ULTRASONIC MOTORS

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1. Introduction

Ultrasonic motors, which have superior characteristics like high torque at low speed, absence of magnetic interference, and compactness in size, are good candidates for medical applications, automation, robotics, aerospace engineering and various other fields. Many different types of ultrasonic motors have been proposed up to date [1]-[5].

The stator of an ultrasonic motor that is excited by piezoelectric elements in ultrasonic frequency range develops different kinds of vibrations depending on its structure. From the way of creating an elliptical motion on the stator, ultrasonic motors were classified into two major groups, such as standing wave and traveling wave types. Further classifications include mode-conversion, multi-mode [6,7,8] and mode-rotation types of motors [9] that are suitable for miniaturization and can be manufactured less costly.

Ultrasonic motors are of great interest due to the flexibility of miniaturization in comparison with conventional electromagnetic motors whose efficiency decreases significantly. Especially in information systems [4] and medical industry [10], compact size of these motors makes them find wider applications.

2. Objective

The miniaturization of a mechatronic device depends on the size of the motor equipped in the device to run it. Miniaturization of conventional electromagnetic motors to several millimeters with high efficiency is difficult since a gear mechanism is required to obtain a high torque from the electromagnetic motor. This mechanism adds additional

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mass, volume and complexity and also increases the number of components of the system, which decreases the motor system reliability. On the other hand, piezoelectric ultrasonic motors are suitable for miniaturization in terms of their compactness and low power consumption.

Our main objective is to design, fabricate and characterize piezoelectric ultrasonic motors for micromechatronic devices. The approach in designing these piezoelectric motors were as follows:

i. To simplify the structure including the poling configuration of piezoelectric element used in stator.
i. To reduce the number of components in order to decrease the cost and enhance the driving reliability.

The designed motors are a multi-mode-single-vibrator excitation type, which uses two orthogonal bending modes of a hollow cylinder. Since the structure and poling configuration of the active piezoelectric elements used in the stator are simple, these motor structures are very suitable for miniaturization. Moreover, a single driving source can excite two bending modes at the same time, thus generate a wobble motion.

There are 3 types of ultrasonic motors. The piezoelectric stator structure is the same for all of these motors. However, the dimensions of the motor are reduced by almost 50 percent. Starting with a 10 mm long stator, we reached down to 4 mm in the last model. The initial diameter was 2.4 mm and it went down to 1.6 mm. In the final design, the rotor part of the motor had been changed and this resulted in a reduction in the number of components. In terms of driving circuit, a single driving source was enough to run the motor and a conventional switching power supply type resonant L-C circuit was used.

3. Structures and Operating Principles of Motors

A square beam has two orthogonal bending modes whose resonance frequencies are equal to each other. The first bending mode frequencies in any direction for circular cylinders are also equal to each other. The stator of the motor combines the circular and square cross-sections.

The outside surface of a hollow metal cylinder was flattened on two sides at 90-degrees to each other and two uniformly electroded rectangular piezoelectric plates were bonded onto these two flattened surfaces (Fig.1 (a)). The basic configuration of the motor is shown in Fig.1 (b). Since the stator is symmetric with respect to the x'-axis, the area moment of inertia about the principal axis is on the x'-axis. The area moment of inertia about the other principal axis is on the y'-axis. This causes the stator to have two degenerated orthogonal bending modes, whose resonance frequencies are close to each other. The split of the bending mode frequencies is due to the partially square/partially circular outside surface of the hollow cylinder. Driving one piezoelectric plate (while short circuiting the other to ground) at a frequency between the two orthogonal bending mode frequencies excites both modes, thus, causing the cylinder to wobble. When the other piezoelectric plate is driven at the same frequency, the direction of wobble motion is reversed.

