

Flextensional Ultrasonic Piezoelectric Micro-motor

J.T. Leinvuo[†], S.A. Wilson, R.W. Whatmore and M. Cain^{*}
Cranfield University, Cranfield, Bedford, MK43 0AL, UK
National Physical Laboratory, Teddington, Middlesex, UK
[†] Present address: VTI Technologies Oy, Vantaa, Finland

Abstract

This paper presents the experimental design, construction and operational characteristics of a new type of standing wave piezoelectric ultrasonic micro-motor. The motor uses a composite stator, consisting of a metallic flextensional mode convertor, or “cymbal” bonded to a 2 mm square piezoelectric plate. The cymbal converts contour-mode vibrations of the plate into oscillations in the cymbal, perpendicular to the stator plane. These are further converted into rotational movement in a rotor pressed against the cymbal by means of an elastic-fin friction drive to produce the required rotary actuation. The motor operates on a single-phase electrical supply and direct control of the output speed and torque can be achieved by adjusting the amplitude and frequency of the supply voltage. Non-contact optical techniques have been used to assess the performance of developed micro-motor. The operational characteristics were developed from the acceleration and deceleration characteristics. No load output speed (11 s^{-1}) and stall torque (27 nNm) were derived using a high-speed imaging and image analysis. Maximum efficiency was 0.6 %.

Keywords

Ultrasonic, piezoelectric, flextensional, micro-fabrication, electrolytic, MEMS, cymbal, standing-wave, elastic-fin, high-speed imaging

Introduction

Piezoelectric ultrasonic motors [1] have a number of potential advantages. They maintain relatively high torque at relatively low speed without a reduction gear and exhibit a self-locking feature when electric power is turned off because the driving mechanics use friction between the vibrating stator and the rotor. They are light compared with electromagnetic motors and their equivalent inertias are low. They neither create electromagnetic fields nor are they affected by them. They also have many advantages for applications in micro- electromechanical systems (MEMS) because in contrast with electromagnetic motors, their simple construction makes them well suited for miniaturization and their overall efficiency is relatively insensitive to size. In order to compare ultrasonic and electrostatic motors, it is important to consider energy densities [J/m^3] of these two motor types. The maximum energy density for an electrostatic micro-motor is defined as $0.5\epsilon_{air} E_{bd}^2$, where E_{bd} is the maximum electric field before breakdown

($\sim 10^8 \text{ V/m}$ for $1 \mu\text{m}$ gaps) and ϵ_{air} is the permittivity of free space ($\epsilon_0 = 8.854 \times 10^{-12} \text{ Fm}^{-1}$) [2]. For the piezoelectric motor, the energy density becomes $0.5 \epsilon_{\text{PZT}} E_{bd}^2$, where the electric field can be equivalent to that with an electrostatic motor. A three magnitudes larger dielectric constant (PC4, $\epsilon_{\text{PZT}} = 1000 \epsilon_0$ [3]) is possible with piezoelectric materials. The greater the energy density is, the greater potential there is to have higher torque outputs from the motor. Several micro-motor designs have been published in the past years based on the travelling-wave principle. In general, travelling wave motors require at least two piezoelectric elements shifted in space, which are excited by AC signals shifted in phase. As a result, two-directional rotation can be achieved by changing a phase angle. Travelling wave principle is interesting because of its functional characteristics (two directional operation), but complex when realizing the design [4,5]. Another principle to drive micro-motors is a *standing wave*. Benefits of this method are a one phase driving method, which allows unidirectional rotation, and a relatively simple mechanical construction, which provides good opportunities for miniaturization [6].

This paper presents the design, construction and operational characteristics of the developed flextensional piezoelectric micro-motor. The 2 mm square motor, which is based on a meso-scale prototype [7], uses a composite stator, consisting of a metallic flextensional mode convertor, or “cymbal” bonded to a 2 mm square piezoelectric plate. The cymbal converts contour-mode vibrations of the plate into oscillations in the cymbal, perpendicular to the stator plane. These are further converted into unidirectional rotational movement in a rotor pressed against the cymbal by means of an elastic-fin friction drive to produce the required rotary actuation [8]. The driving mechanism is very simple since only a single-phase sinusoidal voltage is needed in contrast to traveling wave type motors [9], which need two-phase control electronics and are more difficult to manufacture. The manufacture of the micro-motor used a combination of novel microfabrication processes, including electrolytic etching and a microstamping technique to manufacture a matrix of 2 mm cymbals from a metal sheet. The cymbal matrix was further bonded onto the PZT with an epoxy resin. Indirect adhesive bonding is especially attractive in the manufacturing of piezoelectric devices. It is important to stay below the Curie point, which is, for example, 328°C for PZT 4 [10], in order to avoid the need to re-pole the bonded structure. The operational characteristics of the practical micro-motor were evaluated using high-speed imaging to measure the mechanical transient characteristics of the rotor. Based on the analysis of the images and a knowledge of the moments of inertia of the rotating parts (the rotor and encoder) and the acceleration, it was possible to calculate the torque. Measurement of the transient characteristics in this non-contact manner permitted the characterization of torques in the range of a few nNm's. Alternative contact based methods, such as pulley-brake or using an external encoder would have had more frictional losses and would have made measurements difficult in this range [11]. Parallel measurements of the electrical characteristics such as supply voltage, current and phase angle allowed measurement of the motor's efficiency.

Design and operational principle

The design of micro-motor is shown in Fig. 1. A square plate stator is attached at the plate's center point to allow free contour movement of the PZT driver. A static load is

applied to press the rotor in contact with the cymbal, and some lateral movement is allowed at the shaft to ensure even contact. The rotor has a jewel bearing in the middle to align the bias force pin. The jewel has so called olive shape center, to facilitate centering of the bias force pin. The practical dimensions of the motor are tabulated in Table 1. An operation of the flextensional micro-motor is as follows (in outline): the metallic cymbal flextensional amplifier converts vibrations of the piezoelectric plate to oscillations of the metal cymbal in a direction principally perpendicular to its plane. An elastic-fin rotor [12] further converts these cymbal oscillations to rotary actuation via three inclined fins pressed out of the rotors. As the vibrating surface is moving upwards (along the z-axis), the tip of each fin is held in contact with its surface by static friction. The rotation is generated by the horizontal component of the reactive force. When the vibrating surface is moving downwards the tips of the fins slip across the vibrating surface. Speed and torque are adjusted by varying the frequency and amplitude of the (single-phase) sinusoidal supply voltage.

Fig. 1. Schematic diagram of the micro-motor construction.

A PZT wafer (Ferroperm PZ26™, Ø50 mm, $t = 2$ mm) was lapped to 235 μm thickness. The flatness across the surface of the PZT was measured as ± 5 μm . Ti/Au electrodes were RF sputtered onto the lapped surface. The Ti and Au thicknesses were ~ 8 and 100 nm respectively. The surface roughness was measured as $R_a = 0.2$ μm using a Dektak 3ST surface profiler.

