How to make High-Efficiency Ultrasonic Motors

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Abstract

Efficiency is one of the most important issues in designing ultrasonic motors. Hence, authors introduce a practical way of analyzing the efficiency and power loss of the motor. Mainly, this paper focuses on ring-type and bar-type motors developed by Canon Inc. First, fundamental ideas and experimental methods for analyzing the cause of frictional loss, loss by supporting stator and internal loss are shown. Then, results of numerical simulation of frictional loss using finite element analysis are shown. Methods for reducing supporting and internal loss are discussed as well. Finally, performance of high-efficiency ultrasonic motor is shown.

1. Introduction

In recent years, more than a million ultrasonic motors are mass-produced every year. More than a half of them are products of Canon Inc. Such ring-type and bar-type traveling wave ultrasonic motors are mainly used for auto focus lenses and photocopying machines. For making high-performance ultrasonic motors, efficiency is one of the most important issues. In order to increase the efficiency of ultrasonic motors, the causes of power loss and method for reducing power loss should be clarified. In this paper, methods for analyzing the causes of power loss and a method for reducing it are shown.

2. Analysis of power loss

Fig. 1 and Fig. 2 show a schematic view of a ring-type ultrasonic motor developed by Canon Inc. and its driving principles. The stator has a PZT (Piezoelectric ceramic) sheet bonded to the bottom side of the metal vibrator. The stator has teeth on the upper surface of the vibrator. Two natural vibrations with frequencies of about 30 kHz with a phase difference of 90 degrees are excited by AC voltage input to the PZT. This generates a traveling wave that creates an elliptic locus at the surface of the teeth. The teeth are for increasing the vibrating amplitude of the stator. As shown in Fig. 2, point P on the surface of the teeth moves counter clockwise along its locus when the traveling wave moves to the right. The rotor has a ring and a flange-shaped spring to generate certain contact duration to the surface of the traveling wave.

Authors have analyzed the causes of power loss of the ring-type ultrasonic motor [1]. Fig. 3 shows the changes in power loss when the torque of the motor is changed at a fixed stator amplitude of 1 μm. The amount (a) shows a frictional loss at the contact interface between the rotor

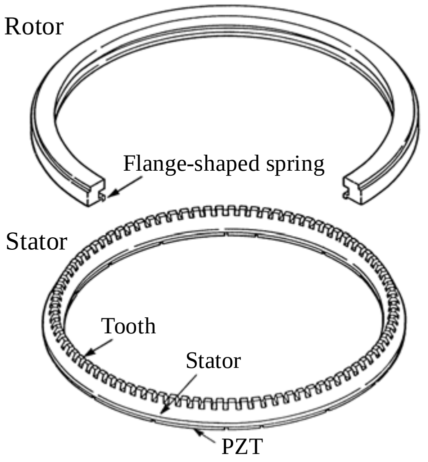


Fig. 1 Ring-type ultrasonic motor (70 mm in diameter)

