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DESIGN AND PERFORMANCE OF AN ELECTROSTRICTIVE-POLYMER-FILM ACOUSTIC ACTUATOR

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This paper discusses a novel electroacoustic transducer that uses the electrostrictive response of a polymer film. The active element of the transducer is a thin silicone-rubber film, with graphite powder electrodes on each side, that forms an array of bubble-like radiating elements. In experiments, radiated acoustic pressure and harmonic distortion of the electrostrictive-film actuator were measured in the frequency band 50–2000 Hz. A simple acoustic model was also developed to study the effect of various design and operating parameters on the actuator performance. Preliminary results from the experiments and simulations show that the electrostrictive-polymer-film actuator has the potential to be an efficient, compact, and lightweight electroacoustic transducer.

1. INTRODUCTION

This work involves the preliminary development of a novel electroacoustic transducer in which the sound-producing element is an electrostrictive polymer film. The transducer has been developed for application to active noise control (ANC), but is a general-purpose device. The motivation in this research is to determine how the characteristics of electrostrictive polymer films can be exploited in designing an electroacoustic actuator, and to see if electrostrictive actuation offers advantages over other approaches.

There are numerous types of electroacoustic transducers, based on electromagnetic, electrostatic, piezoelectric, and magnetostrictive actuation. The most common is the conventional electrodynamic (moving-coil) loudspeaker. Moving-coil loudspeakers tend to be relatively large and heavy, and there has been considerable effort to develop smaller and lighter loudspeakers [1]. Size and weight are a serious disadvantage in some applications, such as ANC systems in aircraft cabins, where weight restrictions can limit the allowable number of secondary sources. Electrostrictive polymer (EP) actuators are compact and very lightweight. Large displacements are achievable with electrostrictive actuating elements, making them good sound generators at low frequencies. Low-frequency performance is an issue for all electroacoustic transducers of limited size, and is especially important for transducers in ANC systems, since passive noise-quieting methods are ineffective or impractical at low frequencies.

Acoustic actuators based on the electrostriction of polymers have been proposed previously. Scheinbeim *et al*. [2, 3] describe an actuator that produces motion from the electrostriction of various polymer films. This device produces sound primarily by the change in thickness of a polymer film (or stack of films) caused by the electrostrictive effect. In contrast, the actuator described in this paper makes sound by using in-plane strains to produce essentially diaphragm bending (i.e., out-of-plane deflection) of the film. The

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apparent stiffness and mass of a polymer film that deforms in this manner can be orders of magnitude less than that for compression of the solid polymer. This means that our actuator couples well acoustically to the air and gives greater acoustic output (per surface area and per weight) for a given electrical input than other actuators based on polymer electrostriction.

2. PRINCIPLE OF OPERATION OF ELECTROSTRICTIVE FILMS

The actuator depends on a form of electrostriction of a polymer dielectric. In general, the term *electrostriction* refers to the generation of stresses or strains in a material in response to an electric field. However, the mechanism of electrostriction used by the acoustic actuator described in this paper is believed to be different from that of the more common electrostrictive ceramics or semicrystalline polymers. In the type of electrostriction used by our actuator, the strain results principally from the external forces caused by the electrostatic attraction of compliant electrodes, rather than from internal intermolecular forces due to lattice deformation.

Figure 1 shows the basic functional element of an electrostrictive-film actuator. A thin elastomeric polymer film is sandwiched between compliant electrode plates. The elastic modulus of the electrodes is much less than that of the film, and the length and width of the film are much greater than the thickness (edge effects are ignored). When a voltage is applied across the electrodes, the unlike charges on the two electrodes attract and the film is compressed by the resulting electrostatic forces.

The force per unit area that acts to squeeze the film is

$$f_{film} = \varepsilon_r \varepsilon_0 E^2 = \varepsilon_r \varepsilon_0 v^2 / h^2, \tag{1}$$

where f_{film} is the force per unit film area, ε_r is the relative dielectric constant of the polymer film, ε_0 is the dielectric constant of free space, v is the applied voltage, E is the electric field, and h is the film thickness [4].

