CLAWAR 2019: 22nd International Conference on
Climbing and Walking Robots and the Support
Technologies for Mobile Machines,
Kuala Lumpur, Malaysia, 26-28 August 2019.
https://doi.org/10.13180/clawar.2019.26-28.08.10

Development of Movement System Using Micro Gear Motor

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We propose a micro mobile robot using the smallest set of micro ultrasonic motor and micro planetary gear. The size of the robot is 16 mm in length and 11 mm in width. Micro ultrasonic motor that we used has output torque power about 10 μNm. It is a powerful motor in one-millimeter size. And after attached to micro planetary gear, the motor reached about 6500rpm in 0.2s. Eventhough the micro geared ultrasonic motor that made is not stabil enough, we succeed to combined motor with gear system in millimeter scale.

1. INTRODUCTION

Endoscopes and fiber scopes are mainly used to inspect cracks inside pipes of buildings. However, even if it can be inspected, these methods still have difficulty to repair the cracks in thin pipes. Various methods have been developed as countermeasures in recent years, and microrobots are used as one method.[2,3]

Inspection in very thin pipes is considered to require miniaturization of the wheel type robot. A high torque motor is required so that robot can pass not only horizontal pipe but also pipe with angle. For this reason, the development of microminiature motors is important, and among them ultrasonic motors are simple in structure and high in torque density, so they are suitable for miniaturization and attracting attention as microactuators.

The micro ultrasonic motor developed in our laboratory is 1 mm square and the output torque is about 10 μNm,[4,5] and the torque density is 10-100 times compared to the actuator of this same size. However, in order to move the microrobot in a harsh environment, it is necessary to improve the torque. In order to fully demonstrate its performance, it is necessary to put a micro speed reducer between the load and the motor.

Therefore, in this research, we aim to develop a moving mechanism with a size of 10-12 mm that can climb the wall using the micro geared motor which build from micro ultrasonic motor and ultra small planetary gear mechanism.

2. DEVELOPMENT OF MICRO GEARED ULTRASONIC MOTOR

2.1. *Micro Ultrasonic Motor*

The motor used in this research is an piezoelectric ultrasonic motor that are known as one of the more promising micro motors because of their simple structure and high torque density.[6–8] The structure of the motor is shown in Fig. 2(a). The prototype of the stator is as shown in Fig. 1 (b), the metal part is a cube of 1 mm on each side and the center has an open through hole of 0.7 mm in diameter. Phosphor bronze with good processability is used for the metal part material. Four piezoelectric elements are adhered to the side surface of the stator. The piezoelectric element is double-sided polarized, its size is 1 mm × 0.8 mm × 0.3 mm thick. This can be cut out from a piezoelectric thin plate by dicing processing. To bond the metal member and the piezoelectric element, an epoxy adhesive is used.

By measuring the frequency characteristic of the impedance of the stator, it is possible to estimate the natural frequency. The stator connects to four contact probes is shown in Fig. 2(b). Fig. 3 is the impedance and phase measured by the impedance analyzer. The red line shows the characteristics of the piezoelectric element in the vertical direction and the blue line shows the characteristic of the piezoelectric element in the horizontal direction. An abrupt change in impedance is observed around 950 kHz to 1050 kHz, and the phase changes from -90 degrees to -70 degrees. As the impedance decreases, the amount of current flowing through the stator increases, and as the phase increases, the power factor (input power) increases. That is, it means that the stator vibrates well around this frequency. Vibration generated by the stator can be measured experimentally using a laser Doppler vibrometer. It is difficult to measure the inner circumferential surface of the stator because the hole diameter is too small, so we measured the vibration of one point on the surface of the piezoelectric element instead. When the amplitude of the applied voltage was kept constant at 50 Vp-p and the frequency with which the most vibration occurred was investigated, it was found that the amplitude becomes maximum in the case of about 990 kHz.

