Operation of a quasi-static piezomotor in transitory frequency range up to resonance

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Short abstract:
Piezo motors are traditionally classified in two families: ultrasonic motors, operating at resonance, and quasi-static motors. However recent attempts have shown that some motor designs such as inertial motors could be used both in quasi-static and resonant mode.
In this paper, this approach is applied to a Piezo Actuator Drive (PAD). Experimental results demonstrate high torque in quasi-static mode and high rotation speed at resonance given the size of the motor. Furthermore, the motor can be operated over the whole frequency range, from 0Hz up to slightly above resonance without losing the position information. On the other hand, analysis shows that power requirements are high in the transition phase up to resonance and heat generation implies that only intermittent operation is recommended.

Keywords: Piezomotor, Resonance, Quasi-static

Introduction

Piezomotors are traditionally classified in two families: ultrasonic motors, operating at resonance, and quasi-static motors [1]. Ultrasonic motors have attracted most attention with numerous designs, while quasi-static motors such as the inchworm type have limited applicability. Nevertheless, both approaches are complementary: quasi-static motors are generally speaking capable of higher force/torque while resonant motors typically provide higher speed. However several attempts presented at the last Actuator conference challenge this classification:

- Some motors combine ultrasonic operation and quasi-static fine adjustment for positioning, for example the Leuven motor [2]. However these represent two independent features with discontinuous operation.
- In [3] a legged motor is modelled and driven both at “nominal” frequency (under resonance) and “overdrive” (above resonance). However the author notes that operation at the vicinity of resonances causes noise and sudden direction changes.
- Cedrat SPA [4] and other inertial motors can be driven in semi-resonant mode using a non-symmetrical square signal which, through the mechanical filter of the device results in the desired sawtooth movement.

The approach presented in this paper aims at merging quasi-static and resonant operation in a single system, providing the whole performance range from ultra low speed to resonance in a continuous sequence. The approach is applied to a Piezo Actuator Drive (PAD).

Construction of the PAD motor

In the PAD principle, two sets of actuators are used to generate a circular movement in the X-Y plane. This “wobbling” movement is converted into a rotation through a microgear [5]. From a modeling point of view, this arrangement can be seen as a simple 2-phase motor in which a voltage/displacement vector is rotated. The microgear adds as a high gear ratio and can be in a first approach modeled by an ideal contact without slippage.

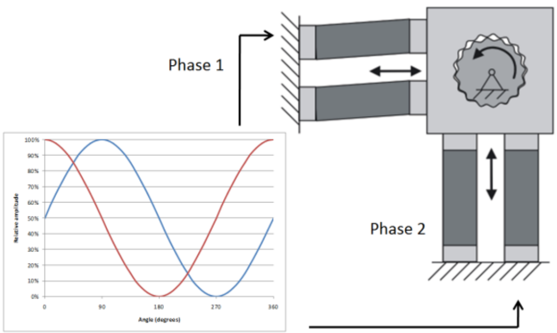

Fig. 1: *Basic principle of PAD motor*

The PAD principle can be applied to different types of piezo actuators. High power versions utilise multilayer piezoelectric stacks, but the principle can also be applied to amplified actuators, bending actuators or multi-axial bending actuators. For the present demonstration, a low power motor was used. It utilises multilayer bending actuators, 2 per phase. The de-coupling between the phases is obtained through a flexible structure machined in PEEK.

On the electrical side, all the benders are interconnected, leading to a 4-wire interface: 0V reference, 200V bias, “X” signal (0 to 200V) and “Y” signal (0 to 200V).

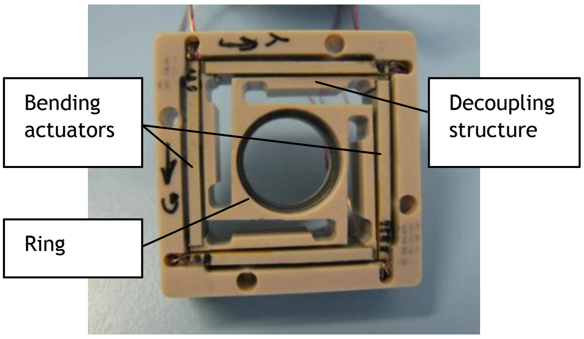

Fig. 2: *PAD motor stator*

The motor is assembled for a stator (with piezo elements), bearings and a shaft, centred on the stator.