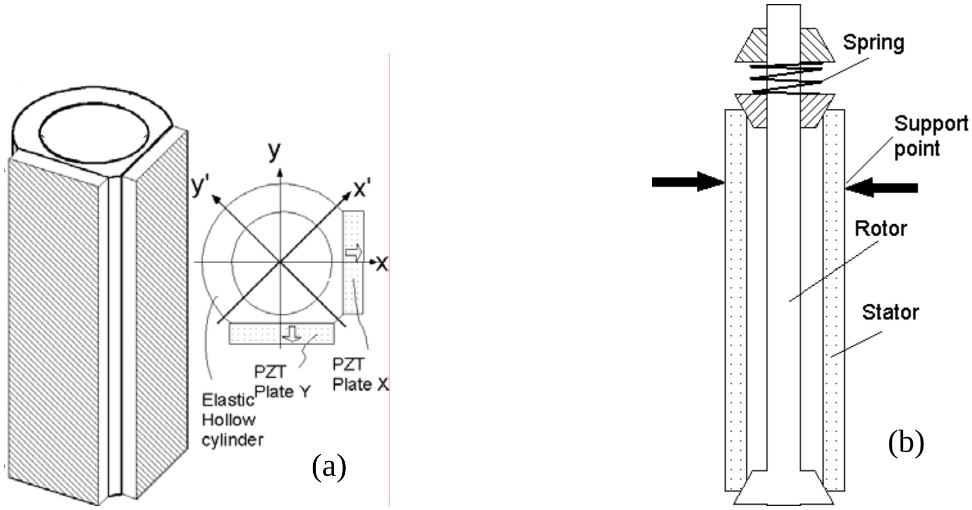
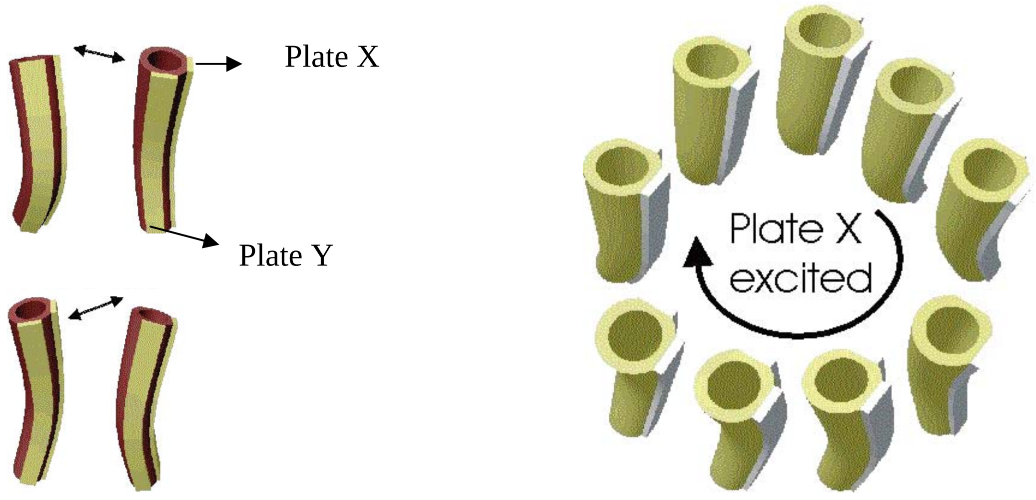


Fig.1. (a) Structure of the stator (b) Assembly of the motor.

4. Finite Element Analysis

The behavior of the free stator was simulated using ATILA finite element software to verify the conceptual operation principle. Tailoring dimensions of the metal and piezoelectric ceramics equated the two orthogonal bending mode frequencies of the stator. The piezoelectric plates on the surface of the cylinder were placed in such a way that one piezoelectric plate can excite the two orthogonal bending modes of the stator.

Fig.2 (a) shows the two orthogonal bending mode shapes when only the plate on the x-axis (plate X) was excited, while the electrode of the plate Y was short-circuited. Wobble motion was generated on the cylinder when only one piezoelectric plate is excited at a frequency between the two orthogonal bending modes frequencies (Fig.2 (b)). When the other piezoelectric plate was excited at the same frequency, the direction of wobble motion was reversed.



(a) (b)

Fig.2. (a) Two orthogonal mode shapes when plate in x-axis was excited, (b) Wobble motion in clockwise direction can be generated on the cylinder when plate in x-axis was excited in between the two orthogonal bending resonance frequencies.

5. Set-up for the Characterization of the Motors

The performance of the motors was measured using a transient characterization method, which was initially proposed by Nakamura [11]. The principle of this method is mounting a load (usually a disk whose moment of inertia is known) onto the motor, running the motor, and, finally, analyzing the transient speed obtained as a function of time. More explicitly, the angular acceleration of the motor is calculated from the speed measurement by Newton's second law.

