feedthrough; Vacuum condition

1. Introduction

A vacuum environment is very important for microscopes, for example, an electron microscope, Auger electron spectroscope, and X-ray micro analyzer. In order to improve the performance of such devices, higher vacuum levels are required. Not only microscopes, but even various systems, including nuclear fusion reactors or accelerators cannot be operated without an ultrahigh-vacuum condition.

For the positioning stages of these devices, advanced actuators are necessary. However, it is difficult to introduce mechatronics elements under vacuum conditions, because conventional motors or sensors generate outgas and cannot withstand baking treatment. Furthermore, magnetic noise might have an adverse influence on electron and ion beams. If magnetic actuators are used, then a magnetic shield is required, resulting in a complicated structure.

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On the other hand, ultrasonic motors have many advantages, for example, a large output force with low speed, brakeless mechanism, and simple construction. Lubricating oil is not required, and no magnetic noise is generated. Consequently, an ultrasonic motor is considered to be a suitable actuator in a vacuum environment [1]. However, there are few experimental studies on it. Ishii et al. reported on the investigation of friction materials of an ultrasonic motor driven in a vacuum environment [2]. A hybrid transducer ultrasonic motor was introduced into a vacuum chamber, and the output torque and revolution speed were measured at various vacuum levels. They also discussed the wear of the driving surfaces. Their paper was outstanding and advanced, although the vacuum level was only 10^{-2} Pa.

Our ultimate target vacuum level is less than 10^{-8} Pa. Under ultrahigh vacuum condition, the piezoelectric ceramics may be a source of outgas and may hinder the baking treatment. The vinyl covering of the electric wire would be melted at a low temperature. Therefore, we positioned the piezoelectric part outside the vacuum chamber.

The results of our research are applicable to the sample stage of a microscope equipment. Also at the same time, our rotational feedthrough would be useful to research on suitable driving surface materials of the ultrasonic motor driven in outer space.

2. Construction and principle

To achieve vacuum conditions, outgas from actuators or sensors must be avoided. The baking temperature is up to 200°C, so these mechanical parts must withstand high-temperature conditions.

Almost all ultrasonic motor parts are metallic. However, piezoelectric ceramics and electric wires generate outgas and cannot withstand baking treatment. Therefore, the piezoelectric ceramics were designed to be outside the vacuum chamber, as shown in Fig. 1(a). All parts, except the piezoelectric material and electrodes, are made of stainless steel (SUS304). Alumina was sprayed to rotor surface so as not to adhere to the stator surface in vacuum. The thickness of the alumina layer was about 0.5 mm.The dimensions of the stator transducer were 20 mm in diameter and 95 mm long. The total length including the output shaft was 196 mm. In the housing, the rotor, whose diameter was 27 mm, was pressed to the stator transducer with a spring. The piezoelectric material was hard PZT (N61) manufactured by TOKIN CERAMICS Co. Ltd. It was a flat ring whose dimensions were 20 mm in outer diameter, 12 mm in inner diameter and 2.0 mm thick. The poling direction was aligned along the thickness direction. Four electrodes were sandwiched by two PZT ceramics fastened with a bolt. The poling directions faced each other.

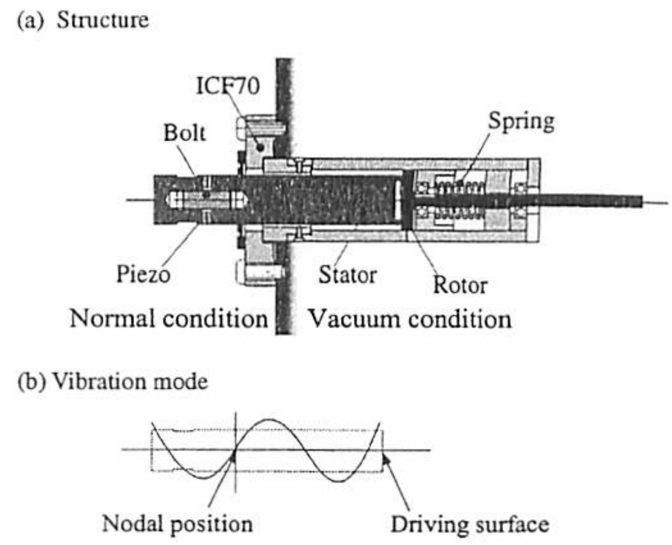

Fig. 1. Construction of rotational feedthrough using an ultrasonic motor (a) and excited vibration mode (b).

