Mesoscale Piezo-Motors: Scaling Issues and Performance Measurement

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Keywords: Piezoelectrics, piezo-motors, steppers, measurement, fine-mechanisms.

Abstract
A novel (~10mm track diameter) piezoelectric/leg motor employed vibrating/standing wave indexing principles to generate arcuate step-motions of the order of 1µm. Measurements were needed for step-actions, speed, acceleration and torque of the order of 500rev/min, 100rad/s² and 0.001Nm (1Nmm) respectively. This placed the work in an interesting scale range where large-scale mechanisms might be scaled down but few demonstrations of this were available.

Motor
The standing wave type piezomotor shown in figure 1 converts contour vibrations of a piezoelectric plate to vertical oscillations of the principal response mode of a beryllium-copper disc 'cymbal' analogously to the musical instrument [1,2]. An elastic-fin rotor converts this to rotary actuation, via three inclined spring legs, the whole having been micromachined from beryllium-copper. The tip of each fin is held in contact with the cymbal surface via a vertical bias force. The fins act as levers and the rotor is propelled about its axis of rotation by the horizontal component of the reactive force. When the vibrating cymbal moves downwards the tips of the fins slip across its surface and the cycle progresses. The fin exhibits Lissajou-type motion components when engaging with the cymbal. Because of the leg-inclination, the motion and friction have greatest effect when the leg slope is ‘leading’ with higher contact force reduced contact when trailing with lower contact force on the return part of the cycle. Speed and torque are adjusted by varying the frequency and amplitude of the (single-phase) sinusoidal supply voltage. In operation the vertical displacement of the cymbal is proportional to the lateral displacement of the PZT plate. The motor design assumes that the fins act as rigid struts [1,3].

![Diagram of piezoelectric motor](image)

**Figure 1. Side profile of pzt-flexural motor.**

Speed and torque characterization stage
The stage employs force through two spring-strip flexures/sensors shown in figure 2. One (Type LCL-816G [4]) is used to measure the frictional force between rotor and stator. Another (LCL-113G) is used to measure torque in the motor. Since the measured voltages are relatively small (~20 mV) compared with actuation voltages (50 Vrms) noise protection for signals was provided. In order to increase signal to noise level signals were amplified 24 times with CM015 signal conditioning modules with signal conditioning adapter CM001 [5].
Figure 2. Structure of force and torque sensing element.

For torque measurements, a capstan pulley brake technique was employed. In this method the load is measured from sliding nylon monofilament line wound once around the rotor with one end attached to a known weight. Alternatively, two flexure force generator-cum-sensors could be used as shown in figure 3 with force sensed by strain-gauges and a bridge. When the rotation commences against the additional frictional force ($F_\mu$), this adds tension to one side of the line and reduces it at the other. Continuous operation requires that line frictional force is in proportion to pulley (bearing) surface length with kinetic friction coefficient ($\mu_k$). Holding torque is determined from the static frictional coefficient ($\mu_s$).

Figure 3. Capstan brake torque measurement using two flexure force sensors.

Speed measurement was made by counting pulses from a fibre optic probe mounted on the test stage, which sensed an angular encoder on the shaft. The sensor (FU-20, FS-V11P [6]) can detect targets as small as 0.01 mm. Achieved pulses (20 pulse /round) were converted to rotational speed information after capture using the high-speed counter of the I/O card (PCI-6023E [7]).

The motor drive was from the signal generator integrated with the PC (PCI-5401 [7]). Since the output signal of the card is ± 5 V there was a need to amplify the signal current and voltage to be suitable for the motor. For this purpose an APEX high power operational amplifier module (PA-90) was used specially designed for driving piezoelectric loads with adequate bandwidth and voltage ranges (± 200 V, 200 mA, slew rate 300 V/μs [8]).

In order to measure the electrical energy supplied to the motor, it was necessary to measure current, voltage and phase difference. Voltage was measured using a voltage divider since the input voltage range of the PC integrated digital scope (PCI-5102 [7]) employed was ± 50V. When calculating motor power it was important to apply power factor compensation in respect of the phase difference between voltage and current (cosΦ) to take account of capacitive and inductive load components. In addition losses caused by resistance in the high voltage circuit were taken into an account. The power factor was calculated from current and phase difference between input current and voltage signal. The phase difference was measured with reference to the unloaded amplifier set up for the same voltage and frequency as for the speed/torque measurements.
Test procedure and results
Referring to Figures 3 and 4, the test motor was mounted between an axial force sensor (force 1) and a micrometer screw slideway. With polymer monofilament line Ø 0.16 mm wound around the outer radius of bearing the axial force (frictional force) was adjusted to the desired level and the force 3 sensor adjusted to zero position with the precision micrometer to take up slack in the line. Another force sensor (force 2) was mounted also to a micrometer slide held stationary while adjusting frictional force via force 3.

Zero values of the sensor-readings were recorded in order to compensate possible offsets in measurements. The motor was driven from PC using specific user interface for the signal generator. The measurement data was collected with a Labview written program. Speed, current, voltage and force sensors were all monitored simultaneously on the screen.

The test was carried out adjusting the force 2 flexure settings until no rotation was detected, indicating stall torque. Columns in the recorded text file present measured data in a 10s time period [speed (rpm), Force 1 (V), Force 2 (V), Force 3 (V), Frequency (Voltage probe)(kHz) Frequency (Current probe) (kHz), Voltage (V rms) and Current (V rms)]. Once all data were collected to the text file it was converted, filtered and responses plotted using MATLAB. The force, voltage and current measurements were filtered using averaging. The result of speed measurement was filtered using media. The test stage allowed relatively easy evaluation of motor speed torque behaviour with different axial load conditions as has been demonstrated [1].

Figure 5 presents the graph achieved from the hard PZT (Morgan Electroceramics™, PC-4 material), 25X25X2 mm motor with \( \cos(\Phi) = 0.4 \), \( U_{in} = 50 \text{ V}_{\text{rms}}, I_{in} = 47 \text{ mA}_{\text{rms}}, f = 66 \text{ kHz} \) and force 1 = 740 mN. The graph indicates that maximum speed is achieved in no load conditions (450 rpm) and stall torque in zero speed (~0.47 Nmm).
Figure 5. Speed torque characteristics of piezoelectric motor.

Figure 6 presents achieved data of power output/input and efficiency. It can be seen that power output reaches its saturation point at 250 rpm i.e. about half maximum speed. This same trend was achieved with other tested combinations. The variation in power input values is practically stable with 8 mW variation shown, only 1% of the mean values. The last graph describes the obtained efficiency of power input and output which is calculated using following equation (1):

$$ \mu = \frac{P_{out}}{P_{in}} = \frac{T_m \omega_r}{U_i I_in \cos(\phi)} $$  \hspace{1cm} (1)

where $T_m$ is the torque of the motor and $\omega_r$ the angular velocity. $U_i$ and $I_in$ are RMS voltage and current supplied to motor. $\cos(\phi)$ is power factor where $\phi$ is the phase difference between the voltage and current signals.

Figure 6. Power output/input and efficiency characteristics of piezoelectric motor.
Conclusions
This paper describes a successful demonstration of the capstan pulley brake torque measurement principle and fibre-optic speed measurement at mesa-scale on piezoelectric flexure-motors to measure torque, speed and power efficiency. It is foreseen that considerable further reduction in scale may be possible.

Acknowledgements
The authors gratefully acknowledge the financial support of the Engineering and Physical Sciences Research Council (EPSRC) grant number GR/N 34017 and BAe Systems (Sowerby Research Centre).

References