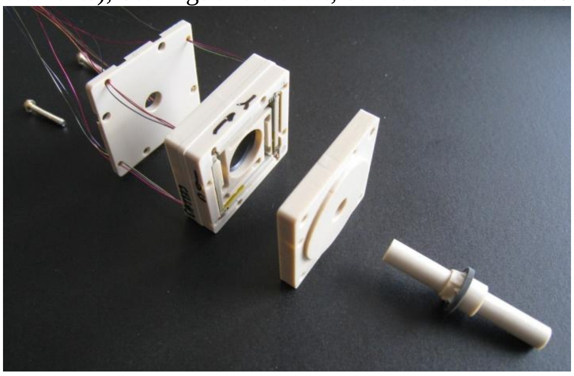

Fig. 3: *Assembly of PAD motor*

The considered PAD motor develops 3N.mm, measured at low frequency (quasi-static mode). Its speed ratio is 100 (i.e. 0,6rpm/Hz on the input signal).

Principle of the demonstration

PAD motors are demonstrated and tested at frequencies far from the first resonance f_0. In order to avoid overshoot, it is normally recommend to stay below $f_0/3$. The target of this experiment is to demonstrate operation up to and beyond f_0. To that purpose, it is important to understand and control the dynamic behaviour of the stator, i.e. phase and amplitude of its movements.

The basic principle behind the PAD motor design is to generate a circular motion from X-Y movements, i.e. combining sine-cosine displacements. In order to maintain the circular motion, it is understood that the X-Y signals must:

- Have a phase shift of 90°
- Have similar amplitude

These conditions lead to a "perfect" circular motion. In practice the motor will turn and provide consistent performance as long as the X-Y motion is larger than the desired circle. Restricting the analysis to sinusoidal input signals, the maximum allowable phase error between X and Y signals can be plotted depending on the relative amplitude of the (X; Y) movements. The nominal operating point is (1; 1), where any phase error would cause the trajectory to intersect with the desired unit circle, leading to lower performance. A margin of 20% on the amplitude of both signals, i.e. operating point (1,2; 1,2) allows an error of up to 17° on the phase.

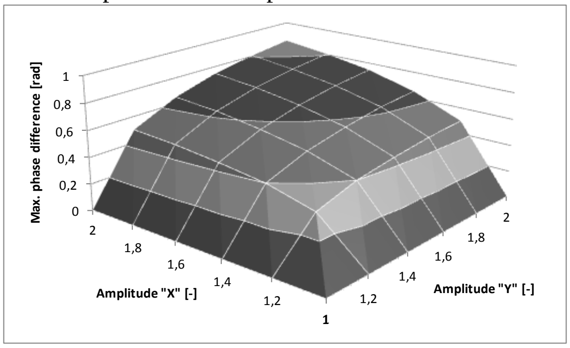

Fig. 4: *Maximum allowable phase error*

At the vicinity of resonance, a simple harmonic system will be affected both by amplitude and phase changes.

When applying an input signal of constant amplitude and increasing frequency, output amplitude (displacement) will increase up to resonance, then will decay rapidly. However it should be noted that for an under-damped harmonic oscillator (as it is the case for most rigid mechanical structures), amplitude only drops below its static value for f/f_0 = 1,3 to 1,4. In other words, there is potential for operation up to 1,3 times the first natural frequency.

Phase changes are more critical for operation, because phase tends to change more rapidly, any mismatch leading to a "flattening" of the trajectory which can affect operation. In extreme cases (more than 90° phase difference), the effect can be a sudden change in motor direction as observed in [3].

Frequency analysis

A simple modelling can be performed. The stator represents a spring-damper-mass system both in "X" and "Y" direction (the two "phases"). The piezo effect is modelled as a force input.

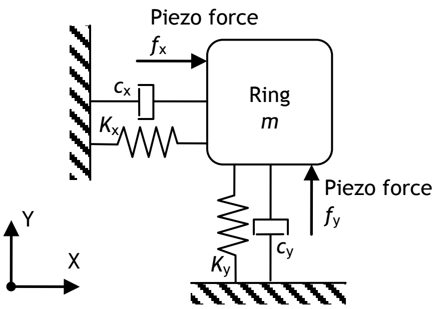

Fig. 5: *Dynamic model of the stator*

In such a system, stiffness and mass can be estimated from the characteristics of the mechanical parts. Damping is more difficult to foresee as it will depend largely on material parameters that are difficult to find (quality factor) as well as the quality of the bonding.