If the polymer film is unconstrained and unloaded, then the strain in thickness resulting from the squeezing pressure represented by equation (1) is

$$s = -\frac{f_{film}}{Y} = -\frac{\varepsilon_r \varepsilon_0 v^2}{h^2 Y}, \tag{2}$$

where s is the strain in thickness and Y is the modulus of elasticity of the polymer film. Figure 2 shows the measured response of a silicone polymer film to an applied electric field. The characteristic quadratic response is evident. Most elastomeric polymers are essentially incompressible materials, with a Poisson ratio of nearly 0·5. Thus, there will be an in-plane strain equal to about one-half of that of equation (2). This linear model is strictly valid only for small strains [5]. However, it serves to illustrate the operation of the actuator. The in-plane strain is tensile and tends to increase the area of the film. It is this area increase that we take advantage of in the acoustic transducer design.

It is worth pointing out the differences between an EP film actuator and a conventional parallel-plate actuator with an air gap, such as might be found in an electrostatic acoustic actuator. Two factors make the driving force on the EP film greater. First, the relative dielectric constant of an electrostrictive polymer is greater than 1, while the relative dielectric constant is equal to 1 for an air-gap electrostatic actuator. Second, the electrodes of the EP film are compliant, and therefore allow conversion of field energy to mechanical work by stretching as well as by squeezing. In contrast, the rigid parallel plates of a conventional electrostatic actuator convert electrical energy to work only by moving closer together (squeezing). Because of this, the force per unit area acting on a parallel-plate

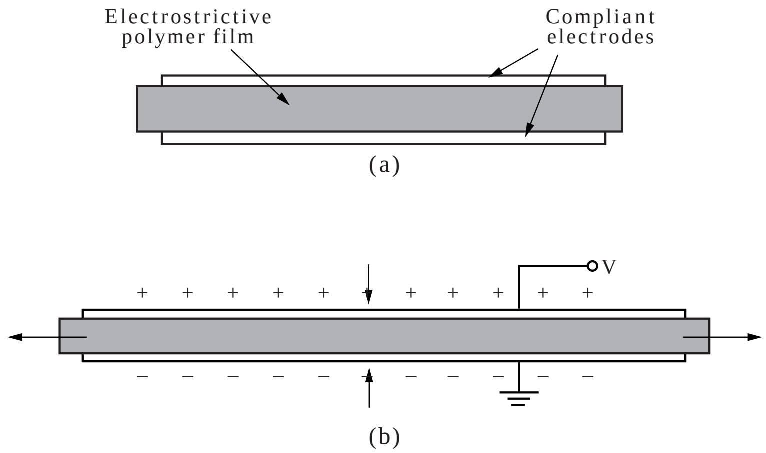

Figure 1. Principle of electrostrictive-polymer actuation: (a) voltage off, (b)voltage on.

electrostatic actuator is less than that of equation (1) by a factor of 2 [6]. Additional advantages of the polymer dielectric include the prevention of dust accumulation and the ability to flex the actuator to conform to curved surfaces.

The method of electrostriction described above has the advantage that the polymer dielectric material can be selected based on desirable physical properties, rather than just on the magnitude of the electrostrictive response for a given field. Desirable properties include high dielectric strength, high volume resistivity, low modulus of elasticity, low hysteresis, and wide temperature operating range (which give high energy density, high electrical to mechanical energy efficiency, large strains, high mechanical efficiency, and good environmental resistance, respectively). Materials with a high electrostrictive response, such as silicone rubber, have produced strains in thickness of over 25% [4]. This strain corresponds to an almost 27% increase in the film area. The literature does not show a material with an electrostrictive response of this magnitude.