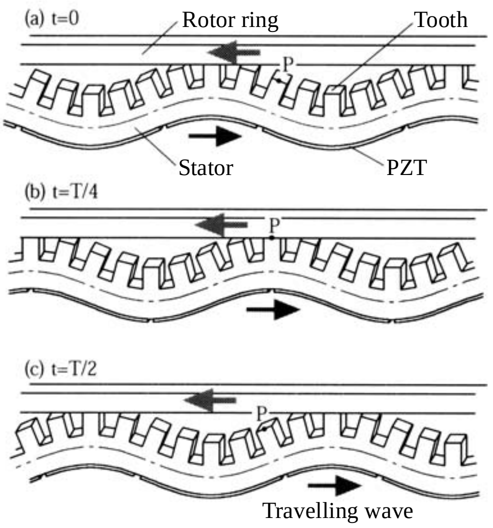


Fig. 2 Driving principle of ring-type ultrasonic motor

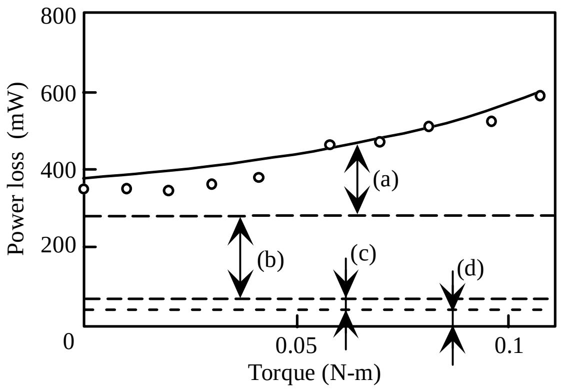


Fig. 3 Measured and calculated power loss of ring-type ultrasonic motor

(a) Calculated frictional power loss
(b) Measured power loss by supporting felt
(c) Measured internal power loss of PZT and bonding
(d) Measured internal power loss of metal ring of stator
○ Measured total input power

and stator calculated by finite element analysis, which will be discussed in chapter 3.1. The frictional loss increases when the torque is increased because the contact condition between the rotor and stator changes, whereas, other types of power loss are independent to the change in torque. Amount (b) represents power loss by the supporting felt. In order to support the stator, a felt sheet is usually placed under the stator. This constrains the stator vibration and becomes the cause of power dissipation of about 200 mW. Amounts (c) and (d) are internal frictional loss within the stator. Amount (c) is lost within the PZT and at the bonded interface between the PZT ring and the metal ring. Amount (d) is lost within the metal ring of the stator. The plotted circles show the measured total power loss of the motor.

3. Ways to reduce power loss

Efficiency of ultrasonic motors can be increased by decreasing power loss, because it is obvious that;

(Efficiency)
= (output power) / (loss power + output power)

In this chapter, ways to reduce the power loss as shown in Fig. 3 are described in order (See Table 1).

Table 1 How to reduce power loss of ultrasonic motors

Source of power loss	Ways to reduce power loss
Frictional loss at contact interface	Make contact duration small by making stiffness of rotor spring large
Loss by supporting element	Optimize supporting element design
Internal frictional loss of metallic portion of stator	Minimize strain of metallic portion of stator Select materials having small structural damping
Internal frictional loss by PZT and bonding	Make use of stacked PZT Make strain of PZT small by making force factor small

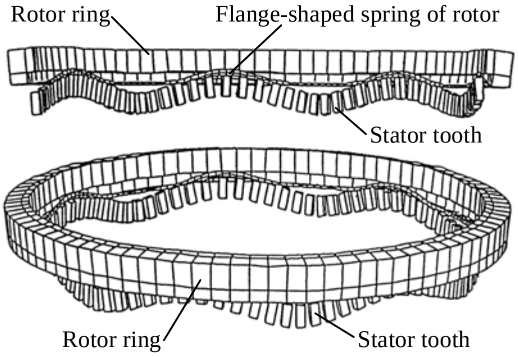
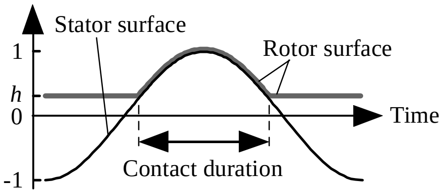


Fig. 4 Finite element model of rotor and stator teeth

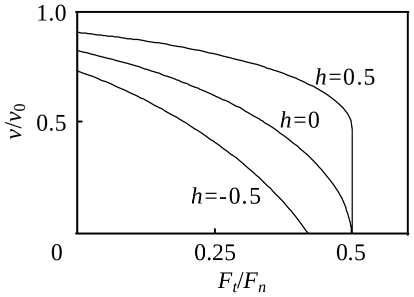
3.1 Frictional loss at contact interface

In order to reduce the frictional loss at the contact interface of the rotor/stator, contact conditions between the two should be analyzed. Therefore, authors have conducted FE (finite element) contact analysis [1]. Fig. 4 shows a FE model of the stator teeth and rotor. Typical results of the FE analysis are shown in Fig. 5. Fig. 5 (a) shows the contact condition between the rotor and stator schematically. Value h denotes the height of the rotor surface from the center of vibration of the stator traveling wave. Value h varies according to the stiffness of the flange-shaped spring at the contact interface of the rotor ring. If the stiffness of the rotor spring is large, the deformation of the flange-shaped spring of the rotor in the normal direction becomes small and indentation of the wave-shaped stator to the rotor also becomes small. Figure 5 (b) shows the velocity of the rotor divided by maximum velocity (or rotating speed) at the teeth of the stator when the force (or torque) and h are changed. F_t and F_n represent the tangential and normal force applied to the motor. The velocity of the rotor is large when h is large. This is because the rotor is in contact with the stator only at the top of the elliptic locus, when the tangential velocity is large in a cycle of vibration of the stator. This is because in a single cycle of vibration, only when the tangential velocity is large does the rotor touch the stator at the top of the elliptic locus.