The driving principle is similar to the conventional mode-rotation ultrasonic motors [3]. The vibration mode was dual wavelength resonance, as shown in Fig. 1(b). The nodal position of the vibration mode corresponds to a flange (ICF70) position. The flange was welded to the stator transducer; hence, the vacuum environment was perfectly sealed. As shown in Fig. 2, with the driving electrical sources whose phase shift was 90 or −90°, a progressive wave was generated on the end surface of the stator transducer. Vibration energy is transmitted via the stator transducer and utilized to drive a rotor under vacuum conditions.

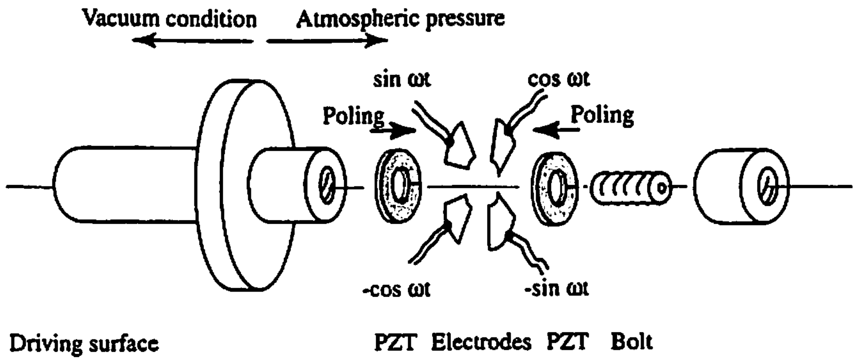

Fig. 2. Bolted Langevin transducer for bending vibration.

Generation of outgas could be avoided since only metals and a small amount of ceramics are present on the driving surface. The stator transducer was a bolted Langevin type, so the piezoelectric ceramic and electrodes could be easily removed during baking treatment.

3. Experiments and results

3.1. Vibration property and force factor

An ultrasonic motor converts electrical energy to mechanical energy by means of the converse piezoelectric effect. A force factor is an important factor that indicates the output force per unit input voltage. This value could be calculated by dividing the motion current and vibration velocity. To measure the force factor, one of the four electrodes was used and the others were opened. The rotor and housing of the ultrasonic motor were removed and the input voltage was maintained at $20\,V_{p\text{-}p}$. The input current was measured as the voltage between a resistor connected in series with the piezoelectric material.

For the measurement of vibration velocity, a laser Doppler velocimeter was utilized. The laser was irradiated on the side surface near the driving surface of the stator transducer. As shown in Fig. 3, the resonance frequency was 34 kHz, which agreed with the results obtained using the impedance analyzer HP4194A. At the resonance frequency, a few vibration modes were degenerated. The resonance curve was distorted and the quality factor could not be measured. The reason for this is a disagreement between the nodal position and holding position, namely, the flange position. The maximum vibration velocity was $22\,mm_{p\text{-}p}/s$ and the force factor was 0.175 N/V. This force factor was by no means inferior to that of the vibration transducer 30 mm in diameter that was reported by Koike et al. [4]. Our stator transducer was expected to be available as an ultrasonic motor. Output force was utilized not only for rotation of the rotor, but also for pushing up the rotor in the longitudinal direction. Therefore, the maximum output torque could not be estimated solely from this force factor. Assuming that all output force is utilized for the rotational drive, the maximum output torque would be 1.4 Nm with $800\,V_{p-p}$ input voltage. This value was a very rough calculation result. The slip phenomenon and other frictional loss should be considered for precise estimation. Regarding the vibration displacement, more than $1\,\mu m_{p-p}$ amplitude was gained with $100\,V_{p-p}$ without any preload. This value would be sufficient to drive a rotor.