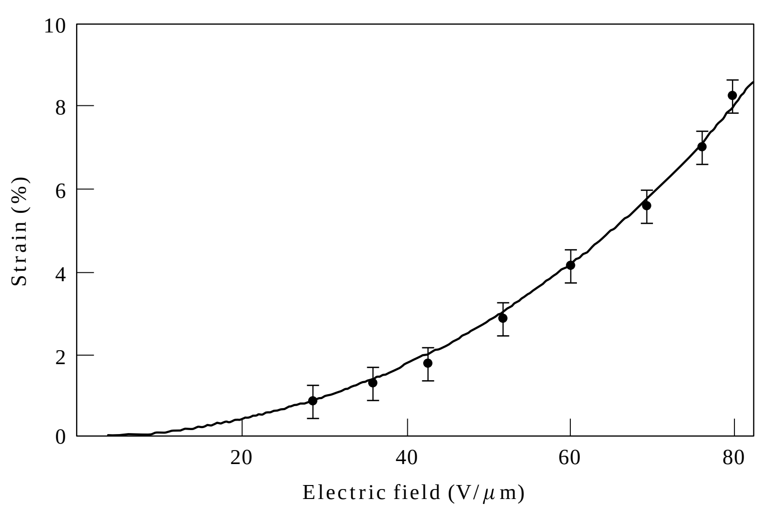

Figure 2. Experimental strain response of a silicone polymer film to an electric field.

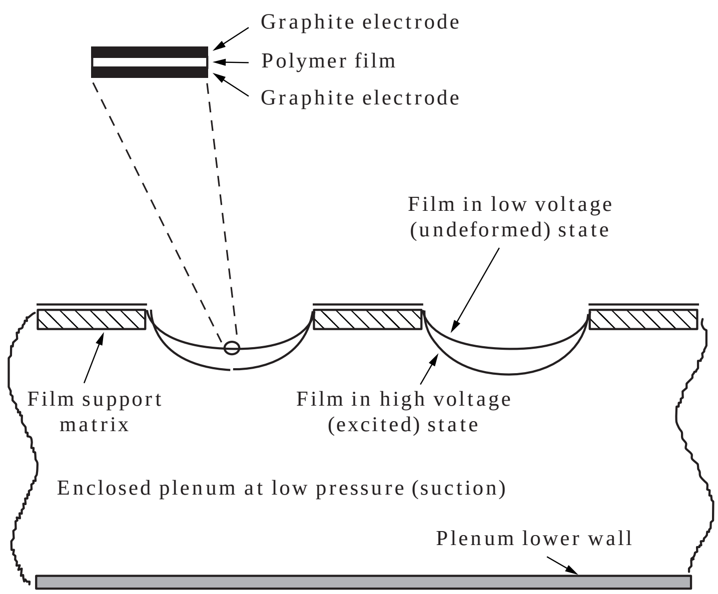

Figure 3. The electrostrictive polymer-film transducer (cross-sectional view), showing the design approach for obtaining out-of-plane film displacement.

3. ELECTROSTRICTIVE-FILM ACOUSTIC TRANSDUCER

To be an effective acoustic radiator, the film must displace a large volume of air (more precisely, it must produce a large volume acceleration). We achieved this in the transducer design by using the area change of the film under applied voltage to produce an out-of-plane (normal to the film surface) displacement.

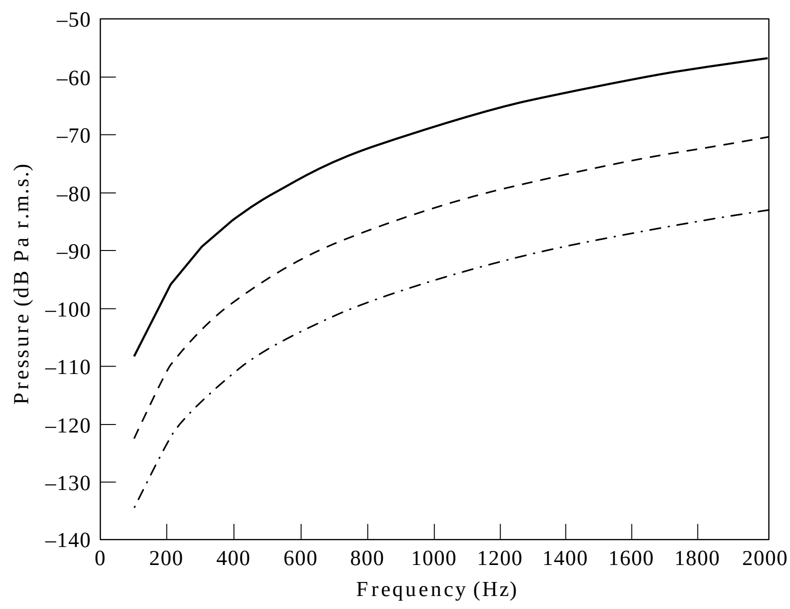

Figure 4. Effect of bias voltage on acoustic pressure 1 m from a bubble element: bias = 250 V (– · –), 500 V (- - -), 1000 V (—). Ratio of modulation to bias voltage = 0·25, bubble base radius = 1·25 mm, ratio of bubble height to base radius (z_0/a) = 0·5.