The transient torque is then calculated by multiplying the angular acceleration with the moment of inertia of the load. Using this method, the starting transient response of the motor gives the speed-torque relation. A load is mounted onto the stator and the motor is then driven with an AC voltage. The position of the rotating disk is detected through an optical encoder. The transient position data were then converted into voltage signal using a frequency-to-voltage converter.

Since the output voltage of the converter is proportional to the input frequency, the speed of the motor was obtained. The angular acceleration of the motor was estimated using the derivative of the angular speed. Finally, the transient torque was calculated by multiplying the angular acceleration with the moment of inertia of the rotating disk.

6. Structural Properties and Characteristics of the Motors

So far, 3 motors were fabricated. Table 1 summarizes the structural properties of these motors. As can be seen from Table 1, there is a gradual reduction in the dimensions and a reduction in the total length of the whole motor structure.

Table 1. Structural Properties of the Motors

Dimensions	**1st Design**	**2nd Design**	**3rd Design**
Outer Diameter (mm)	2.4	1.6	1.6
Inner Diameter (mm)	1.6	0.8	0.8
Thickness of Ceramic Plates	0.5	0.3	0.3
Length of Stator	10	6	4

1st Design

The outside surface of the metal cylinder was ground on two sides at 90-degrees to each other to obtain two orthogonal flat surfaces. The PZT plates, which were electroded uniformly and poled in the thickness direction, were bonded onto the flat orthogonal surfaces of the cylinder using an epoxy. The rotor was a cylindrical rod and it was pressed by a spring using a pair of stainless steel ferrules. A picture of this motor can be seen in Fig.3.

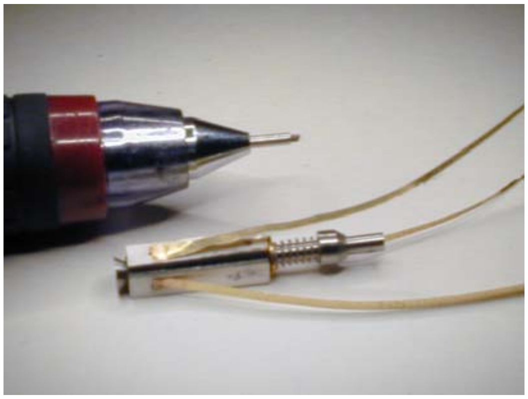


Fig 3. 1st design

As a first step to clarify the behavior of the stator, the admittance spectra of the free stator were measured (Fig.4) when plate X or Y was excited. When plate X was excited while short-circuiting the electrode of plate Y to the ground, the stator had two degenerated bending mode resonance frequencies around 71.8 and 74.0 kHz. When plate Y was excited, the stator showed a similar behavior.

