Performance limitations of piezoelectric and force feedback electrostatic transducers in different applications

S. Hadjiloucas¹, G.C. Walker¹, J. W. Bowen¹ and L.S. Karatzas²

¹Cybernetics, School of Systems Engineering, The University of Reading, RG6 6AY, UK

²Temasek Polytechnic, School of Engineering, 21 Tampines Avenue 1, Singapore, 529757

email: s.hadjiloucas@reading.ac.uk

Abstract. Current limitations in piezoelectric and electrostatic transducers are discussed. A force-feedback electrostatic transducer capable of operating at bandwidths up to 20 kHz is described. Advantages of the proposed design are a linearised operation which simplifies the feedback control aspects and robustness of the performance characteristics to environmental perturbations. Applications in nanotechnology, optical sciences and acoustics are discussed.

1. Introduction

Electrostatic actuation has distinct advantages over piezoelectric actuation such as large bandwidth, small size and ease of fabrication, these characteristics are particularly useful in a range of micromechanical applications. After discussing some important application areas where current actuator technology hinders further progress and identifying electromechanical limitations, in the following section, the design of a force-feedback controlled prototype electrostatic capsule is presented. Such a transducer exhibits high linearity, minimal self-noise and extremely large bandwidth capability under closed loop operation. In sensing applications, these characteristics can be particularly advantageous. The issues involved in employing such a transduction topology in actuation applications will be also discussed.

1.1. Application areas dependent in advances in current piezoelectric actuator technology.

An increasingly large number of important advances in acoustics, ultrasonics, optical technologies and nanotechnology applications are linked to progress in piezoelectric transducers. In the optical sciences, maintaining accurate resonator lengths is of importance to continuous wave laser technology as many applications nowadays require improved frequency stability [1]. Furthermore, femtosecond pulse laser systems in ring resonator topologies also require tight control of resonator length so as to ensure carrier envelope stabilization or carrier offset phase control, e.g., for the generation of X-ray attosecond pulses [2] and in optical frequency metrology [3]. There are also important experimental techniques where two Ti:sapphire femtosecond ring oscillators must be operated in a master-slave configuration, e.g., in frequency comb spectrometry [4] where heterodyning of the individual frequency components of the femtosecond pulses leads to an infrared to RF frequency down-converted...
spectrum, or in asynchronous optical sampling experiments [5] for THz spectrometry. Insertion of
acousto-optic modulators within the resonator to modulate the path length is undesirable because of
insertion loss and dispersion issues, so piezoelectric transducers with a micro-mirror attached at the
front are the preferred solution. Carrier envelope stabilization schemes with a 50 kHz bandwidth are
commercially available from many manufacturers, but there is significant scope for improving this
bandwidth. The proportional, integral and derivative (PID) controllers needed may be implemented
using first order or higher order lead-lag (high pass) or lag-lead (low pass) analog compensators, with
appropriately tuned corner frequencies. In 30 cm long Ti:sapphire resonators, producing pulses at a
repetition rate of 1 GHz, state of the art piezoelectric stabilization schemes [6] show a jitter of around
0.45 fs over a bandwidth of 1 to 100 Hz, which increases to 1.5 fs in the 1 to 100 kHz bandwidth. This
jitter corresponds to a fractional frequency instability in the repetition rate (Allan variance) below
2.3 × 10^{-15} s^{-1}. Improving upon this figure will have profound implications in optical time metrology;
the goal for the next generation of optical frequency standards is a stability at the level of 10^{-18} per
year [7]. In addition, locking two oscillators in a master-slave configuration, becomes progressively
more difficult as the resonator lengths become progressively shorter and the repetition rate is increased
to 10 GHz (which corresponds to current state of the art systems). For a 1 GHz pulse repetition rate
system, a jitter of 1.5 fs corresponds to an ambiguity in the resonator length of 0.3 μm. For the 1 GHz
system, a 10-fold reduction in jitter would be needed for the system to be equally well locked. This
again demonstrates that a critical performance limitation in many femtosecond laser systems stems
from the performance limits of the associated piezoelectric stabilization scheme.

Furthermore, photo-acoustic imaging, as applied in anatomical and physiological studies, as well as
molecular imaging [8], also relies on developments in ultrasonic transducers that operate in the region
of 10 to 40 MHz. Applications such as skin, ophthalmic or intravascular imaging also require such
bandwidth. For acoustic microscopy applications where spatial resolution is the goal, a need for
transducers in the 100 MHz to 1 GHz range also exists.