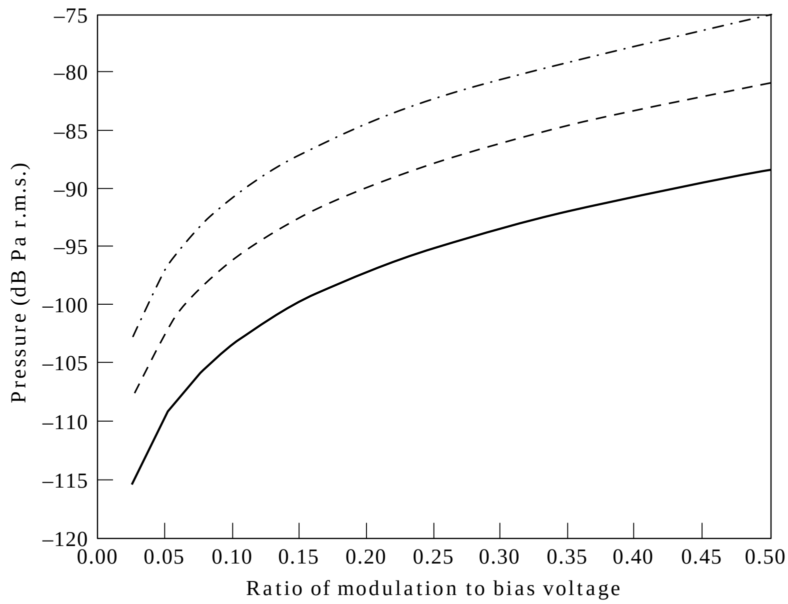

Figure 5. Effect of initial film thickness on acoustic pressure: $h_0 = 76$ μm (—), 51 μm (- - -), 38 μm (– · –). Bias = 700 V, frequency = 700 Hz, ratio of bubble height to base radius $(z_0/a) = 0{\cdot}5$, bubble base radius = 1·25 mm.

As shown in Figure 3, a section of film is electroded on top and bottom. Silicone rubber, based on commercially available blends of polydimethyl with other siloxanes, was used as the film material because of its large strain capabilities, low hysteresis, and stable physical properties over a wide temperature range. Powdered graphite was selected as the electrode

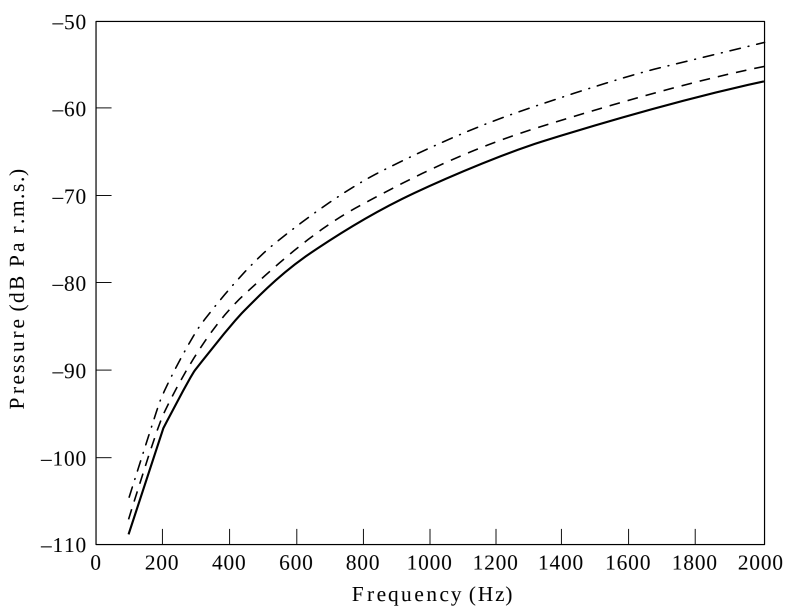

Figure 6. Effect of initial bubble height (z_0) on acoustic pressure: $z_0/a = 0{\cdot}5$ (—), 0·25 (- - -), 0·1 (– · –). Bias = 700 V, modulation amplitude = 350 V, bubble base radius $a = 1{\cdot}25$ mm.