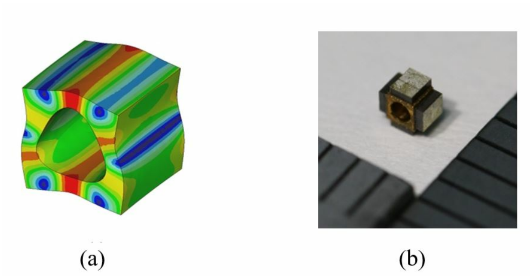


Fig. 1. (a) Vibration mode of stator (b) Prototype of stator

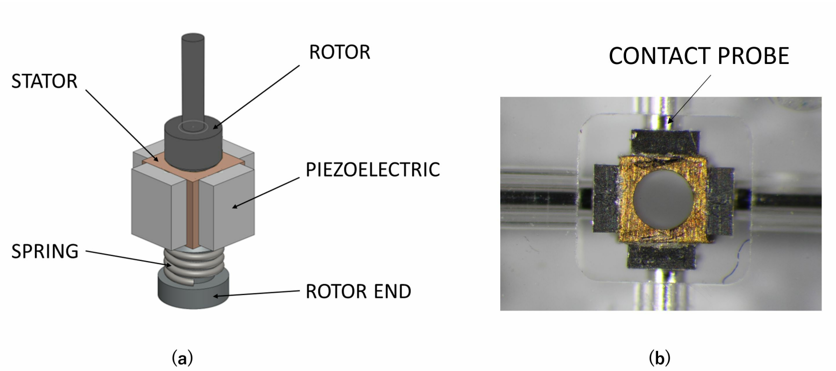
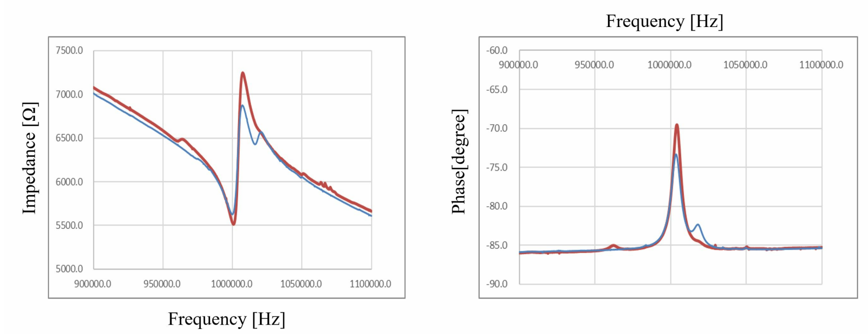


Fig. 2. (a) Structure of MUSM (b) Connection of the PZT to contact probe

2.2. *Micro Planetary Gear*

Planetary gears are one type of the most commonly used gear trains. They are composed of a sun gear connected to an input axis, planet gears mounted on a carrier, and an annular gear meshed with the planets. The carrier functions as an output shaft of the current stage and transfers an output torque to the next stage. By using the multiple stages of these gears, planetary gears have large reduction ratio and high torque-to-weight ratio. The planetary gears have been widely used from mechatronic devices such as prostheses[9] and bipedal robots[10] to miniature devices such as pipe inspection robots[11] and micro medical devices.[12]



(a) (b)

Fig. 3. Frequency response at (a) Impedance and (b) Phase

Our micro planetary gear components are made of metallic glass (Zr55 Cu30 Al10 Ni5 at%) which is a solid amorphous metal with disordered atomic-scale struture that is expected as a material for microgears.[15–18] These miniature components can be formed by injection molding processes using metallic powders.[13,14] As another injection molding method of metallic glass, a viscous liquid over glass transition temperature has been studied.[20] However, the completion of microgears using the melted metallic glass over the melting temperature seems to be better than that using the viscous liquid. The processes of the injection molding over the melting temperature are the following:
1) shaping the ingot from metallic glass mother alloy;
2) injection molding;
3) detachment from molds and gate cutting;
4) surfacing.