Micro-90[®] (International Products Corporation) cleaning solvent. Both sides of the wet sample were laminated with a photoresist 30 μm in thickness using a Dynachem 350 HR hot roll laminator. Photoresist was exposed with UV-light (Riston PC Printer 130) through a plastic phototool having cymbal features in it. The cymbal matrix was electrolytically etched using ferric chloride (FeCl_3). It was important that only the features to be etched were in contact with electrolyte during etching. The backside of the sample electrode was covered with an electric insulating tape. Only the top was left uncovered for the electrical connections. Both of the electrodes were assembled in parallel (spacing = 10 mm) in a specially engineered plastic jig. The sample electrode was connected to the anode (+) and the back electrode to the cathode (-). In practice, the etching time for a stainless steel cymbal matrix (AISI 316 HV 210, $t = 40 \mu\text{m}$) was 22 min when the area etched was $\sim 426 \text{ mm}^2$. The starting direct current and voltage were adjusted to 1200 mA and 2.12 V respectively. One sample of the etched cymbal matrix is shown in Fig. 2

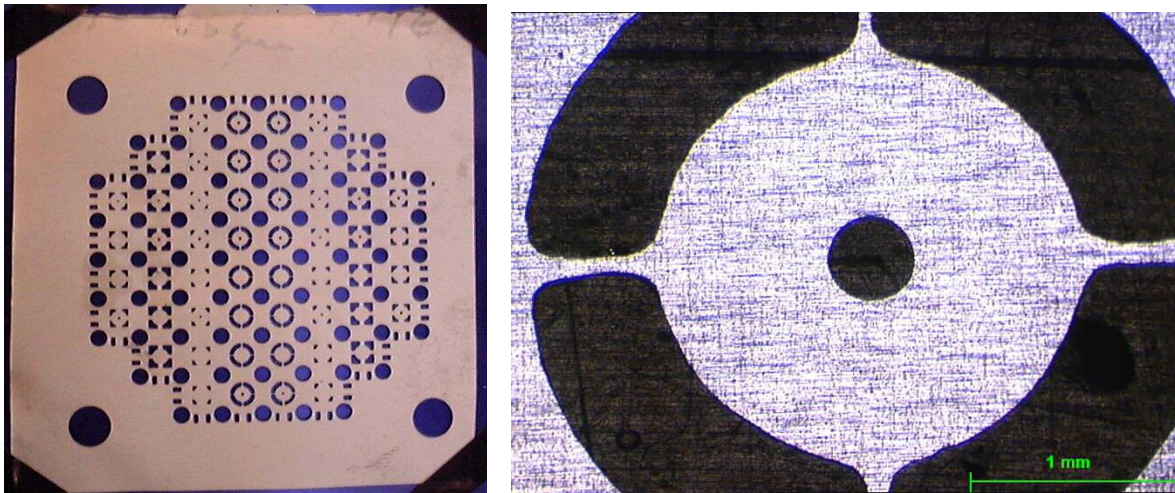


Fig. 2. At left a matrix of cymbal discs. At the right is shown the close-up of the individual disc etched from a stainless steel. Four supports locate a disc.

The sheet of cymbal discs were individually deformed to the designed cavity by stamping with matching punches and dies (Fig. 3). Fig. 4 and Fig. 5 show these in close up. Four guiding pins, shown in Fig. 4, center the tool parts. As a result the 3D matrix with 52 pieces of the cymbals were achieved.

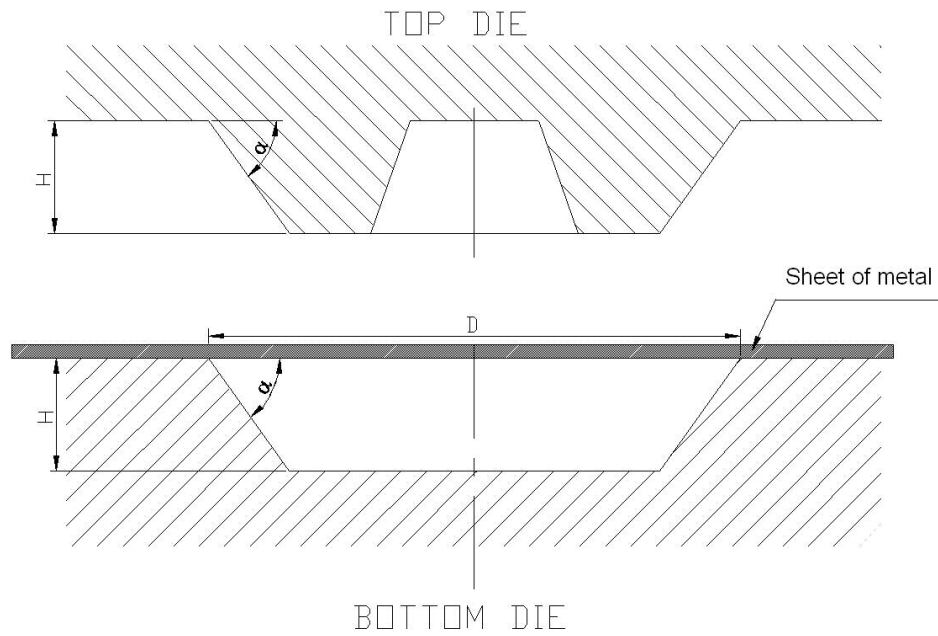


Fig. 3. Basic principle of the stamping technique. Parameters for D , H and α are 1.73 mm, 0.18 mm and 37° respectively

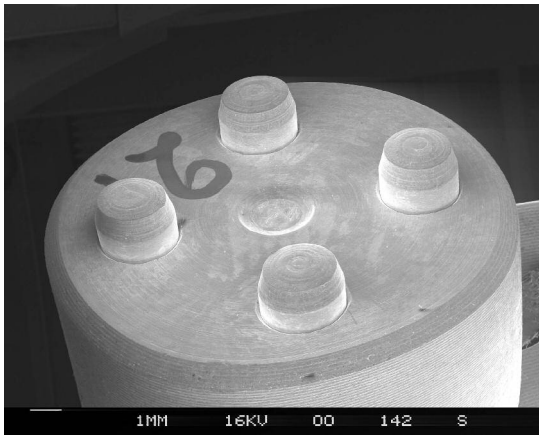
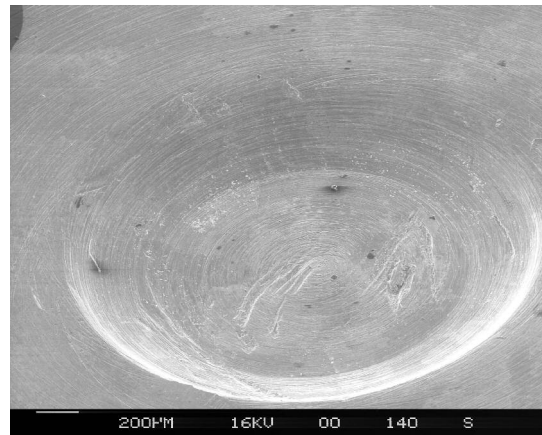


Fig. 4. On the left view of the base part with four guiding pins and on the right a close-up of the die in the base part.

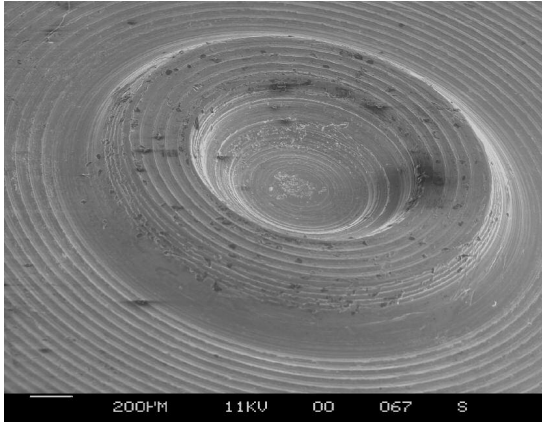


Fig. 5. A close-up of the matching die in the top part.

The 3D cymbal matrix was bonded onto the PZT disc using indirect adhesive bonding with an epoxy resin. The surface of the PZT and the cymbal matrix were both cleaned with 4% Micro-90[®] (International Products Corporation); the cymbals ultrasonically for 10 min and the PZT by wiping. After this, the PZT was covered with the adhesion promoter Ken-React LICA 38 from Kenrich Petrochemicals (mixture: 0.2 % with isopropanol) and then rinsed in a spin coating machine with isopropanol. Electrically non-conductive epoxy resin Epo-tek 301-2 was spin coated onto the PZT wafer. The bonding tool was coated with Loctite Frekote[®] Aqualine[™] C-200 mould release agent in order to avoid sticking. The bias force of 75 N at the temperature of 82 °C was applied for three hours. After bonding the electrical connections were opened by oxygen plasma etching (ashing) in a Polaron PT 7160 RF Plasma Barrel Etcher. The stators were separated from each other with a semiconductor saw (MicroAce Series 3 from Loadpoint). A cymbal matrix bonded onto the PZT can be seen in Fig. 6.