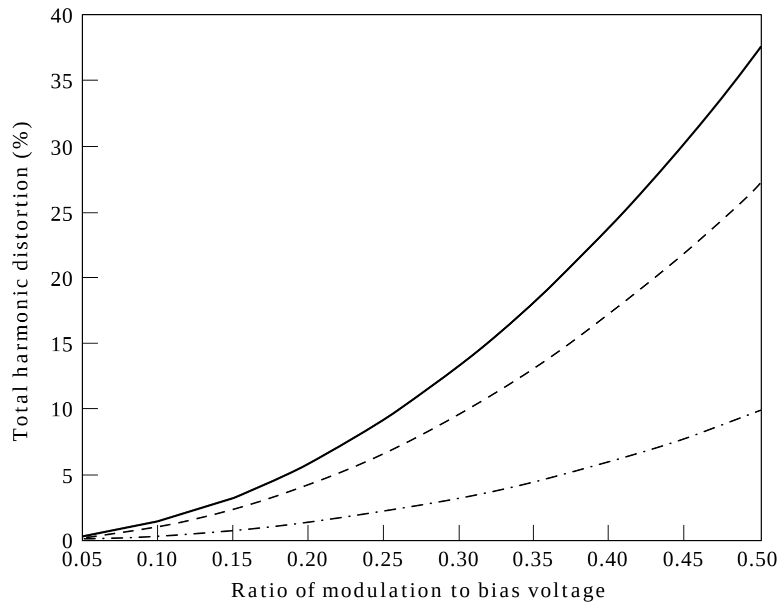

Figure 7. Effect of initial bubble height (z_0) on total harmonic distortion: $z_0/a = 0{\cdot}5$ (—), 0·25 (- - -), 0·1 (– · –). Bias = 700 V, bubble base radius $a = 1{\cdot}25$ mm.

material because it offers high compliance with sufficient conductivity, and is simple to deposit on the polymer film with a stencil.

When excitation voltage is applied, the film surface area increases, causing the film to buckle. To make the film radiate sound effectively, the film is subdivided into small regions and placed on a plate which has a dense matrix of holes. A slight negative pressure is also applied to the plenum beneath the plate, which draws the film into the holes of the grid and creates film "bubble" elements (alternatively, we could apply a slight positive

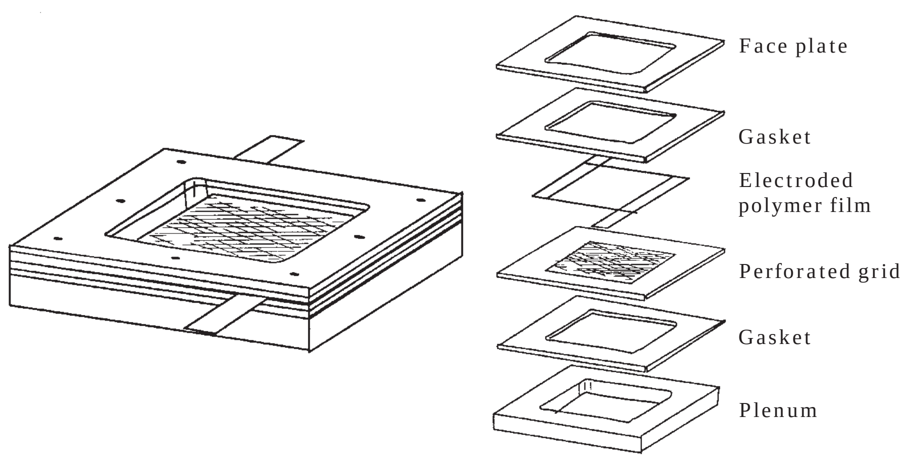

Figure 8. The electrostrictive polymer film electroacoustic transducer. The silicone film (third layer from top) is electroded on top and bottom and is separated from the lower cavity by a perforated grid.