Parameter	Value	Unit
Bender stiffness	44	N/mm
Stator mass	1,9	g
First resonance	1080	Hz

Table 1: *Expected parameters*

From an electrical point of view, due to the electro-mechanical coupling, mechanical characteristics are measurable from the electrical side. Applying a simple Mason model to each axis leads to:

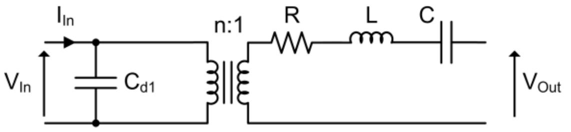

Fig. 6:*Mason model (one phase)*

V_{out} corresponds to a force applied on the moving member. R, L and C represent respectively damping, mass and stiffness. The conversion factor n represents the ability of the piezo element to generate a force. The parameters of the Mason model can be identified on the impedance spectrum, measured with HP4194A.

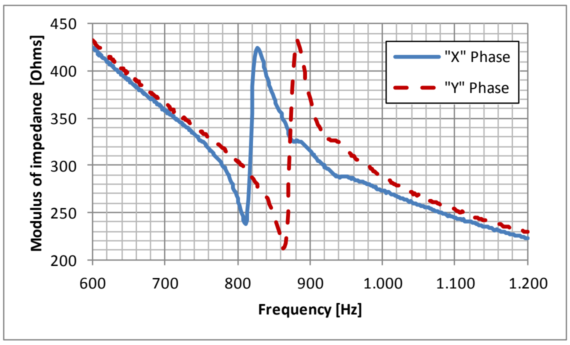

Fig. 7: *Impedance spectrum measurements*

Measurements on this particular sample indicate a significant difference between the two phases. The differences are due to variations in the position and on the quality of the epoxy bonding for each of the four bending actuators. This means that operation “at resonance” will not be ideal. Nevertheless this particular motor was demonstrated across the frequency range up to overdrive.

Impedance measurements indicate a first resonance at 820-870 Hz, lower than the calculated results. This is expected as the model only includes the compliance of the piezo elements, not the compliance of the PEEK structure. From these measurements it is possible to identify the mechanical parameters for each phase:

Parameter	Phase X	Phase Y	Unit
Electro-mech. coupling	49,7	45,1	mN/V
Damping	0,27	0,32	N.s/m
Stiffness	56,9	50,1	N/mm
First resonance	872	818	Hz

Table 2: *Identified parameters*

The overall stiffness is lower than indicated in theory due to the compliance of the housing, in series with the piezo benders. Damping is high due to the plastic structure. In practice this can be an advantage as ringing will be avoided and a wider resonance will lead to smoother phase transition.

It is however well known that resonance shifts for large signal excitation. An investigation was performed with large signals and identified the resonances at 6% lower frequency. These values were used in the compensation model.

Experimental setup

The experimental setup is composed of signal generators and drivers for each axis. The signals are generated on a PC and transferred to the signal generators through USB/GPIB interface.

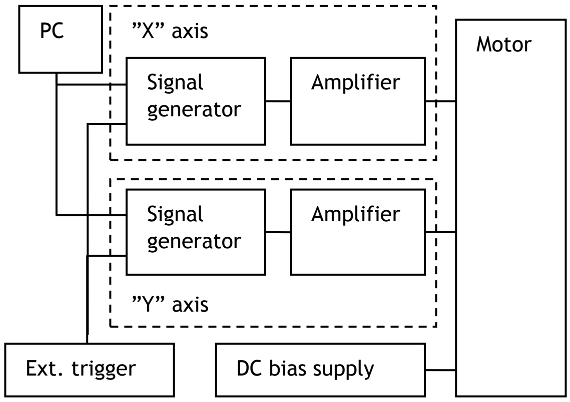

Fig. 8: *Test setup schematic*

In a first approach, input signals for X and Y are generated using the inverse of the frequency response, i.e. based on the frequency, defining for each point the phase and amplitude that have to be applied in order to obtain a “nominal” displacement. This approach assumes that transients are negligible; a more advanced method would be to solve the differential equation of movement. Still, in this example the method doesn’t affect the demonstration.