3.2. Motor characteristics under atmospheric condition

The relationship between mechanical load and revolution speed was measured under atmospheric conditions. For this measurement, various weights were pulled up with a thread. The driven rotor was used along with a digital video camera and the rotational speed was measured. Under the vacuum conditions, namely in a vacuum chamber, such measurements were difficult; hence only rotational

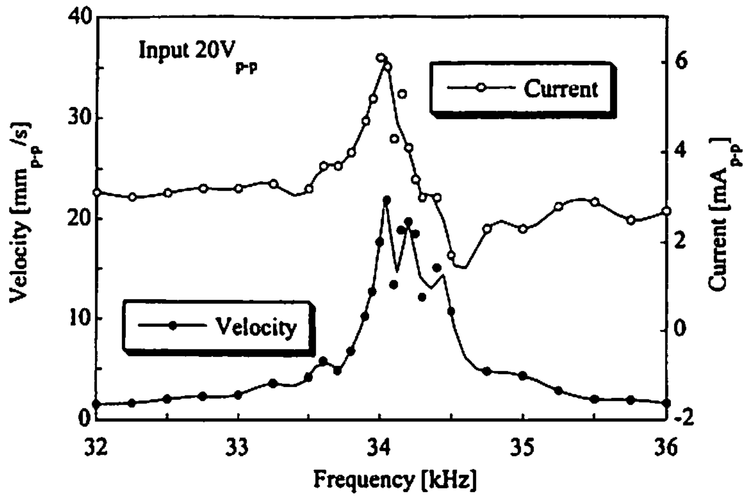

Fig. 3. Vibration velocity and driving current versus frequency.

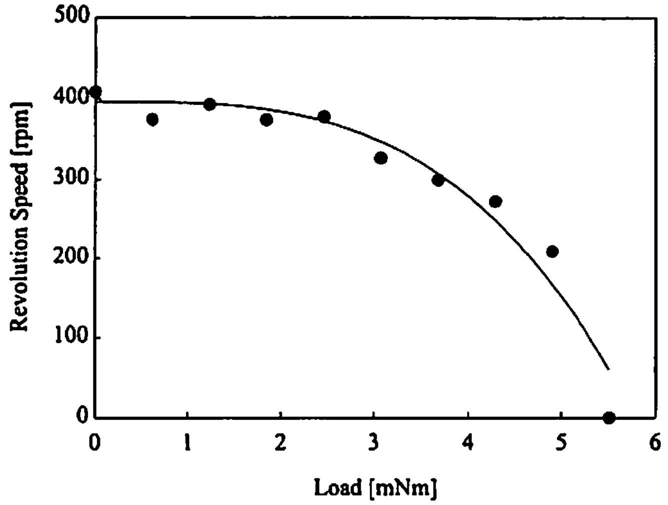

Fig. 4. Speed–torque characteristics of the motor under atmospheric conditions.

speed was measured with no load as shown later. The input voltage was $800\,V_{p-p}$ and the driving frequency was 33.4 kHz. Preloading might cause a slight change in the resonant frequency. The rotational direction was reversed by changing the phase shift from 90° to −90°, or from −90° to 90°. As shown in Fig. 4, the maximum output torque was 5.5 mN m and the maximum revolution speed was 400 rpm. Preload was 2.6 N, so the frictional parameter was calculated to be 0.21. The output torque was very small compared to the estimated value due to the slippage of the rotor and stator transducer. In general, soft materials such as plastics are utilized as the friction material for a traveling-type ultrasonic motor. However, we could not use plastic because it generates outgas. An insufficient preload was another reason for small output torque. When the preload was increased to generate a larger output torque, the vibration amplitude was decreased. As a result, the rotor was not driven with a larger preload. Improvement of a quality factor will be useful for higher output torque in the future.

The main target of this study was to achieve operation under vacuum condition; hence, we did not improve the performance, but managed to operate the ultrasonic motor as a rotational feedthrough under vacuum condition.

3.3. Experiment under ultrahigh vacuum condition

This ultrasonic motor was driven as a rotational feedthrough under vacuum condition. The setup is shown in Fig. 5. The baking treatment was not carried out in this experiment. Since we could not use the rotational sensor under vacuum condition, the rotational speed was measured by the observation through a view port using a digital video camera as shown in Fig. 6. Before the operation, the new rotor was installed and the top of the surface of the stator transducer was polished with #2000 sandpaper. The relationship between the revolution speed and the operation time is shown in Fig. 7. As shown in Fig. 4, the revolution speed with no load was 400 rpm under atmospheric