First, the metallic glass mother alloy is shaped to the ingot to facilitate the injection molding. The appropriate quantities of the metallic glass mother alloy are put into a bronze mold. They are moved to a vacuum chamber in a vacuum arc melting furnace. After being vacuumed and argon gas filled inside the chamber, the metallic glass is melted by arc discharge. Fig. 4(a) shows the metallic glass mother alloy and Fig. 4(b) shows the metallic glass ingot. Second, the metallic glass ingot is formed to a gear by an injection molding process as shown in Fig. 4(c). The ingot is placed into the sleeve inside the other vacuum chamber and melted by high-frequency induction heating under a vacuum environment. The melted metallic glass, the temperature of which is over 1173 K, is rapidly poured into the molds by using an automatic plunger. After a cooling period, the gears are detached from the molds, and the gates used for pouring the liquidmetal are removed. Finally, the burrs occurring at the gear edges are removed by an ultrasonic burr remover as the surface finishing. Fig. 5(a) shows the components of the micro planetary gear: an output carrier, two kinds of sun gears a carrier, and two kinds of planet gears. The sun gears with a carrier are built by a single injection molding process. All of these gears have an accuracy within ± 2 μ m and an average surface roughness of approximately 0.2 μ m. The micro planetary gear treated in this paper has four stages as shown in Fig. 5(b). For a given sun gear, four planet gears are used in each stage. There are sun gears and planetary gears with long and short lengths. One stage is composed of a short sun gear and short planetary gears, and three stages have the same composition of the gears.Aset comprising of a long sun gear and long planetary gears is located at the output side to enable large torque transmission against an external load. Also, it enhances the stiffness against radial forces such as a load and disturbance. Fig. 6(a) shows the micro planetary gear assembly with an outer diameter of 2 mm and a length of 7 mm. One stage has a gear ratio of 1/4, so the total gear ratio of the micro planetary gear with three stages becomes $1/4^3 = 1/64$. Fig. 6(b) shows the inside of the micro planetary gear, where the rotor with a sun gear of the micro ultrasonic motor is inserted.

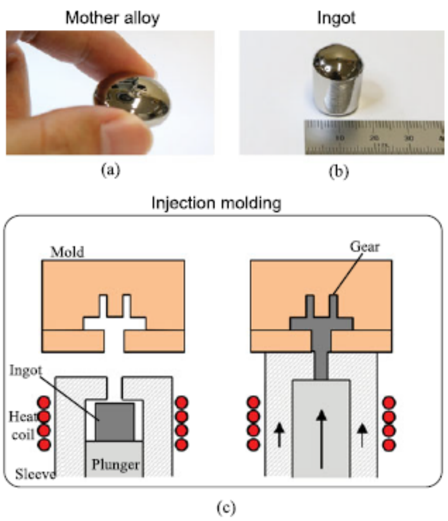


Fig. 4. Fabrication of the microgears. (a) Mother alloy of metallic glass. (b) Ingot built by a vacuum arc melting furnace. (c) Ingot is formed to microgears by injection molding.[19]

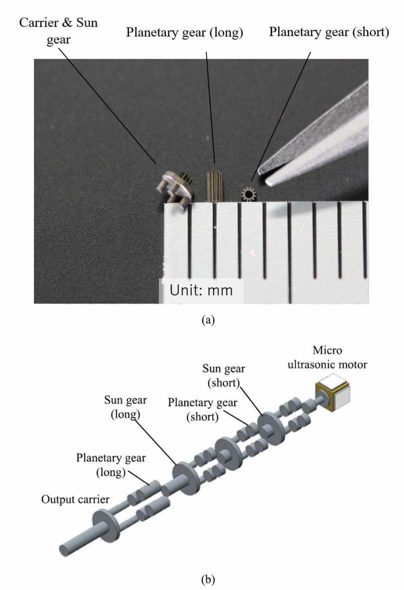
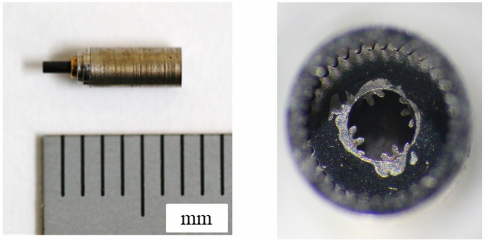


Fig. 5. (a) Components of microgears (b) Structure of the planetary gear: The proposed planetary gear with a gear ratio of 64 uses an output shaft, four long planetary gears, a long sun gear, 8 short planetary gears, and a short sun gears.