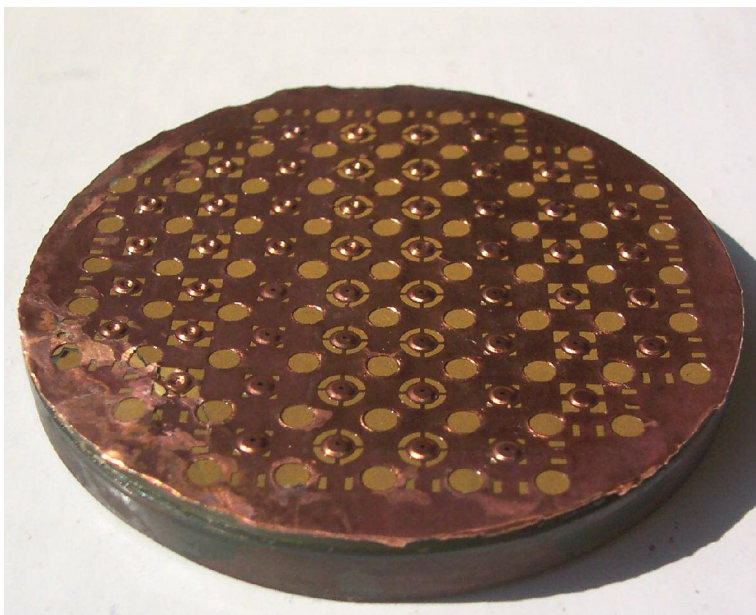


Fig. 6. A matrix of cymbals bonded onto the PZT.

The SEM image of a completed stator, after applying the signal wire, is shown in Fig. 7. A low frequency resistance of the electrical connections (50 kHz) was measured using Wayne Kerr Precision Component Analyzer 6425 integrated to the precision probe station. Resistance on the top was measured as $2\ \Omega$ across the corners of a square plate. The bottom electrode (fired-on Ag) was checked between two points and gave a resistance of $100\ \text{m}\Omega$. The resistance between cymbal and top electrode was measured as $8\ \Omega$. Signal wire (Au, $t = 40\ \mu\text{m}$) was bonded manually under a microscope by using CircuitWorks[®] CW2400 conductive silver loaded epoxy from Chemtronics. Bottom of the stator (center point) was connected to the steel post by a same conductive epoxy as mentioned above. Prior to testing it was connected into the electrical ground.

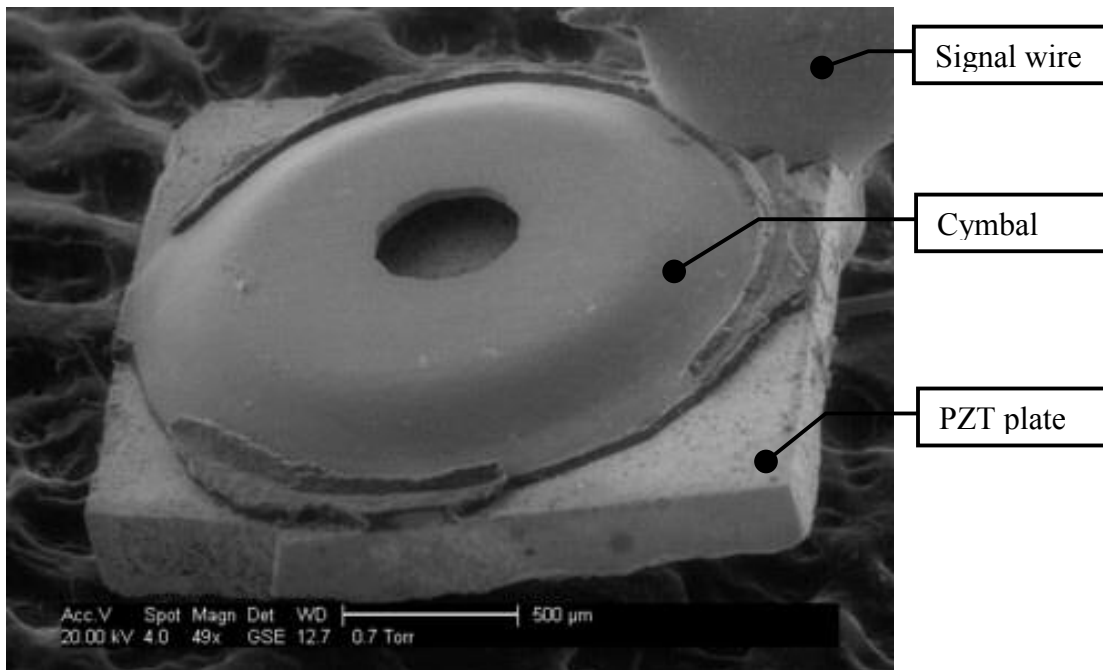


Fig. 7. SEM image of the practical stator with electric wire bonded onto the top right hand corner.

Rotors (Fig. 8 and Fig. 9) were manufactured using the same electrolytic etching process as explained above. In practice, the etching time for the stainless steel (AISI 302 (FE/CR18/NI8) HARD), $t = 25\ \mu\text{m}$) rotor matrix was 10 min when the area etched was $\sim 126\ \text{mm}^2$. The starting direct current and voltage were 1210 mA and 2.89 V respectively. Etching time for the encoder matrix (annealed copper, $t = 38\ \mu\text{m}$) was 22 min when the area etched was $\sim 26\ \text{mm}^2$. The starting direct current and voltage were 1235 mA and 4.43 V respectively. The fins were manually bent to the desired angle

under the microscope. The bearing (watch jewel) was also manually bonded under the microscope.

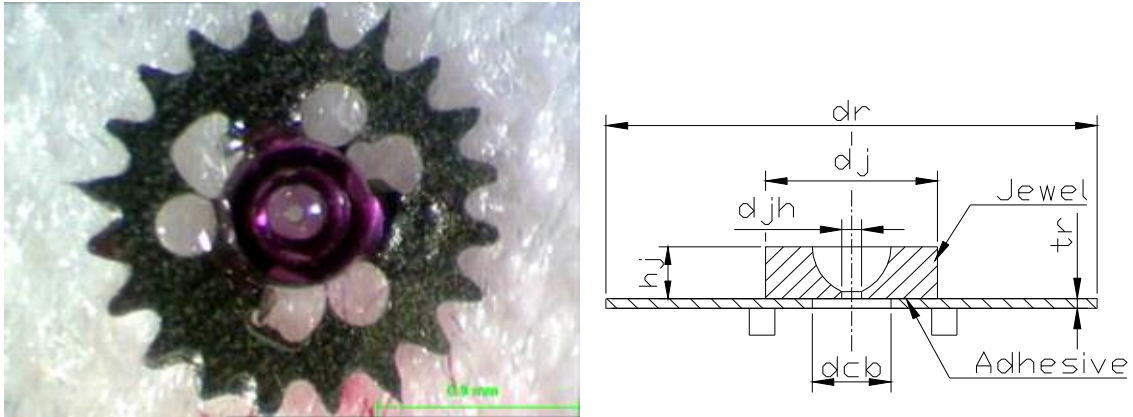


Fig. 8. On the left an image of the ready stainless steel rotor with a jewel bearing. On the right a cross sectional view of the jewel and the rotor.