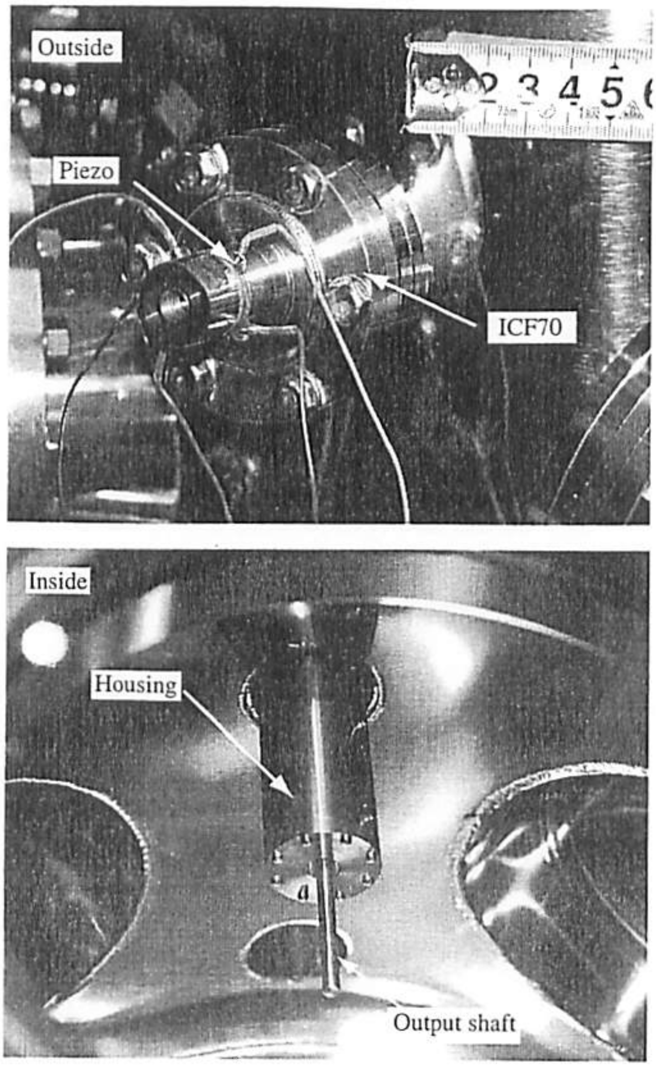

Fig. 5. Setup for the experiments of vacuum operation: (a) exterior and (b) interior of the chamber.

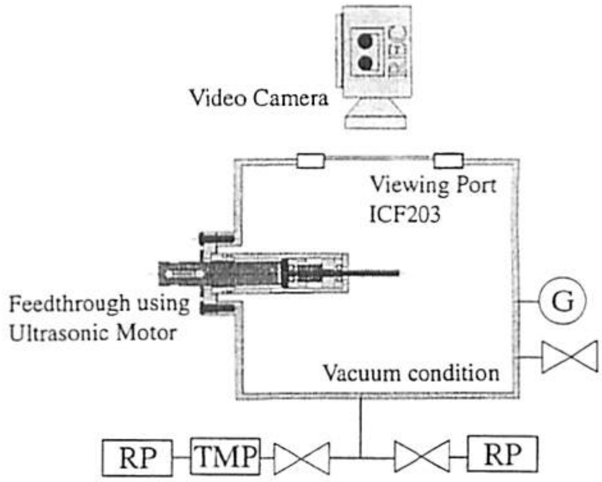

Fig. 6. Schematic setup including the vacuum pump, the vacuum level and the measurement method for rotational speed.

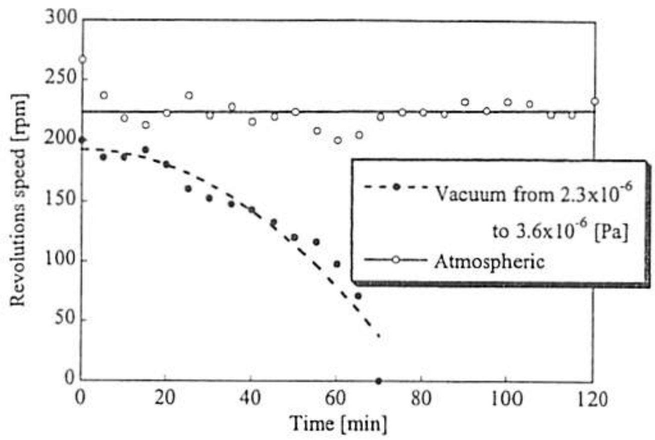

Fig. 7. Change of revolution speed under atmospheric and vacuum conditions.

condition, and it was 250 rpm in this experiment in spite of performing the experiments under atmospheric conditions. The change in the holding condition might be the reason for this difference, although the reason is unclear at this stage.