2.3. *Experiment*

In order to attach the micro planetary gear mechanism to the micro ultrasonic motor, it was necessary to design the part indicated by the yellow part in Fig. 7. This part has the role of fixing the motor side pinion to the gear of micro planetary gear mechanism. An adhesive was applied to the surface of the motor on the pinion side, and the motor and the micro gear

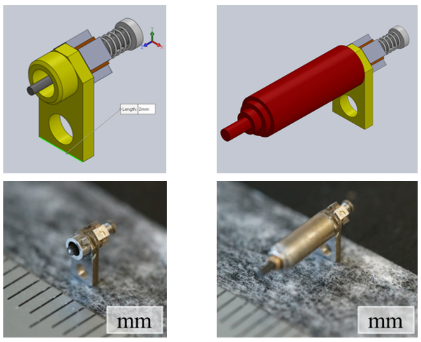


(a) (b)

Fig. 6. (a) Micro planetary gear assembly. (b) Inside of the micro planetary gear.

were manually connected. The one produced is shown in Fig. 7(b). Next we will describe necessary operating environment for experiment of micro geared motor.

Two types of AC voltages generated by the waveform output device (WF1974, NEF circuit block) are amplified using an amplifier (BA4825, NEF circuit block) and applied to each piezoelectric element. Two types of standing waves as shown in Fig. 1 (a) is generated and then a traveling wave is created. In order to create a standing wave from two pairs of traveling waves, the spatial phase of the vibration is 90 ° in phase as shown in Fig. 1(a) It is necessary to set the temporal phase to 90 ° . Therefore, one of the AC voltages to be output is solved by making the Sin wave and the other Cos wave. As for the direction of the traveling wave, it is possible to reverse it by changing the delay and advance of the phase. Therefore, in the case of reversing the rotation of the motor, it is possible to rotate it in the reverse direction by using the -Sin wave or -Cos wave. In the experiment, it is used in the range of 975 to 1000 [kHz], 100 to 120 [V_{p-p}].



(a) (b)

Fig. 7. (a) MUSM with micro planetary gear connector (b) MUSM with micro planetary gear

2.3.1. *Movement and Torque Experiment of Micro Geared Ultrasonic Motor*

We conducted a driving experiment of the micro geared motor in the operating environment. In order to confirm the deceleration of the motor by the gear, a mark was affixed to the output shaft of the micro planetary gear mechanism, and another mark was affixed to the rotor side. Voltage was applied to the motor and the operation was confirmed. However, the behavior of the motor was unstable, and rotation and stoppage frequently occurred. One possible cause is that the engagement between the rotor and the micro gear has not been successful. Even though it could rotate, the micro geared motor stopped when voltage was applied for a long time. It is considered that heat is generated in the piezoelectric element of the motor by applying a voltage, which is made the frequency at which the motor vibrates changes.

Next, we will describe about the torque experiment of the micro geared motor. The state of the torque experiment is shown in Fig. 8. The experimental apparatus was designed to be able to perform fine position adjustment. Connect the output shaft to the coupling so that the micro geared motor rotates the pulley as shown in the figure. By turning the coupling the pulley rotates and lifts the weight. The torque of the micro geared motor is measured by the weight of this load. However, similar to the driving experiment, if the connection between the micro geared motor and the coupling is shifted even a little, the motor does not turn and the pulley can not be rotated. In order to experiment with the micro geared motor, it was found that precise position adjustment is very important.

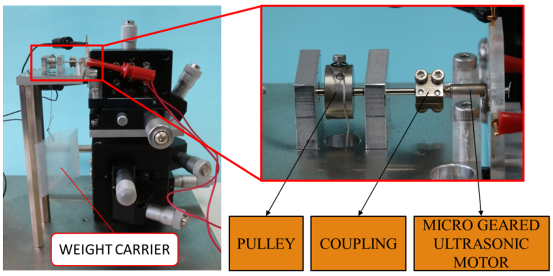


Fig. 8. Experimental setup for measuring torque of micro gear motor

2.3.2. *Transient Response of Micro Geared Ultrasonic Motor*

As shown in Fig. 8, in order to evaluate the performance of the micro geared motor, we measured the rotation number on the rotor side. To measure the rotational speed of the rotor, rotary encoder is generally used. But, in the measurement of the micromotor, viscous friction and inertia moment of the rotary encoder is relative large so that cannot be negligible. Therefore, the rotation of the rotor is photographed using a high-speed video camera, the number of rotations is calculated from the angular displacement of each frame, and the number of rotations is measured by tracking on the PC screen and processing the data. Voltage is applied to the micro geared motor, transient response of the rotational speed is photographed with a high speed camera, and it is represented by a time history. The result is shown in Fig. 9. The amplitude of the applied voltage at this time is 100Vp-p and the frequency is 985kHz, this frequency is a value adjusted in advance so that the motor rotates well most. It is understood that the rotation number reaches approximately 6500rpm or more at about 0.2s from the start of rotation. However, it seemed that there was noise until the rotation speed of the motor reached a steady state from the start of rotation. This is thought to be caused by the position adjustment of the connection part between the motor and the gear and the effect of the engagement of the gear in advance.