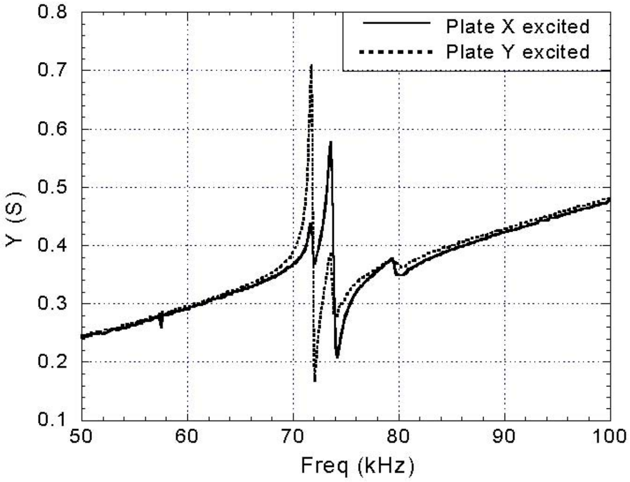
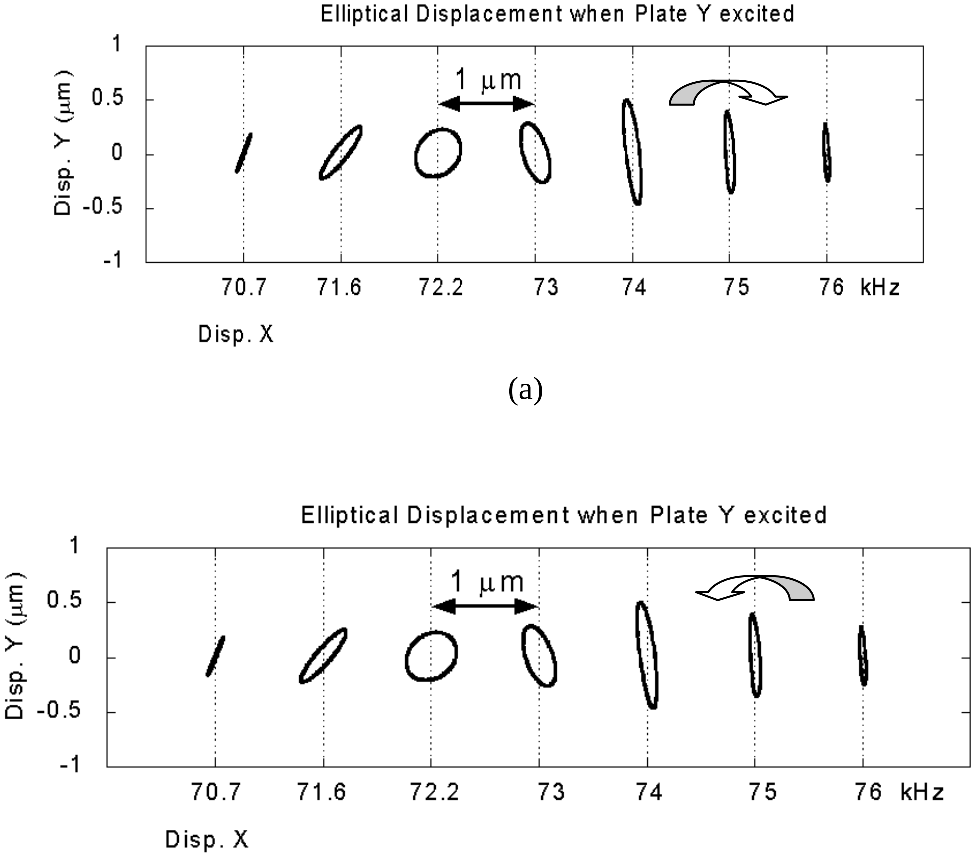


Fig.4. Magnitude of admittance spectrum of the free stator when plate X or Y was excited

The wobble motion in the XY-plane was also verified by measuring the magnitude of the vibration velocity in x and y directions at the same time. A function generator (HP33120A) and a power amplifier (NF4010) were used to excite the stator. By exciting either plate X or plate Y, the elliptical displacements in x and y directions were measured with two laser fiber optic interferometers.

First, plate X was excited at frequencies of 70.7, 71.6, 72.2, 73, 74, 75, 76 kHz, with an input voltage of 112.0 V p-to-p. The results are plotted in Fig.5 (a). The measurements were repeated by exciting only plate Y and the results are shown in Fig.5 (b).



(a)

(b)

Fig.5. Elliptical displacements at frequencies 70.7, 71.6, 72.2, 73, 74, 75 and 76 kHz (a) when plate X was excited and, (b) when plate Y was excited.

The interesting points here are: i) the direction of wobble motion when only plate X was excited was clockwise, and counterclockwise when only plate Y was excited, ii) the wobble motion, when only plate X was excited, was almost identical to the wobble motion when only plate Y was excited at the same frequency. In conclusion, the designed motor can be driven with a single AC source and exciting either plate X or Y, the direction of the rotation can be reversed.

In terms of load characteristics of the motor, transient speed, torque and efficiency were measured and calculated. A load, a metal disk (60 g) with a diameter of 34 mm and moment of inertia (8.6 kg·mm^2) was mounted onto the stator. As shown in Fig.6, the steady state speed reached 86 rad/sec in 7 sec. A starting torque of 1.8 mNm at 120 Volt is similar to other bulk piezoelectric cylindrical type micro motors in literature and almost one order of magnitude higher than that of a thin film motor with a similar size [12-14].