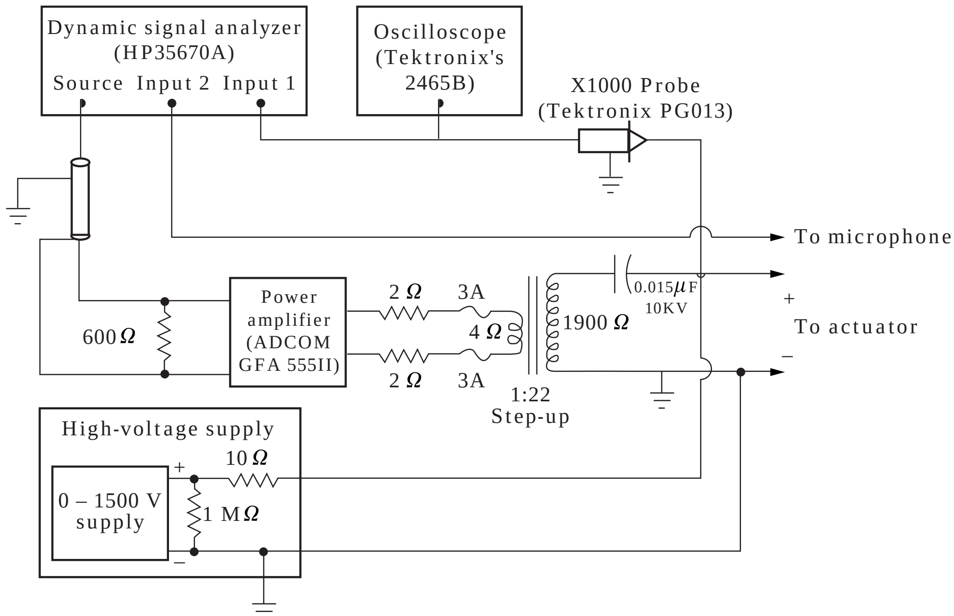

Figure 9. Actuator excitation and measurement circuits.

pressure). The subdivision and pressure differential allow film buckling to be controlled in response to in-plane strain. For good sound power output at low frequencies, each film element is required to vibrate up and down uniformly (i.e., in its lowest order mode), since higher-order-mode displacements reduce the volume acceleration of air at the film surface. Note that the plenum is a closed volume; this is essential if the bubble motion is to generate a net volume acceleration.

4. FILM-ACTUATOR MODEL

This section develops a simple acoustic model for the "bubble" elements of the electrostrictive polymer film transducer described in the preceding section. The purpose of the model is to predict trends in the actuator acoustic performance and to enable comparisons with the experimental measurements.

The model predicts acoustic radiation in the far field from a single film bubble element of the actuator, shown schematically in Figure 3. The model is valid for frequencies at which the acoustic wavelength is much greater than the size of the film-bubble element, i.e., for $ka \ll 1$, where k is the wavenumber and a is the base radius of the bubble element.

It is assumed that the film bubble vibrates as a monopole acoustic source. The bubble grows and shrinks under applied voltage and radiates acoustic pressure in proportion to its volume acceleration.

When voltage is applied to the electrostrictive-polymer film, the film is squeezed and its thickness is reduced. The pressure on the film due to the applied voltage is

$$f_{film}(t) = \frac{\varepsilon_r \varepsilon_0 v(t)^2}{h^2}, \tag{3}$$

where ε_0 is the permittivity of free space, ε_r is the relative dielectric constant of the polymer, h is the film thickness, and $v\ (t)$ is the applied voltage as a function of time. Equation (3) is valid for dynamic response as long as the charging (RC) time constant of the film is small relative to the period of the voltage excitation. This is true at the low acoustic frequencies of interest here. The film thickness h varies according to

$$h = h_0 - (h_0/Y)f, \tag{4}$$

where h_0 is the film thickness at zero voltage and Y is the elastic modulus of silicone. Eliminating f from equations (3) and (4) gives a relation for film thickness as a function of applied voltage:

$$h^3 - h_0 h^2 + (h_0/Y)\varepsilon_r \varepsilon_0 v^2 = 0. \tag{5}$$

Since the polymer (silicone) is essentially incompressible, the film area increases as its thickness decreases. This is the mechanism by which the bubble element grows. The model assumes that as the film area increases and decreases, the bubble always maintains a shape that is a spherical *section*. If the maximum bubble height is restricted to the case when the bubble is a hemisphere, then for a hole radius a and a bubble height z, the following relations hold:

$$\text{bubble surface area} = \pi(a^2 + z^2), \qquad \text{bubble volume} = \frac{\pi}{6} z(3a^2 + z^2). \tag{6, 7}$$