3. DESIGN OF THE MICRO MOVEMENT SYSTEM

In order to realize the ultra compact moving mechanism with a size (width) of 10-12mm that can climb the wall, we proposed a wheel type moving mechanism as shown in Fig. 10. To make moving mechanism that has sufficient torque, design of the transformation mechanism shape is important. There are many transmission methods for transmitting the driving force from the motor to the tire, but there is a method called a bevel gear mechanism which is often used. In this mechanism, gears are generally used, but in this research we used friction drive instead of gear for the driving part, because it is difficult to make ultra small size of bevel gear and it is highly cost. The designed parts are printed with a 3D printer and

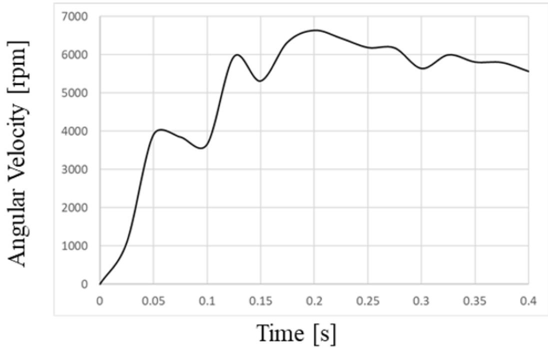


Fig. 9. Transient response of micro gear motor

attached to the micro geared motor. The designed friction drive is shown in Fig. 11. The yellow part indicates the part transmitting the driving on the motor side, and the green part indicates the part transmitting the driving on the tire side. Both have a diameter of 3 mm. The efficiency of the transmission mechanism is evaluated by the expression 1.

$$F = \mu N \tag{1}$$

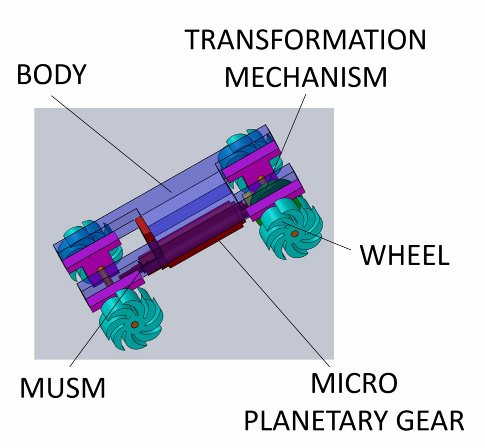


Fig. 10. Design of micro mobile robot

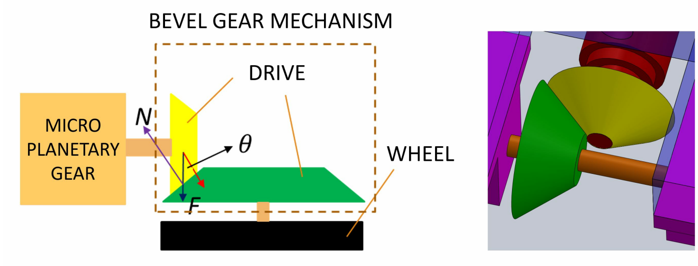


Fig. 11. Design of friction drive

After the designed moving system is printed, the overall length of the moving mechanism is about 16 mm and the overall width is about 11 mm. In addition, the weight is 216.8 mg.

4. CONCLUSION

As a result obtained in this research, we could evaluate the performance of micro geared motor using micro ultrasonic motor and micro planetary gear mechanism. However, if voltage is applied to the micro ultrasonic motor for a long time, the motor becomes hot, the frequency changes, and the motor can not turn. Therefore, it is necessary to improve and adjust the temperature of the environment so that the motor can rotate for a long time.

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