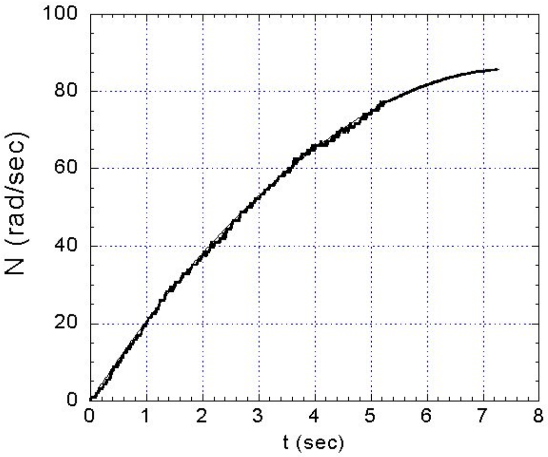


Fig.6. Transient response of the motor

The product of output torque with output speed gives the output power. A maximum power of 60 mW was obtained at a speed of 60 rad/sec and a torque of 1 mNm. The maximum efficiency of 25 % (Fig.7) at 120 V is similar to other bulk cylindrical type micro piezoelectric motor [14].

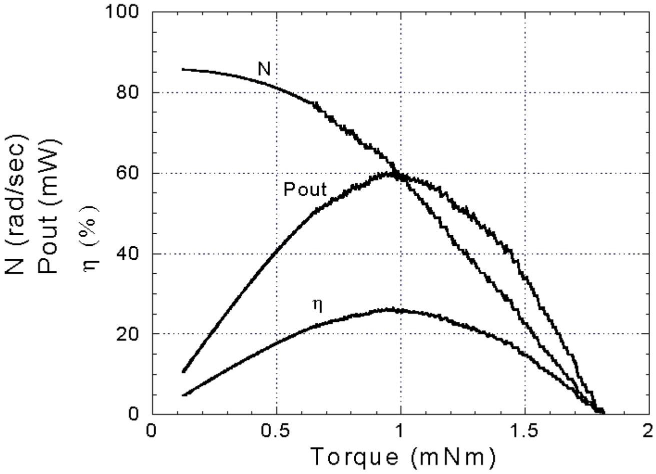


Fig. 7. Load Characteristics of the Motor

2nd Design

The principle is the same as the previous motor. The important improvement is in the reduction of the dimensions of the stator almost by half of the previous one. Fabricated motor can be seen in Fig.8.

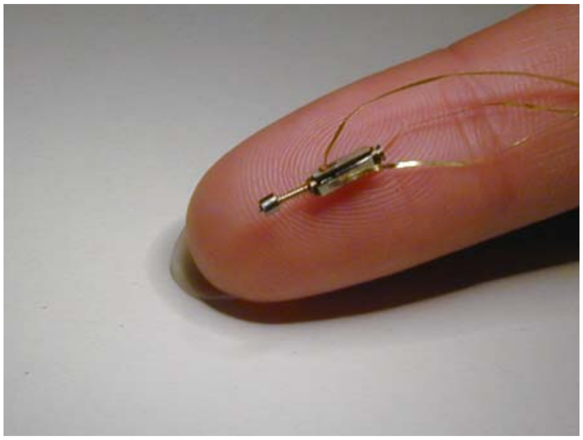


Fig.8. 2nd design

Simulation of the stator was performed by ATILA finite element software to determine the bending modes of the structure. The two orthogonal bending frequencies were observed at 128 kHz and 132 kHz.

Experimental set-up for measuring load characteristics is the same as the previous one and the results are as follows. The steady state speed was obtained as 67 rad/sec in 7 sec. A maximum torque of 0.87 mNm was obtained. The motor reached a maximum power of 45 mW at a speed of 45 rad/sec. The maximum efficiency was 12 %. The power of the motor is dependent on the size of the piezoelectric ceramics used. As the thickness and the length of the components were reduced, a lower output power was obtained.

3rd Design

This motor is the smallest of all three designs. The diameters of the stator part are the same as that of 2nd motor. However, the length is reduced to 4 mm and also the rotor part has changed completely. Instead of a solid metal rod, a spring was used as a shaft. This spring acts as a rotor and as a pre-stress element, as well. Apparently, the number of components was minimized. A picture of this motor can be seen in Fig.9.