Finally, in nanotechnology applications, scanning-probe microscopy is extensively used in imaging
of nanoscale features and estimation of intra-molecular forces, as well as to perform both localized
chemical vapor deposition and localized etching [9, 10] of a surface using a gas or electrolyte. Island
structures with dimensions below 100 nm can be produced in this way. Throughput-limitations,
however, imply that it can take a prohibitively long time to perform the scanning process in a serial
manner. In order to make such sensing and fabrication solutions attractive to industry, implementation
at video rates is required. Viable solutions in the future are likely to come in the form of a parallel
topology with many probes operating simultaneously. In addition, an increase in the electro-
mechanical gain-bandwidth product of the associated control loop, will also lead to an increase in the
positioning speeds of existing piezo-based systems.

1.2. Limitations in current piezoelectric actuator technology.

Unfortunately, positioning speed of piezo-based systems is limited by the lowest structural vibrational
frequency, because structural vibrations become substantial at frequencies close to the resonant
frequency, and can cause significant positioning errors [11]. Other practical limitations are a) the
actuator’s limited strength in tension (the tensile strength of a cylindrical actuator is approximately
10% of its strength in compression), b) hysteresis in the movement and c) the boundaries on
acceleration when driven by a periodic waveform. Acceleration increases exponentially with
frequency and the power dissipation demands upon the op-amp driving circuitry stemming from the
mass of the actuators increases significantly at higher frequencies.

Furthermore, there are electrical limitations in piezoelectric actuators. When these are driven by a
periodic voltage source of frequency below their resonant frequency, the system can be modeled as a
single capacitor which presents a frequency dependent impedance to the driving circuit:

\[ Z_{load} = 0.5 \pi f C_{PA} \]

where \( f \) is the driving source frequency and \( C_{PA} \) is the equivalent capacitance of
the piezoelectric actuator [12]. Step loads on the actuator contain high frequency Fourier components
which often result in large changes in \( Z_{load} \) overloading the driving circuitry. In addition, the non-
linearities and hysteresis present when large range displacements are needed limit the associated positional accuracy of current piezoelectric actuators unless more elaborate control schemes are adopted. For applications requiring the highest precision, it is possible to eliminate more than 80% of the non-linearities of the system dynamics by inverting the hysteresis nonlinearity, as this can be modeled as an input-nonlinearity using feed-forward control structures implemented using digital control. Although inversion-based approaches can achieve exact tracking of the desired position-trajectory, a key issue is the design of the output position trajectory. Some output trajectories might require very large inputs to achieve exact-tracking and such inputs can lead to an accelerated depoling of the piezo-positioners. In addition, the exact-tracking inputs found from inversion might exceed bandwidth limitations of the available piezo-drivers that supply the input voltages. Although the exact-tracking inputs found from inversion are unique, a compromised optimal input is usually sought that trades the exact tracking requirement to achieve other goals like reduction of input bandwidth and input amplitudes.

Digital control at high bandwidth can be conveniently implemented using National Instruments’ new R-series Field Programmable Gate Array-based (FPGA) Reconfigurable I/O (RIO) devices which are available in PCI, PXI and compact stand-alone programmable automation controller (PAC) formats, or using proprietary controllers from nano-positioning equipment manufacturers (such as PI’s E-712 nano-positioners) [13].

Generally, there are several manufacturers that will provide the subsequent high voltage amplification needed to drive the piezoelectric transducers. Off-the-shelf drivers have typical slew rates of up to 500 V μs⁻¹ and a large signal bandwidth in the region of 250 kHz. Unfortunately at higher frequencies, many of these drivers exhibit some pure time delays rendering them unsuitable for most demanding applications. Alternatively, APEX Microtechnology Corporation op-amps may be used in the control loop, to directly amplify the input signal from a PID or FPGA-based controller in a single stage [14, 15]. Such an approach can be superior to that offered by off-the-shelf drivers because the associated pure time delays can be eliminated while sufficient electrical bandwidth is maintained (a competitive slew rate of 300 V μs⁻¹ can be achieved for a system comprising of an AD817 pre-amplifier with a preset gain of 100 in conjunction with a PA78). Furthermore, the associated harmonic distortion and overall noise figures are superior. More importantly, the use of two monolithic op-amps in the design process to generate the high voltages required to drive the transducers, permits full access to the individual signals for simple open and closed loop characterisation of the controller-amplifier system using a vector network analyzer, so that the overall electro-mechanical feedback system can achieve the maximum possible bandwidth while maintaining adequate gain and phase margins.

2. Electrostatic transducer design considerations

2.1. Electrostatic sensing

The technology for electret transducers is well established [16] and a variety of acoustic sensors have been manufactured based on this principle. A significant advancement to this technology has been proposed at Reading, with the development of a force-feedback optical microphone [17]. The capsule comprises a partially metalised mylar film of very low mass, in an appropriately designed partly reflecting -to infrared wavelengths- housing.