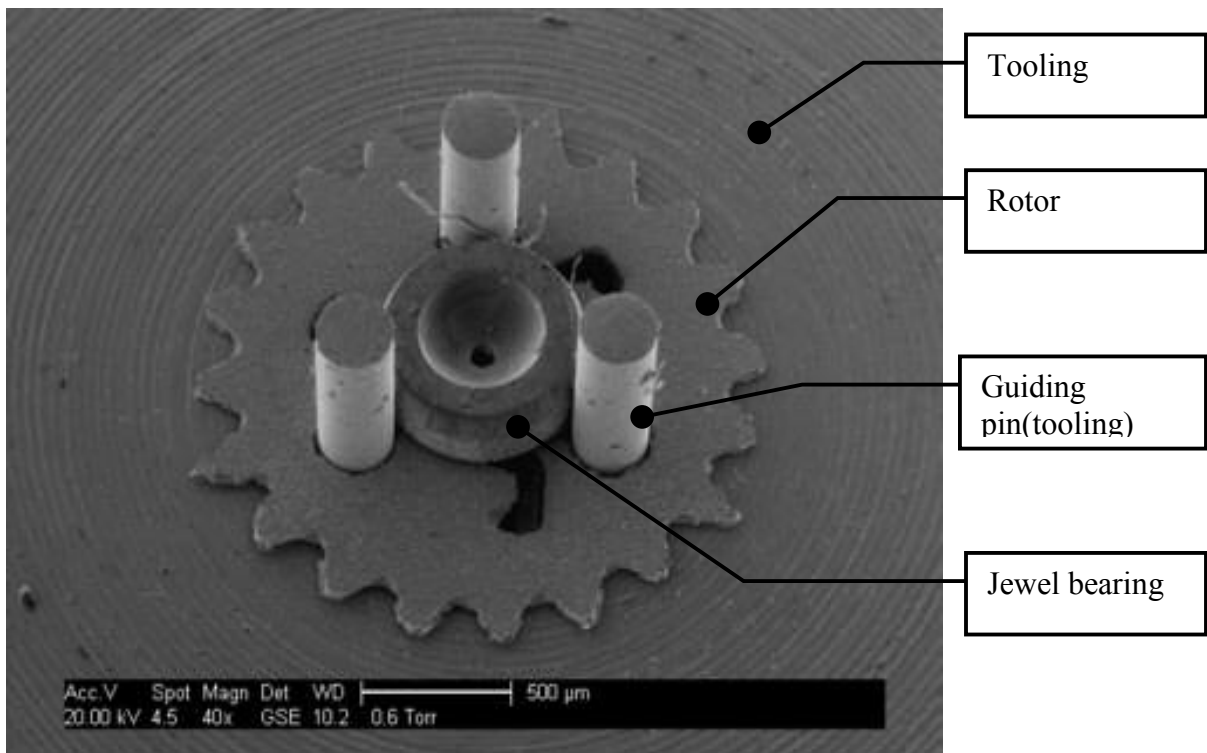


Fig. 9. SEM image of the fin bending and bearing centering tooling. Rotor is mounted onto the three centering pins and jewel bearing is located a middle. Diameter of each pin is 0.25 mm.

Table 1. Variables of the practical micro-motor.

Rotor variables	Copper encoder (Cu encoder), [mm]
Rotor diameter, d_r	4.9
Rotor thickness, t_r	0.038
Fin length, $l_f(1;2;3)$	0.17;0.16;0.15
Fin width, $w_f(1;2;3)$	0.08, 0.08, 0.11
Fin angle, $\theta(1;2;3)$	15;24;30
Radius of contact, $r_r*(1;2;3)$	0.43;0.36;0.47
(*) r_r is being defined in the middle of the fin	
Jewel dimensions	[mm]
Jewel diameter, d_j	0.7
Jewel hole diameter, d_{jh}	0.08
Jewel height, h_j	0.2
Stator dimensions	[mm], $\alpha = [^\circ]$
PZT width, w_s	2.03
PZT length, l_s	1.96
PZT thickness, t_p	0.235
Top electrode thickness, t_t	0.0001
Bottom electrode thickness, t_b	0.01
Bond thickness t_{bo}	0.004
Radius of mechanical boundary, r_p	0.40
Cymbal radius, r_c	0.95
Bonding ring radius, r_{cb}	0.88
Cymbal apex radius, r_{ca}	0.64
Cymbal's center hole radius, r_{cc}	0.21
Cymbal height, h_c	0.165
Cymbal side angle, α	35
Cymbal thickness, t_c	0.048

Stator characterization

Impedance characteristics of the micro-stator were evaluated by an impedance analyzer HP4192A. In practice, the stator was fixed onto the steel post. No rotor was attached during the measurements. An excitation voltage of $1V_{rms}$ was connected to the signal wire on the top electrode and the bottom electrode grounded via a steel post. Impedance and phase characteristics were downloaded to the database for analysis. The close-ups of the

characteristic are shown in Fig. 10. Resonance (f_m , Z_m) and antiresonance (f_n , Z_n) frequencies and impedances are 222 kHz, 4401 ohms, 223.5 kHz and 4942 ohms respectively. Mechanical quality factor $Q_m = 53$ was calculated by using equation (1). Capacitance $C_d = \epsilon_r \epsilon_0 A / t_s = 0.2$ nF, where $\epsilon_r = 1300$ (relative permittivity of PZ26 at 1 kHz), $\epsilon_0 = 8.854 \times 10^{-12}$ Fm⁻¹ (vacuum permittivity), $A = 4$ mm² and $t_s = 0.235$ mm (thickness of the practical PZT element). Effective coupling coefficient k_{eff} was evaluated as 0.12 (equation (2)).

$$Q_m = \frac{f_n^2}{2\pi f_m Z_m C_d (f_n^2 - f_m^2)} \quad (1)$$

$$k_{eff}^2 \approx \frac{C_m}{C_d + C_m} = \frac{f_n^2 - f_m^2}{f_n^2} \quad (2)$$

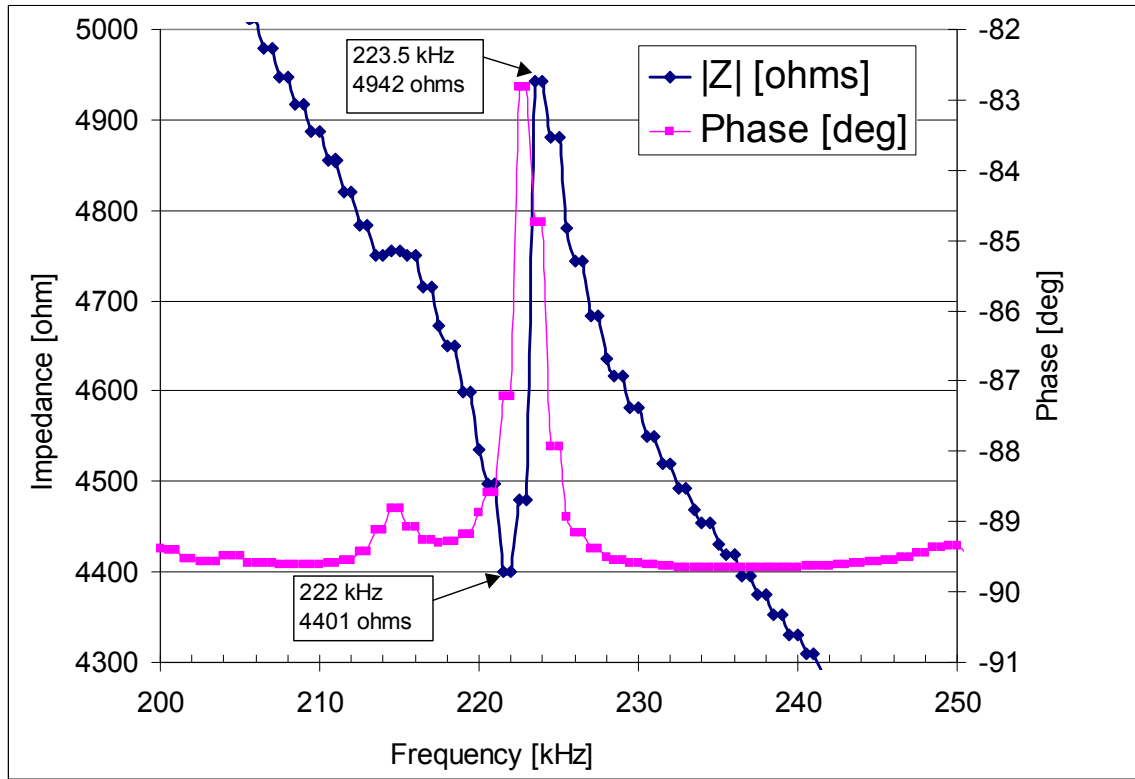


Fig. 10. Measured impedance and phase characteristics of the practical micro-stator close to operational frequency.