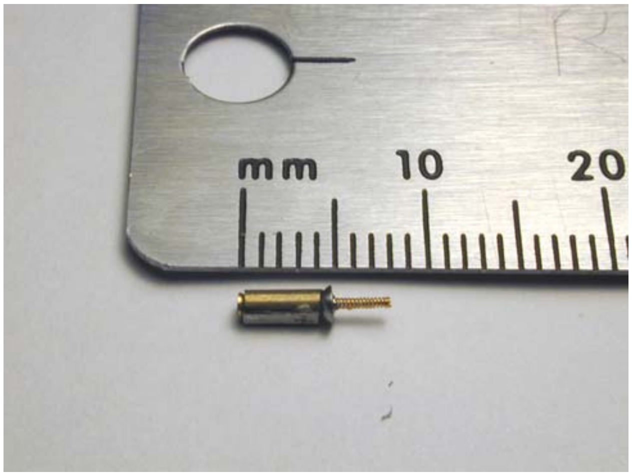


Fig.9. 3rd design

The resonance frequency of the stator is in the range of 230-245 kHz. As the length of the ceramic plates reduced down to 4 mm, the working frequency increased relatively. Maximum torque and power are 0.3 mNm and 25 mW, respectively. Table 2 summarizes the important characteristics of all motors.

Table 2. Characteristics of the motors

	1st (10 mm)	**2nd (6 mm)**	**3rd (4 mm)**
Frequency Range	65-75 kHz	125-140 kHz	230-245 kHz
Steady State Speed	86 rad/sec	67 rad/sec	50 rad/sec
Torque	1 mNm	0.87 mNm	0.30 mNm
Power	60 mW	45 mW	25 mW

To summarize, Table 3 compares the structural differences of all fabricated motors. The objectives to miniaturize and to simplify the structure of the proposed motor design were achieved successfully.

Table 3. Comparison of the designs

	1st	***2nd***	***3rd***
Length of the Stator	10	6	4
Total Length of the Motor	~ 15	~11	~5
Number of Components Used	2 piezoelectric plates + spring+ferrule+rotor **5**	2 piezoelectric plates + spring+ferrule+rotor **5**	2 piezoelectric plates + ferrule+ spring (as a rotor) **4**

7. Driving Circuit

Current trend for driving ultrasonic motors consists of using switching amplifiers. The reason is that they considerably reduce the heat generated by the piezoelectric element.

For the 3rd design, a switching power amplifier type driving circuit was used. Major feature of this kind of circuit is that it acts as a voltage regulator. As load requirements change, voltage variations also occur. This kind of voltage regulator circuit is capable of establishing and maintaining a nearly constant dc output voltage.

A schematic diagram of the circuit is shown in Fig. 10.

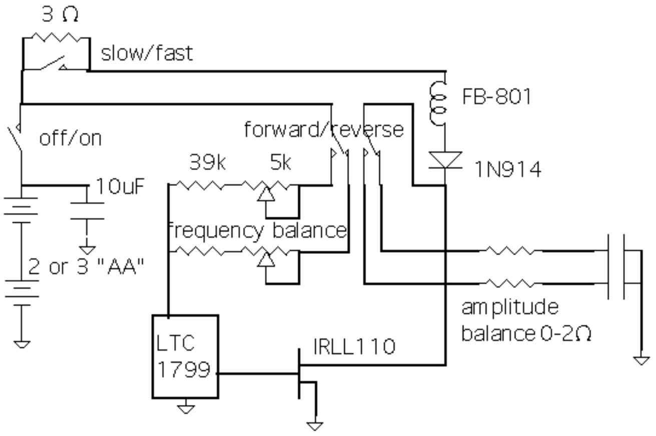


Fig. 10. Schematic of the driving circuit

8. Conclusion

The design, fabrication and characterization of a piezoelectric ultrasonic micromotor have been investigated.

The piezoelectric motor makes use of two orthogonal bending modes of a hollow cylinder. The vibrating element, stator, of the motor consists of a brass tube and two piezoelectric plates bonded to two flattened surfaces of the tube.

Three different motors were fabricated. In the first two designs, a solid stainless steel was used as a shaft, a spring as a pre-stress and a ferrule to hold the rod and the spring. Major improvement of the 2nd motor with respect to the 1st one was the reduction in the dimensions of the stator. 3rd motor was the smallest in length of all and the shaft was replaced with a spring. Consequently, miniaturization and simplification of the proposed design were achieved.

All three motors were characterized individually. Admittance spectra of the free stators, torque, power and efficiency values of each motor were presented.

Driving of the motor was enabled by a switching power supply. It is conventional and cheap.

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