For the electrode topology depicted in figure 1, assuming a polarization voltage \( V_p \), the electrostatic Coulomb force \( F \) between the electrodes exerted on the membrane of surface area \( A \) for an electrode-membrane separation \( s \) is given by:

\[
F = \frac{A \varepsilon_0 (V_p + V_s)^2}{2s^2} - \frac{A \varepsilon_0 (V_p - V_s)^2}{2s^2} = \frac{2A \varepsilon_0 V_p V_s}{s^2}
\]
where $\varepsilon_0$ is the permittivity of air. The important advantage of the chosen electrode topology is that the force applied to the metalized membrane is linear with respect to electrode signal voltage $V_s$.

Sensing the motion of the membrane involved in the transduction process is performed interferometrically. In the case of Michelson interferometry (MI), the fringes can be linearised with appropriate sine and cosine transformations whereas in the case of Fabry-Perot interferometry (FPI), the linear part of the Fabry-Perot fringe dictates the dynamic range and responsivity of the transduction process. The use of an optical method for detecting diaphragm displacement provides a fast non-contact measurement signal of high responsivity and low-noise figure suitable for feedback applications. Furthermore, it ensures that the membrane displacement measurement does not interfere with the electrical feedback signal that controls the diaphragm behavior.

In order to minimize errors in the sensing scheme (laser intensity and phase noise), good practice requires the use of a Zeeman-stabilized He-Ne laser under closed loop operation to sense the fringes associated with the membrane motion. The control signal for Zeeman stabilization can be obtained by monitoring fringes in a separate temperature controlled Fabry-Perot cavity. Alternatively, one can use the intensity signal from a molecular fluorescence transition to generate the required feedback control signal in the laser stabilization scheme.

2.2. Electrostatic actuation

The combination of optical sensing and force feedback has only been previously discussed within the context of acoustic detection. In that work, the aim of the electrostatic force was to maintain the membrane in the same position throughout the duration of the disturbance whereas in an actuator application, the objective is to use an interferometrically generated control signal to drive the electrostatics so that the membrane moves along a desired trajectory.

A drawback in electrostatic actuation is the existence of pull-in instability (force proportional to the inverse of the square of electrode separation) which typically limits the stable travel distance of the actuators. There are three approaches to minimize such instabilities, the tunable capacitor (zipper) method, the leveraged bending method, which alters the area of the corresponding capacitor formed between the two electrodes, and the non-linear strain stiffening method, where a spring is used to pull one plate away from the other. In the three electrode topology depicted in Figure 1, the plate area in the electrodes is much larger than the gap, so fringing fields can be neglected and one can tune the position of the conductors by controlling the voltage or charge. A zipper stabilization technique [18] using a matched MOS capacitor of capacitance $C_1$ in series with the electrostatic actuator of capacitance $C_0$ can lead to a partly linearised motion over a limited range. The series capacitor and original actuator form a voltage divider that provides negative feedback to stabilize the system [19].
Controlling the charge rather than the voltage on parallel plate actuators is considered a superior method as it increases stability [20].

3. Some results and discussion

Figure 2 shows the response of a prototype capsule with and without negative feedback. It can be seen that the application of feedback linearises the transducer response across a range of frequencies (from 10 Hz up to 20 kHz).

![Natural frequency response of capsule](image1)

![Feedback controlled frequency response](image2)

Figure 2. Bode electro-mechanical response of prototype capsule across a range of frequencies with and without negative feedback.

A small deviation from linearity may be observed at 7.5 kHz. It should be possible to eliminate this non-linearity using an improved compensator design. The current experimental set-up precludes further testing at ultrasonic frequencies although there is significant scope for extending the transducer frequency response in the MHz range. The controlled response, however, is already demonstrating a useful bandwidth beyond the capabilities of most commercially available piezoelectric transducers.

4. Conclusion

For the implementation of an ultrasonic transducer, future efforts will concentrate on further improving the attainable bandwidth well beyond 20 kHz by choosing a controller roll-off frequency much smaller than 12.5 dB per decade which was used in the current prototype and adopting an integrated interferometric fibre optic method for monitoring the motion of the diaphragm. An analog PID control scheme is sufficient for generating the required control action because the proposed system is linear. The long term stability is immune to environmental perturbations because the associated Coulomb force remains the same for a fixed electrode-membrane separation, polarization voltage and electrode area. With further developments, the proposed transducer has the potential to be employed as a sensing microphone suitable for observing biophotonic related photoacoustic and photothermal phenomena at high modulation frequencies, permitting superior spatial resolution measurements to be performed.

In the case of using an electrostatic actuator, it should be possible to tune the position of the conductors by controlling the plate charge according to the information obtained from the interferometric signal. The goal is the reduction of pull-in instability which typically limits the stable travel distance of electrostatic actuators. A high bandwidth electrostatic actuator exhibiting high
linearity would be useful in a range of nanotechnology as well as continuous wave laser and femtosecond pulse laser optics applications.

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