Motor characterization

In practice, the rotor was assembled on the top of cymbal under a microscope by a pair of needles. After this, bias force i.e. a static load (pin + load) was applied into the middle of the jewel bearing by a specially engineered sharp pin 0.8 mm in diameter. The encoder disc used in the characterization of the motor is presented in Fig. 11. The Cu disc is 5mm in diameter, 36 μm in thickness and has 70 holes on its outer radius. The black line in the north west of the disc is used as an indicator in transient and constant speed measurements as will be discussed below. Small holes on the disc's outer radius are used with fiberoptic sensor based constant speed measurements.

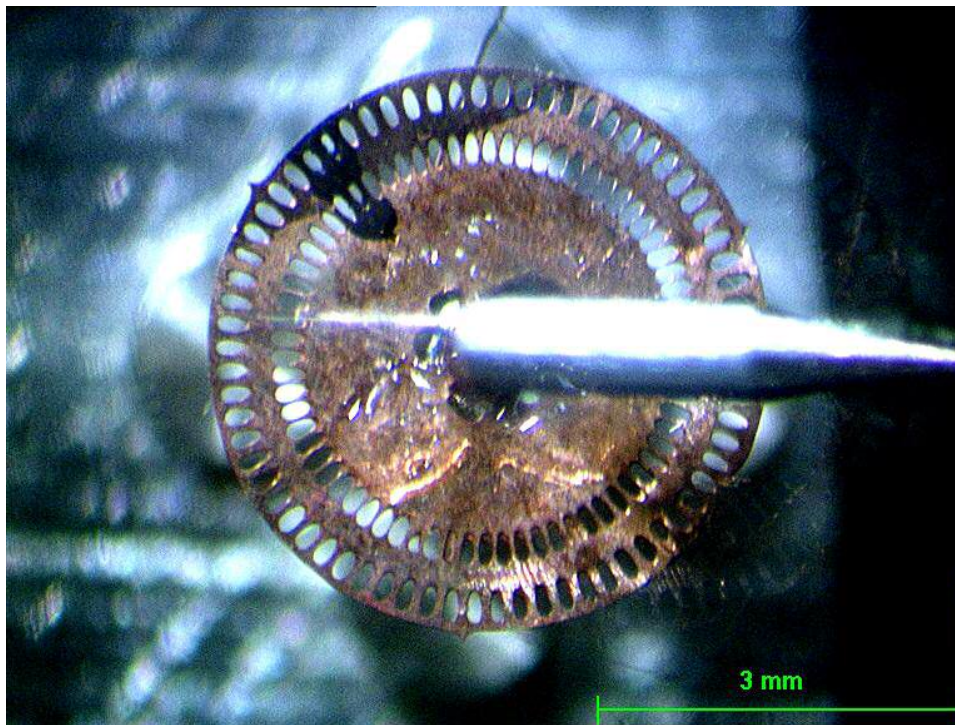


Fig. 11. Top view of the micro-motor with the Cu encoder disc ($\varnothing 5$ mm).

Motor's constant speed

An integrated encoder technique was used in parallel with the stroboscopic measurements when the constant speed of the motor was evaluated. In this technique the through-beam sensor head (FU 32) was connected to fiber optic amplifier unit (FS-V11P), which converted optical signal to the digital pulses [13]. In stroboscopic measurements the flash rate of the stroboscope was adjusted to a level where the black marking line became visible when the motor was operated. The constant speed was then read from the digital oscilloscope (National Instruments PCI-5102 [14]) based on the pulse rate. The rotational

speeds obtained with a stroboscope and fiberoptic probe were 11.2 s^{-1} and 10.2 s^{-1} respectively. The latter is approximately 9 % lower than that obtained with the stroboscope. The difference may have been caused by the uneven holes in the encoder disc (Fig. 11) or visual error in the stroboscopic method.

Evaluation of the motor's transient characteristics

Perhaps the most important measurement to characterize the micro-motor's mechanical characteristics are those of acceleration and deceleration. Once acceleration is known, the mechanical torque of the motor can be calculated from the rotor moment of inertia [15] (see equation (8)). Several potential measurement methods can be found in the macro scale. One of the most common methods is to use a ready-made encoder. The rough estimation from the similar macro motor shows that the use of the integrated encoder technique is difficult to apply since the number of encoder features is inadequate. In comparison the similar macro motor with a stator of size 25 mm (side length of the square plate is 25 mm) has stall torque of 0.47 Nmm [16]. The dimensional scale for the frictional force is two (L^2) and for the length one (L^1) [17]. The dimensional scale for the torque is then three, because the torque is a product of frictional force and fin-stator contact radius ($L^2 \times L^1 = L^3$). As a comparison dimension between macro and micro scale the side lengths of the stators can be used, which are 25 and 2 mm respectively. This leads to the scale ratio of $L = 25 / 2 = 12.5$. The estimated micro-motor torque is then $0.47 \text{ Nmm} / 12.5^3 \approx 0.24 \text{ } \mu\text{Nm}$. The acceleration for the micro-motor is now evaluated as 15484 rad/s^2 and time for acceleration $t_a = 4.5 \text{ ms}$, where the maximum speed is 11.2 s^{-1} (70.4 rad/s) and the moment of inertia of Cu encoder $J_{zz} = 15.5 \times 10^{-12} \text{ kgm}^2$. The time for one revolution is $1 / 11.2 \text{ s} \approx 89 \text{ ms}$. Using a linear relationship between the t_a , time per one revolution and a number of encoder features per one revolution, the number of encoder features per t_a becomes approximately three. This shows that the number of encoder features in a region of interest is not sufficient to evaluate acceleration. The minimum number of spatial sample points is four, in order to evaluate linear approximation of acceleration, which is the second derivative of displacement (d^2s/dt^2). Another way to use the encoder principle would be to increase the moment of inertia of the encoder in order to increase t_a , as was for example done in [18]. Because of difficulties to use integrated encoder technique in the transient measurements, here an alternative way to measure micro motor's transient characteristics will be described using a high-speed camera.

High speed imaging

The Phantom V4.0 is a color high-speed digital imaging system. The camera uses a CRS-CMOS imaging sensor with 512×512 pixel resolution. The frame rate can be adjusted from 1000 pps (i.e. pictures per second) with full pixel resolution up to the 30000 pps with allocated memory use. The imager is controlled via a FireWireTM (IEEE 1394) using Phantom[®] image analyzing software. Images are grabbed to the 256 Mb internal memory. 1024 images can be stored in a one second of time with 1000 pps. Once images are captured from the camera they can be played on the screen and processed.[19]

In order to gather angular velocity data, the position of the black marking line on the encoder disc (see Fig. 11) was recorded using the ready-built algorithm in Phantom[®] software. Collected points were arranged in Cartesian co-ordinate system as a function of image numbers (N) and time (t_N). The linear approximation of the radial displacement $z_N = \sqrt{(X_{r,N}-X_{r,N-1})^2 + (Y_{r,N}-Y_{r,N-1})^2}$ can be defined from co-ordinate points X_N and Y_N . Since the frame dependent time t_N is known from the sampling rate, the velocity v_N can be calculated as shown in equation (3)

$$v_N = \frac{z_N}{t_N - t_{N-1}} \quad (3)$$

Collected points (X_N , Y_N) were further converted to an angular velocity using equation (4), where the radius r_N was defined as $r_N = \sqrt{X_N^2 + Y_N^2}$.

$$\omega_N = \frac{v_N}{r_N} \quad (4)$$

It is now possible to evaluate the angular acceleration by taking the derivative of the angular speed (equation (5)).

$$\alpha_N = \frac{\omega_N - \omega_{N-1}}{t_N - t_{N-1}} \quad (5)$$

Now the angular displacement θ_N can be developed from linear displacement z_N by using a cosine rule (equation (6)).

$$\theta_N = a \cos \left(-\frac{(z_N^2 - 2r^2)}{2r^2} \right) \quad (6)$$

As a result, the rotational speed can be represented as a function of time (Fig. 12). The shown transient characteristics have been achieved by averaging eight measurement points in series. The fitted speed is based on the equation (10), where the time constant $\tau_a = 28$ ms. The fitted angular acceleration is achieved as a derivative of the fitted rotational speed (equation (5)).