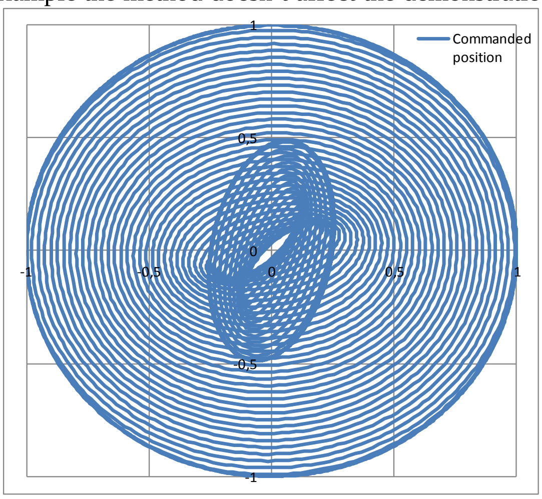

Fig. 9: *Sample trajectory of the voltage vector*

In addition, in order to cope with errors in the estimation of phase as described above, a “margin” of 20% is added on the amplitude, with the limit of the nominal voltage (200V). The resulting signals on an X-Y plot resemble a spiral as amplitude decreases up to resonance, then phase evolves leading to elliptical trajectory. Amplitude increases again in “overdrive” conditions.

Test results

During the experiment, the motor was accelerated from 0 to 900Hz (540rpm) in 0,12s, corresponding to an acceleration of 4500rpm/s. Maximum speed is maintained during 0,102s, enough to perform 330° of rotation, then the motor is decelerated back down to 0Hz. Overall, the motor travels exactly 2 full turns in 0,34s. The fact that the motor performs the expected 2 full turns repeatedly shows that the position information is not lost. In other words, there is no “step” loss.

However, tests showed that it was easier to “jump over” the resonance regime than to sustain continuous operation at resonance. This is probably due to the lack of resonance tracking as well as to inaccurate model parameters.

Prospective system

From a motor point of view, being able to operate continuously from quasi-static to “overdrive” is tremendous. Normally, the system would need to be limited to a fraction of the resonance frequency. Being able to “overdrive” brings the possibility of a factor 3 on peak speed.

From a driver point of view, operation over a very wide frequency and voltage range (from a few volts to 200V) can be a challenge. On the other hand in the presented case, operation from 0 to 900Hz can rely on the same hardware. The issue would be more critical if the first resonance was higher.

The controller required for such a system would be relatively easy to integrate. The algorithm based on frequency only (neglecting transients) required only few very simple calculations and readily available hardware is already fast and powerful enough.

A further refinement could be the implementation of resonance tracking based on current/charge measurements. That method would eliminate the uncertainties in the measurement of the initial dynamic characteristics

Discussion

Conditions for resonance and “overdrive” operation

The approach presented above can be generalised to other motor types. Similarly, the process demonstrated on a 2-phase motor can be applied to more complex structures. The basic requirements for operation in the transitory range (from quasi-static to over-resonance) are:

- Sufficient displacement for quasi-static operation
- Reliable dynamic characteristics, relatively low quality factor

In theory, motors with very different phase to phase characteristics, for example “legged” motors, could also use that simple approach, i.e. it should be possible to compensate for the characteristics of each phase individually. However it is an advantage to have both phases resonating at about the same frequency because higher amplitude on one phase can help accept errors in phase adjustment due to the other phase. In addition, the characteristics of these motors tend to change according to the load, whereas for a PAD a load change affects both phases in the same way. Finally, intermittent contact causes the dynamic characteristics to be unstable. As a comparison, a PAD relies on a continuous contact in rotation in the plane.

Power requirements

In quasi-static operation, the electrical load is mostly reactive, with an active component due to the hysteretic losses. Both components are proportional to frequency. Around resonance, in that particular case due to low coupling, the load is still mostly capacitive. However impedance is low and lower driving voltages imply that power requirements decrease. In overdrive, power requirements increase again.

This can be a challenge for the driver.

Conclusions

In this research, it was demonstrated that it was possible to operate a 2-phase motor across a wide frequency range, from quasi-static operation up to ”overdrive”, 10% above resonance. This enlarges the operating range of the motor by a factor 3.

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