The result indicates that the revolution speed decreased gradually and after 70 min of operation, the rotor stopped. On the other hand, the revolution speed under atmospheric conditions remained almost constant. After the stoppage under the vacuum condition, we attempted to drive the rotor again by adjusting the driving frequency, but this was unsuccessful.

The reason for the phenomenon described above was considered to be the wear of the driving surfaces. Alumina was sprayed onto the friction surface of the rotor in order to prevent adhesion in the vacuum. The driving surface of the stator transducer was made of stainless steel. Alumina is harder than stainless steel, so the stainless steel was shaven during the operation. One of the evidences is a black trace on the rotor surface. Stainless steel dust was generated and contaminated the alumina surface, causing the rotor and the stator to adhere to each other. Under atmospheric conditions, adhesion does not occur because an oxide layer was immediately formed on the surface.

The vacuum level was also measured during motor operation, using an ionic vacuum gage (LEYBOLD IM520). The result is shown in Fig. 8.

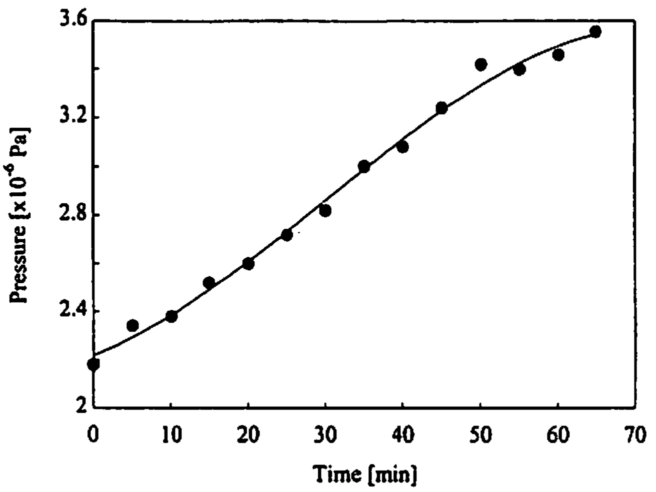

Fig. 8. Change of vacuum level caused by motor operation.

The vacuum changed from 2.3×10^{-6} to 3.5×10^{-6} Pa during 70 min of operation. Alumina has a porous property. Rubbing may cause alumina to discharge outgas. Another reason might be the generation of outgases from the stator transducer because of vibration. If the latter was the main reason, then the baking treatment would be useful for eliminating outgas.

4. Conclusion

In this paper, we proposed a rotational feedthrough using an ultrasonic motor. The principle of this motor was mode-rotation; the generated vibration was in a dual wavelength mode. The stator transducer was welded to the flange at the nodal position. Consequently, leakage was completely avoided. The parts were made of piezoelectric material and the electrodes were designed to be outside the vacuum chamber in order to suppress outgassing. The stator transducer was a bolted Langevin type; hence, the piezoelectric ceramic and electric wire could be easily removed when baking treatment was required. The maximum output torque of the fabricated ultrasonic motor was 5.5 mN m, and the maximum revolution speed was 400 rpm under the atmospheric conditions.

This ultrasonic motor was applied for rotational feedthrough under the vacuum condition. The vacuum level was 10^{-6} Pa, which is the best level for an ultrasonic motor driven in vacuum. In this measurement, we did not carry out the baking treatment. In the next study, a higher-level vacuum condition should be achieved with baking treatment. The operation of rotational feedthrough was confirmed, although the durability was insufficient. The revolution speed was decreased, and after 70 min, the rotor stopped. One reason for this phenomenon was the change of the driving surface. The rotor surface was made of alumina and was harder than the stator made of stainless steel. During the motor operation, the stainless steel was worn away and it contaminated the alumina. Therefore, the material of both the driving surfaces became similar, and adhesion might occur.

The experimental results indicated that outgas was generated, possibly from the alumina. Alumina is porous and the wear of the surface might have resulted in the generation of outgas. A detailed investigation of this is required.

Currently, we are attempting to find a suitable frictional material for the driving surface and to improve the performance of the ultrasonic motor. In order to make the surface harder, carbon metal was sprayed onto the driving surface of the stator transducer. The driving test under atmospheric conditions indicated that the alumina rotor was worn away by the stator transducer. The performance of the ultrasonic motor was improved by adjusting the holding position precisely. The maximum output torque was improved to 40 mN m and the maximum revolution speed was 220 rpm. Subsequently, the baking treatment will be carried out and an operation test at 10^{-8} Pa will be performed.

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