The maximum acceleration $\alpha_{\max} = 270 \text{ s}^{-2} \approx 1700 \text{ rad/s}^2$ can now be evaluated from Fig. 12. The angular displacement θ during the acceleration is approximately 43° . It is important to notice that the step response of the motor is under damped thus 1st order approximation does not fully model the motor's transient characteristics. Under damping may be an indication of insufficient frictional contact between the rotor and the stator. Another indication of the insufficient friction is the stepwise movement of the rotor. When visually analyzing the data the motion indicated stick / release while acceleration

and during the constant speed. In practice, the fin dimensions are not equally the same in the practical micro-motor (see Table 1), which can easily be an origin of the stepwise movement and under damped characteristics. It should be noted that noise in the video signal, manually digitized co-ordinate points and lack of pixel resolution generated uncertainty in the measurements.

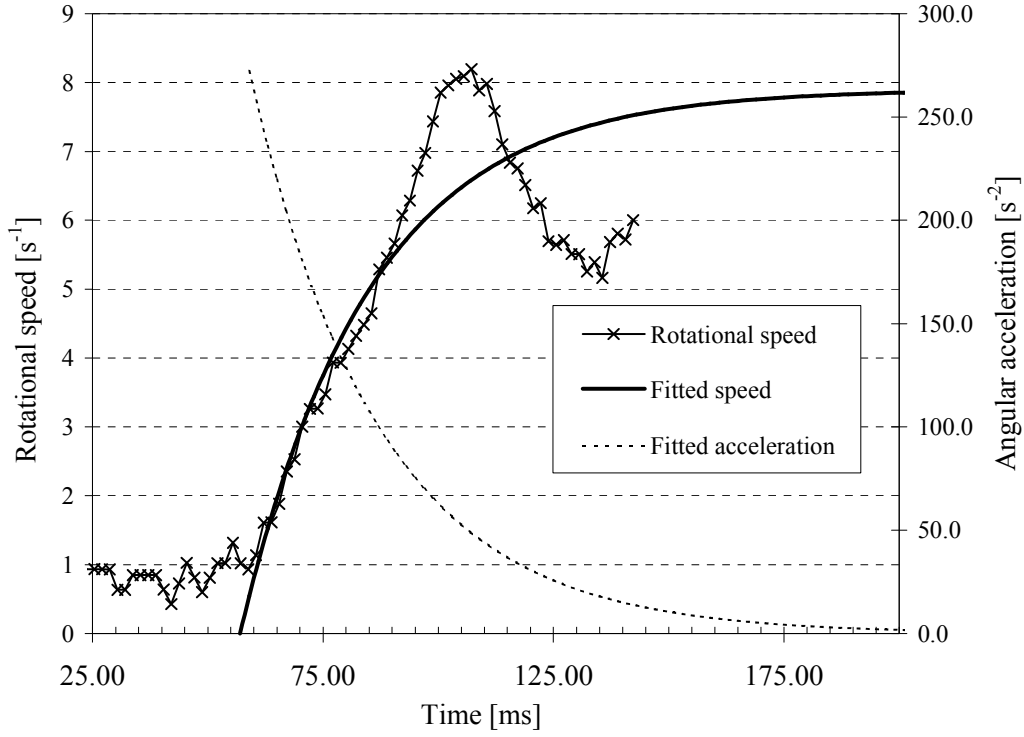


Fig. 12. Micro-motor's transient characteristics represented as a function of time.

The achieved deceleration characteristics of the micro-motor are represented in Fig. 13. The deceleration $\alpha_d = -730 \text{ s}^{-2} \approx -4600 \text{ rad/s}^2$ is evaluated by $d\omega/dt$ (equation (5), $t_1 = 114 \text{ ms}$, $t_0 = 102 \text{ ms}$, $\omega_1 = 1.6 \text{ s}^{-1}$, $\omega_0 = 10.4 \text{ s}^{-1}$). The fall time is $t_d = \tau_f = 12 \text{ ms}$. Angular displacement during the deceleration is approximately 20° . It is interesting to notice that the speed is not constant prior to deceleration. The same variation in a speed can also be seen after the acceleration. The variation of the data points is an indication of the stick / release of the rotor prior to deceleration.

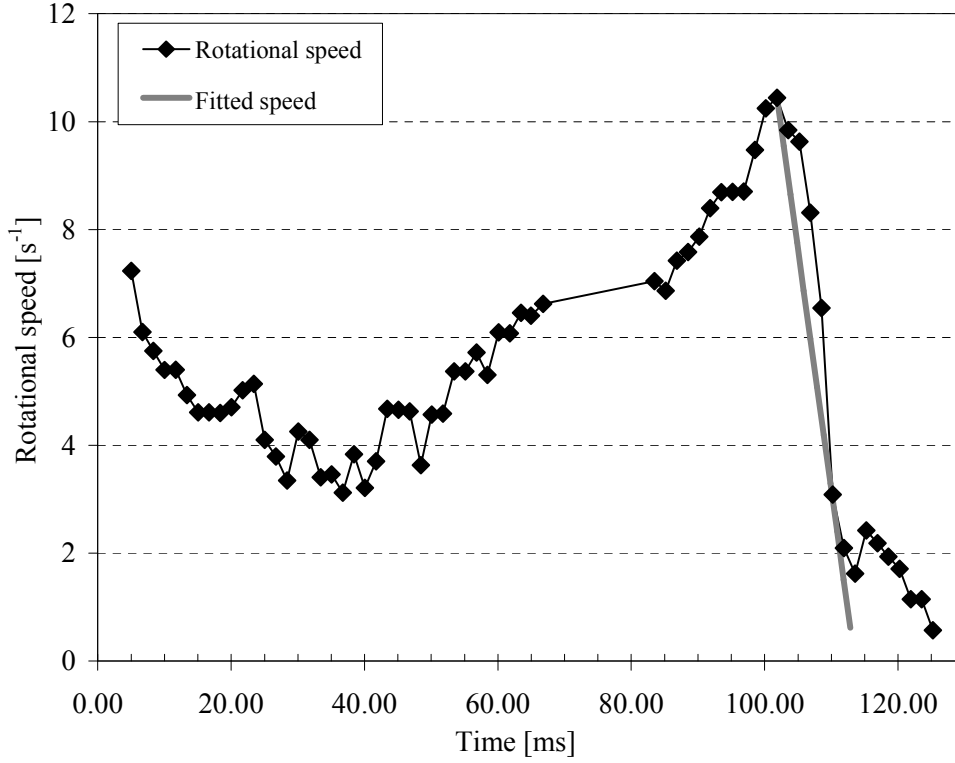


Fig. 13. Micro-motor's deceleration characteristics.

Electrical characteristics and efficiency

Parallel to acceleration and deceleration measurements the electrical characteristics of the micro-motor were evaluated by the PC integrated dual channel digital oscilloscope (National Instruments PCI-5102 [14]). Both of the channels were logged simultaneously, which allowed phase measurements.