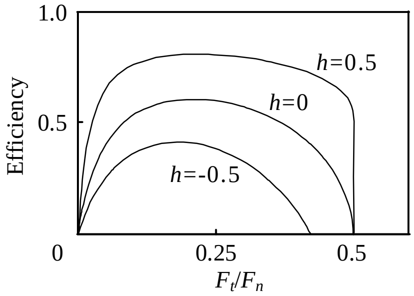
Fig. 5 (c) shows the efficiency of the motor when force and h are changed. In this calculation, supporting and internal power loss are neglected, which means only frictional loss during energy transmission at the contact interface is considered. Frictional loss is calculated as follows:



(a) Definition of *h*



(b) Velocity-force curve



(c) Efficiency at the contact surface

Fig. 5 Performance of the motor when *h* is changed

$$\text{(Frictional loss)}=\Sigma(\,|\,v_{rel}\,f_t\,|)$$

where, v_{rel} and f_t are relative velocity and friction force between the rotor and stator, respectively, at the FE nodes of the stator that are in contact with the rotor. The figure shows that the efficiency improves when *h* is large. This is due to the following reason: When *h* is large, relative velocity between the rotor/stator is small because they are in contact only when the tangential velocity of the elliptic locus is large.

For the specific case in which the value *h* is 1.0, efficiency theoretically becomes 1.0 because no slip occurs as long as the rotor is in contact with the stator teeth at the highest point of the elliptic locus. Hence, we can conclude that the velocity-force curve and the efficiency curve can be controlled by changing *h*, which changes according to the stiffness of the rotor spring.

3.2 Loss by supporting elements

As described in Section 2, the ring-type ultrasonic motor has large energy dissipation inside the felt placed under the vibrator. If the stator is supported adequately by a supporting element without constraining the natural vibration like a tuning fork, the supporting loss power can be dramatically reduced. Hence, authors have developed a bar-type ultrasonic motor [2] by analyzing the vibration mode of the stator shaft when location, length and diameter of the supporting element are changed. We found the adequate geometry of the supporting rod as shown in Fig. 6. First, bending vibration is produces in the stator of the bar-shaped ultrasonic motor as shown in Fig. 7. An optimally designed supporting rod is placed along the central axis of the stator. Experimental results by the authors show that the loss by support is reduced to an almost negligible minimal amount.

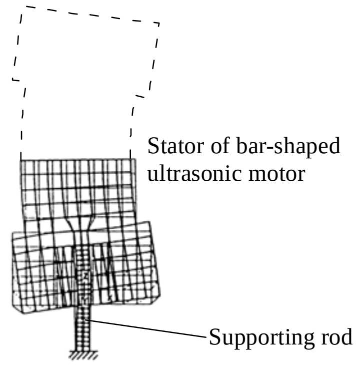


Fig. 6 Result of a half model finite element analysis of stator with supporting element for bar-type ultrasonic motor

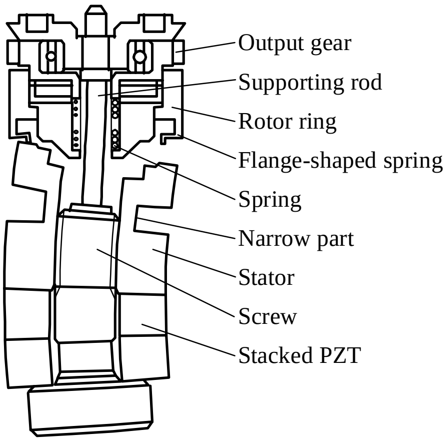
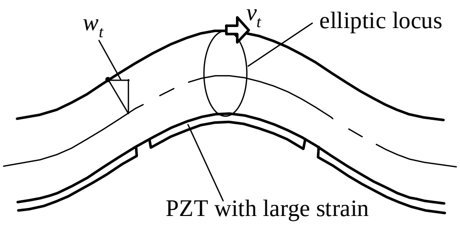