The volume of polymer material in the film bubble is constant and is determined by the fixed hole radius a, the initial bubble height z_0, and the initial film thickness h_0. As film thickness varies, the surface area changes inversely, and the new bubble height and volume are determined by equations (6) and (7).

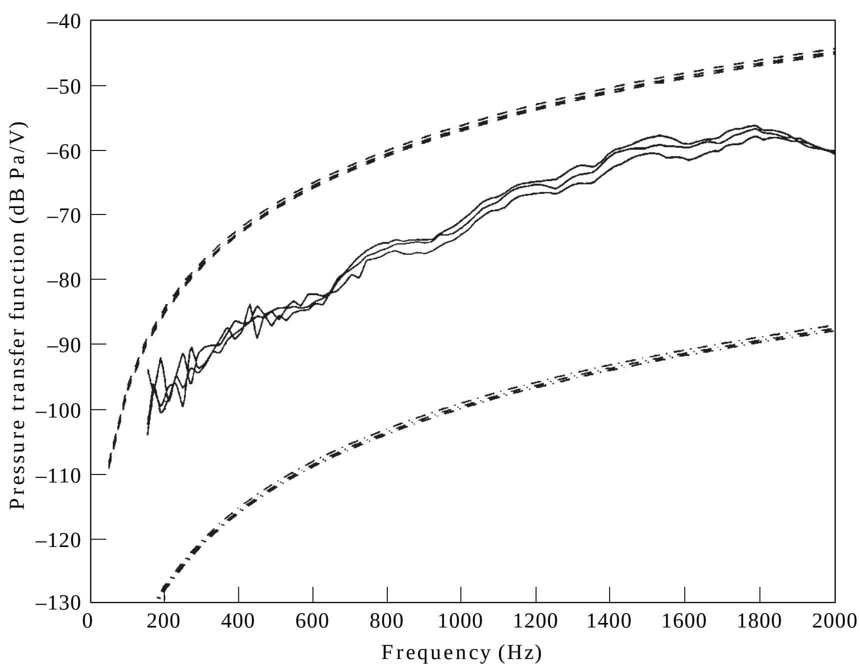

Figure 10. Measured electric-to-acoustic transfer function with model predictions, for modulation amplitudes of 117, 195 and 273 V (bias = 700 V). The graph shows measured data (—), model predictions for one film element (– · –), and model predictions for 140 film elements (- - -). For each set of three curves, a higher curve corresponds to higher applied voltage. Data represent radiated pressure per unit r.m.s. modulation voltage.