The electrical power input, mechanical power output and efficiency are defined with equation (7). P_{loss} defines the electrical power loss generated by the measurement electronics. T_m is the torque of the motor [Nm] and ω the angular velocity [rad/s]. U_{in} and I_{in} are RMS voltage and current supplied to motor. $\cos\phi$ is power factor where ϕ is the phase difference between the voltage and current signals.

$$\eta[\%] = \frac{P_{out}}{P_{in} - P_{loss}} = \frac{T_m \omega}{U_{in} I_{in} \cos(\phi) - P_{loss}} 100\% \quad (7)$$

Torque and frictional coefficient from the transient characteristics

The torque of the piezoelectric motor can be defined using equation (8).

$$T_m = J_{zz} \alpha = J_{zz} \frac{d\omega}{dt} = J_{zz} \frac{d^2\theta}{dt^2} \quad (8)$$

Once the speed decreases from the no-load speed ($\omega_{\max}$) to zero, the torque increases towards the stall torque ($T_{m, \max}$) (equation (9)).

$$\omega = \omega_{\max} (1 - T_m / T_{m, \max}) \quad (9)$$

The solution for the rise curve can be represented with equation (10) after T_m has been eliminated from the equations (8) and (9). τ_r represents the time constant and is given in equation (11).

$$\omega = \omega_{\max} [1 - \exp(-t / \tau_r)] \quad (10)$$

$$\tau_r = J_{zz} \omega_{\max} / T_{m, \max} \quad (11)$$

The maximum torque $T_{m, \max}$ can be defined from the time constant τ_r when the moment of inertia is known. In order to define the speed/torque characteristics, the angular speed derivative $d\omega/dt$ must be calculated at every measurement point on the rise curve and substituted into equation (8).

After the vibrator is turned off, the frictional torque ($T_f = \mu m g r_r$) decelerates the rotation linearly (equation (12)). The μ , m , g and r_r are the frictional coefficient, mass of the rotor (m_r) and load ($m_{\text{load}} = 145 \text{ mg}$), gravity (9.81 ms^{-2}) and the radius of the contact between rotor and stator respectively.

$$\omega = \omega_{\max} (1 - t / \tau_f) \quad (12)$$

The time constant for fall time τ_f is written in a following form:

$$\tau_f = J_{zz} \omega_{\max} / T_f \quad (13)$$

By measuring the τ_f the frictional coefficient μ can be estimated by an equation (14).

$$\mu = \frac{J_{zz} \omega_{\max}}{m g r_r \tau_f} \quad (14)$$

Operational characteristics

The operational characteristics are based on the transient characteristics of the micro-motor. The achieved electrical and mechanical characteristics are tabulated in Table 2. **1. Acceleration characteristics** consist of frequency (f), acceleration time constant (τ_a), angular displacement during acceleration (θ_a), achieved maximum rotational speed ($N_{a,max}$) and maximum angular speed ($\omega_{a,max}$). **2. Deceleration characteristics** consist of the same parameters as are shown for the acceleration. Also, due to the linear nature of the deceleration the deceleration (α_d), frictional torque ($T_f = T_{m,d}$) and generated power ($P_{out,d}$) are included. In addition, calculated dynamic frictional coefficients (μ) are shown in the end. **3. Electrical characteristics** were recorded at the steady state conditions and are same for the acceleration and deceleration analysis. Three first variables starting from the left are the measured voltage (U_{in}), current (I_{in}) and phase angle (ϕ). Then there are shown the input power (P_{in}) and resistive power loss (P_{loss}). This approach differs from [15], where the electrical characteristics were logged simultaneously with the acceleration measurements. However, based on the electrical measurements with a similar macro-motor, the power input values measured in steady state conditions with different torques were in 1 % of margin with no practical effect to the efficiency [11]. The calculated frictional coefficient is in accordance with findings of previous research (for BeCu $\mu = 0.17$ [4]).

Table 2. Collection of achieved electrical and mechanical characteristics of Cu encoder.

1. Acceleration characteristics

f [kHz]	τ_r [ms]	θ_a [deg]	$N_{a,max}$ [1/s]	$\omega_{a,max}$ [rad/s]
224	2850.0	43	8	50
0				

2. Deceleration characteristics

f [kHz]	τ_f [ms]	θ_a [deg]	$N_{d,max}$ [1/s]	$\omega_{d,max}$ [rad/s]	α_d [rad/s ²]	$T_{m,d}$ [nNm]	$P_{out,d}$ [μW]	μ
224	12	20	10	66	5600	870	57	0.15

3. Electrical characteristics

U_{in} [V _{rms}]	I_{in} [mA _{rms}]	ϕ [deg]	P_{in} [μW]	P_{loss} [μW]
7	0.45	269	62	5.6

Fig. 14 represents the fitted speed torque characteristics of the micro-motor with following sampling conditions: $\Delta t = 0.1$ ms when $t \leq 1.3$ ms and $\Delta t = 0.5$ ms when $t > 1.3$ ms. The achieved maximum torque comes as $T_{m,max} = 0.027$ μNm. It is interesting to note that the achieved maximum torque is ~10 % of the estimated value based on the pulley-brake torque measurements of a similar macro-motor ($T_{m,estimate} = 0.24$ μNm [11]). The

difference could be explained by the bearing configuration. The macro-motor used a ball bearing and micro-motor a jewel sliding bearing (i.e. a coefficient of friction for the rolling is generally smaller than it is for the sliding). Detailed analysis related to the frictional losses is not included in this study. The achieved maximum efficiency was evaluated as $\sim 0.6\%$ (Fig. 14).

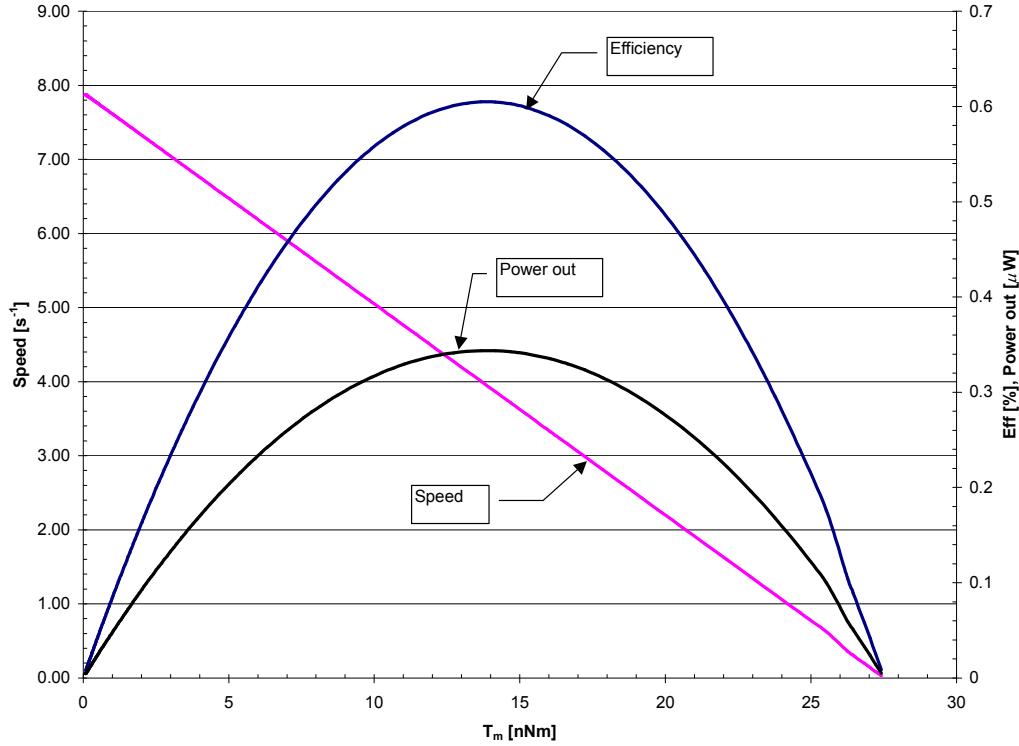


Fig. 14. Fitted speed torque characteristics of the flextensional piezoelectric micro-motor.