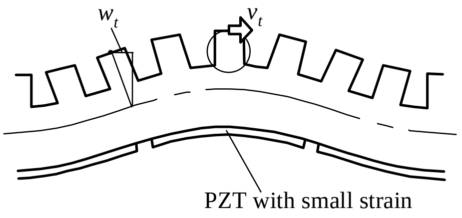
Fig. 7 Sectional view of configuration and natural mode of bar-type ultrasonic motor (10 mm in diameter and 25 mm in length)

3.3 Internal frictional loss

Another type of power loss is an internal frictional loss inside the stator, which can be divided into energy dissipation inside the PZT and metal material of the stator, and energy dissipation at the interface between the PZT and metal material. The former can be reduced when materials with small structural damping are selected. The latter can be reduced by selecting a bonding material with small structural damping and by making the bonding rigid in the ring-type ultrasonic motor.



(a) Case of large force factor



(b) Case of small force factor

Fig. 8 Effect of geometry and natural mode of stators on force factor

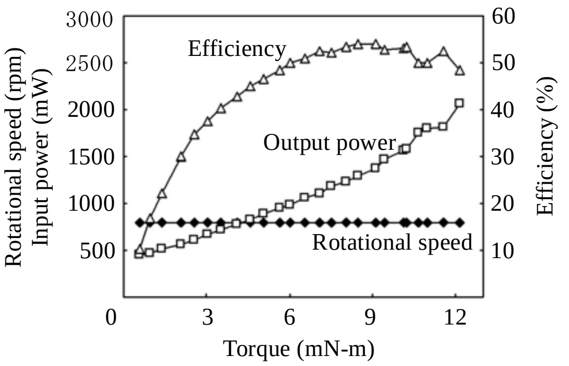


Fig. 9 Performance of bar-type ultrasonic motor

In the bar-type ultrasonic motor shown in Fig. 7, interface between the PZT and metal is bolted instead of bonded. The power loss at the interface becomes larger than those in former bar-type motors because the numbers of PZT and electrode plates are bolted. Hence, authors developed the united stacked PZT. Multiple thin PZT sheets are manufactured as one unit. This design allowed the internal loss due to the interface between the PZT and electrode plates to become sufficiently small.

Another effective approach to reduce internal loss within the stator is to control the force factor of the stator. The force factor is defined as input current divided by velocity of the vibrator. If we put the velocity of the vibrator as a maximum tangential velocity v_t at the contact interface of the stator (see Fig. 8 in the case of a ring-type motor), the force factor is proportional to the strain of the PZT divided by v_t. When the force factor is large, i.e., strain of the PZT is relatively large as shown in Fig. 8 (a), the internal loss at the interface between the PZT and metal also becomes large because the loss is approximately proportional to the square of strain amplitude. If the force factor can be made smaller by placing the teeth, the strain of the PZT becomes relatively small, which results in smaller internal loss. The narrow part of the bar-type motor shown in Fig. 7 is designed to achieve the same effect. Authors have made use of the optimum value of force factor obtained by detailed experiments for designing many kinds of ultrasonic motors having small internal loss and large efficiency.

4. An example of a high-efficiency motor

A bar-type ultrasonic motor with higher efficiency than currently commercialized motors is manufactured by making *h* larger than commercialized bar-type ultrasonic motors shown in Fig. 7. Input power and efficiency of the motor are measured when torque is increased while the rotational speed is kept at a constant 800 rpm. Performance of the ultrasonic motor is shown in Fig. 9. Maximum efficiency is about 55 percent, whereas it is about 45 percent in the commercialized bar-type motors. Efficiency of the motor will become much higher if *h* can be made larger. However, a squeaking sound occurs and rotation of the rotor becomes unstable when *h* approaches 1, whereas, the squeaking sound and instability do not occur in the manufactured motor. It is important to simultaneously improve efficiency, controllability and reliability.

4. Conclusions

In this paper, causes of power loss are analyzed and categorized into frictional loss, supporting loss and internal loss. Then methods for reducing those losses and increasing efficiency are described. An example of a high-efficiency ultrasonic motor is also shown.

5. Acknowledgements

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6. References

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