Discussion

This paper presented the experimental design, construction and operational characteristics of a new type of piezoelectric ultrasonic micro-motor in a range of 2 mm. The design used same principle as a similar macro-motor reported previously [7]. The design was scaled down by a factor of 12.5 and a different bearing configuration was adapted. A macro-motor used a ball bearing and here a jewel bearing was experimented. The motor design described here was especially designed to suit non-silicon MEMS manufacturing processes. Especially the square plate stator gives advantages in matrix based MEMS processes since dicing out of the devices can be made by using a standard semiconductor saw. Practical fabrication process included an electrolytic etching, which was used to fabricate rotors and stators in from the metal sheet. 3D structures were achieved by a stamping technique. Ready stator structures were achieved after bonding the cymbal matrices onto the lapped PZT plate. This manufacturing process proved to work, although

the yield of working stators in this prototype was only 20 %. Problems were mainly encountered in adhesively bonding and dicing. In bonding the cymbal grid stuck onto the bonding tool or was not bonded onto the PZT plate. In dicing some cymbals seemed to collapse. The possible reason for this may have been the water pressure in a dicing saw. With rotors, the bonding of the jewel onto the rotor was demanding. The cyanoacrylate adhesive spread out and control of the drop size was difficult. However, the methodology used here to manufacture 2 mm micro-motors of a relatively simple design is proven and further development could undoubtedly solve the problems outlined above. With the help of modern robotics, the fin bending, bearing attachment and final assembly can be made efficient and accurate. Based on the achieved experiences of the way to manufacture stator elements the adaptation to the series production should not be too difficult. The individual process steps are well known and after the fine-tuning of the separate steps, such as etch time and electrode arrangements, the quality of the end product can drastically be improved.

The stall torque (27 nNm) was evaluated from the fitted nonlinear representation of the acceleration. The transient characteristic was achieved from the recorded stream of images. The acceleration time constant and angle were 2850 ms and 43° respectively. First assumption based on the results from similar macro-motor suggested a factor-of-ten greater torque value should be achievable. The likely reason for the achieved result is the bearing configuration, which was here a jewel slide bearing. In macro scale the used ball bearing, in general, has a smaller frictional coefficient. Therefore it would be interesting to run a test in a macro-scale with a jewel bearing or perhaps in a micro-scale with a ball bearing. The rotor/stator frictional coefficient 0.15, evaluated based on the deceleration characteristics, is in accordance with the previous research where the same value was achieved for BeCu-BeCu interface [4]. This partly proves the reliability of the transient measurements. In the measurements reliability point of view it was important to evaluate no-load speed with fiberoptic sensor and stroboscopic techniques. Results obtained from all these three measurement gave practically the same reading.

The achieved maximum efficiency ($\sim 0.6\%$, Fig. 14) locates close to other micro-motor's using an elastic fin designs (0.17% [20]). In order to improve the efficiency the stick / release found from high-speed images (see Fig. 12 and Fig. 13) should be analysed in detail. Perhaps, a similar experiment as with macro-motor with different fin angles [7] could give answers for the optimal fin angle. Also increasing frictional coefficient with polymer coatings would improve the efficiency.

Acknowledgements

The authors gratefully acknowledge the partial financial support of the Engineering and Physical Sciences Research Council (EPSRC grant number GR/N 34017) and BAeSystems (Sowerby Research Center) in the development of the piezoelectric motor and the National Physical Laboratory in the development of the characterization system.

Reference List

- [1] K. Uchino. *Piezoelectric actuators and ultrasonic motors*, MA: Kluwer Academic, 1997.
- [2] Flynn, A. M., Tavrow, L. S., Bart, S. F., Brooks, R. A., Ehrlich, D. J., Udayakumar, K. R., and Cross, L. E., "Piezoelectric micromotors for microrobots," *Ultrasonics Symposium, 1990. Proceedings., IEEE 1990*, pp. 1163-1172 vol.3, 1990.
- [3] Morgan Matroc Ltd. - Unilator Division, Piezoelectric ceramic products UK.
- [4] Rayner, P., Piezoelectric ultrasonic motors and micromotors 2000. PhD Thesis, Cranfield Univ.
- [5] Maeno T., Tsukimoto T., and Miyake A., Finite-Element Analysis of the Rotor/Stator Contact in a Ring-Type Ultrasonic Motor *IEEE Trans. Ultrason., Ferroelect., Freq. Cont.*, vol. 39, pp. 668-674, 1992.
- [6] Tani K., Suzuki M., Furuta T., Sakuhara T., and Ataka T., "Develeopment of a New Type Piezoelectric Micromotor," Heidelberg, Germany, pp. 396-401, 1998.
- [7] Leinvuo, J. T., Wilson, S. A., and Whatmore, R. W., Flextensional ultrasonic motor using the contour mode of a square piezoelectric plate *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 51, no. 8, pp. 929-936, 2004. 0885-3010
- [8] Uchiki, T., Nakazawa, T., Nakamura, K., Kurosawa, M., and Ueha, S., Ultrasonic motor utilizing elastic fin rotor *Jpn. J. Appl. Phys.*, vol. 30, pp. 2289-2291, Sep, 1991.
- [9] T. Sashida and T. Kenjo. *An introduction to ultrasonic motors*, New York: Oxford Univ. Press, 1993.
- [10] B. Jaffe, Jr.W.J. Cook, and H. Jaffe. *Piezoelectric Ceramics*, London: Academic, 1971.
- [11] Leinvuo, J., Flextensional piezoelectric motors, PhD thesis 2004. Cranfield University.
- [12] Uchiki, T., Nakazawa, T., Nakamura, K., Kurosawa, M., and Ueha, S., "Ultrasonic motor utilizing elastic fin rotor," *IEEE Ultrason. Symp. Proc.*, Orlando, FL, pp. 929-931, 1991.
- [13] Keyence (UK) Limited, Sensors Vision Systems & Measuring Instruments 2001-2002, no. G2001-UK-2-0700, 2000. Keyence Corporation. Japan.
- [14] National Instruments, The Measurement and Automation catalog 2001 2001.

National Instruments. AUSTIN, TX.

- [15] Nakamura, K., Kurosawa, M., Kurebayashi, H., and Ueha, S., An estimation of load characteristics of an ultrasonic motor by *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 38, no. 5, pp. 481-485, 1991. 0885-3010.
- [16] Leinvuo, J. T., Wilson, S. A., Whatmore, R. W., and Gee, A. E., "Mesoscale piezo-motors: scaling issues and performance measurement," *Proc. 17th annual ASPE meeting*, St. Louis, MO, pp. CDROM, 2002.
- [17] I. Fujimasa. *Micromachines: a new era in mechanical engineering*, USA: Oxford University Press, 1996.
- [18] Dong, S., Lim, S. P., Lee, K. H., Zhang, J., Lim, L. C., and Uchino, K., Piezoelectric ultrasonic micromotor with 1.5 mm diameter *IEEE Transactions On Ultrasonics, Ferroelectrics, And Frequency Control*, vol. 50, no. 4, pp. 361-367, Apr, 2003.
- [19] Photo-Sonics International Ltd. Phantom V4 .0 data sheet. 2003.
- [20] Dubois, M. and Muralt, P., PZT thin film actuated elastic fin micromotor *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 45, pp. 1169-1177, Sep, 1998.



DSPACE

<https://dspace.org/>

A new flextensional piezoelectric ultrasonic motor - design, fabrication and characterisation

Leinvuo, Joni T.; Wilson, Stephen A.; Whatmore, Roger W.; Cain, Markys G.

2007-01-08

Elsevier

<http://hdl.handle.net/1826/1853>

Leinvuo JT, Wilson SA, Whatmore RW, Cain MG. (2007) A new flextensional piezoelectric ultrasonic motor - design, fabrication and characterisation. Sensors and Actuators A: Physical, Volume 133, Issue 1, January 2007, pp. 141-151