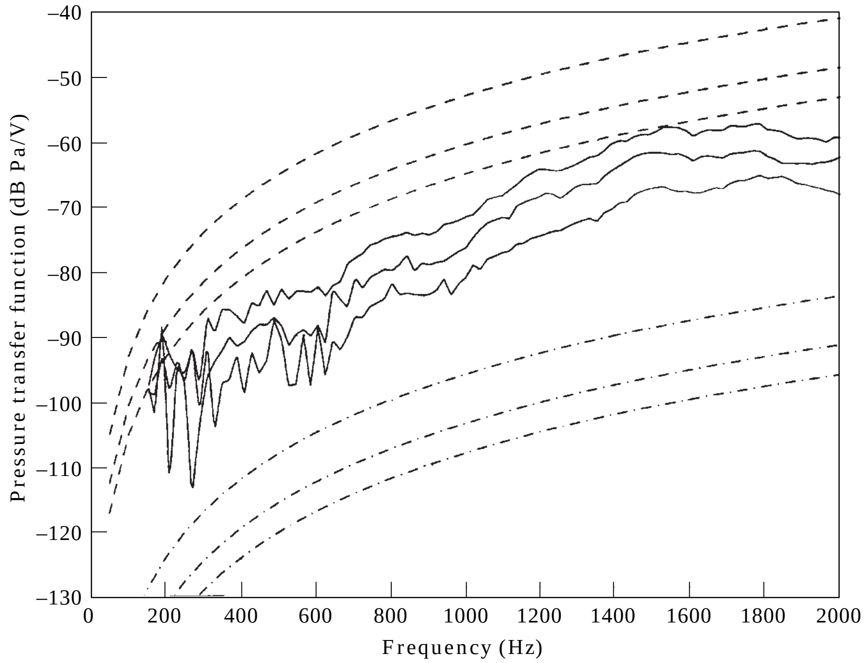

Figure 11. Measured electric-to-acoustic transfer function with model predictions, for bias voltages of 300, 500 and 1000 V (modulation amplitude = 78 V). The graph shows measured data (—), model predictions for one film element (– · –), and model predictions for 140 film elements (- - -). For each set of three curves, a higher curve corresponds to higher applied voltage. Data represent radiated pressure per unit r.m.s. modulation voltage.

For a simple point acoustic source oscillating harmonically, the radiated pressure in the far field is

$$p(r)\,\mathrm{e}^{\mathrm{j}\omega t} = \frac{\rho Q}{4\pi r}\,\mathrm{e}^{-\mathrm{j}kr}\,\mathrm{e}^{\mathrm{j}\omega t}. \tag{8}$$

In this equation, r is the distance from the source to the far-field point, ρ is the density of air, ω is the radian frequency, k is the wavenumber, and Q is the volume acceleration of the source. Equation (8) assumes that $ka \ll 1$, and is valid for a source of any shape that is small relative to the acoustic wavelength.

To determine the radiated pressure for a single bubble element of the polymer film, therefore, it is first assumed that the film is excited by a time-varying voltage

$$v(t) = B(1 + A\cos(\omega t)), \tag{9}$$

where B is the film bias voltage and A is the fractional modulation voltage. The film-thickness variation with time follows from equation (5). By assuming that the film always encloses a spherical section, one can then solve equations (6), (7) and (8) for the radiated pressure at any distance r that is large relative to the size of the bubble.

5. MODEL RESULTS FOR A SINGLE BUBBLE ELEMENT

The predictions in this section illustrate the effects of voltage and bubble height on radiated acoustic pressure and harmonic distortion. In the following graphs, the acoustic pressure is plotted at a distance of 1 m from the surface for a single bubble element.

Figure 4 shows model predictions for radiated acoustic pressure as a function of frequency, from 50 to 2000 Hz. The applied voltage is of the form of equation (9). Note that the assumed base radius of the bubble (1·25 mm) corresponds to the radius of the hole in the perforated grid of the prototype transducer. Acoustic pressure increases with both increasing bias and increasing modulation.

The acoustic pressure also depends on several geometric parameters of the film element, including film thickness, bubble height, and bubble base radius. Figure 5 illustrates that at any applied voltage the radiated pressure and initial film thickness are inversely related. Figure 6 shows the effect of the ratio of initial (zero-voltage) bubble height to base radius. Bubbles with a smaller ratio of height to base radius (i.e., flatter bubbles) are better radiators, at least for $z_0/a \leqslant 0{\cdot}5$. Note that the curve in Figure 6 corresponding to $z_0/a = 0{\cdot}1$ is within about 1 or 2 dB of the limiting pressure approached as z_0/a approaches 0.

Total harmonic distortion (THD) is the ratio of acoustic power in the harmonics to acoustic power at the fundamental frequency. THD increases with both increasing bias voltage and increasing modulation. Figure 7 illustrates the effect of initial bubble height on THD. Reducing the ratio of bubble height to base radius from 0·5 to 0·1 (i.e., making the film bubble flatter) reduces harmonic distortion by a factor of 3. Note that the same reduction in bubble height increases the acoustic pressure by approximately 6 dB (Figure 6).

The model results indicate that in order to obtain a balance between high radiated acoustic pressure and low distortion, the actuator film elements should be relatively flat and driven at high bias and low modulation. Bias voltage can be reduced without reducing acoustic pressure if the film is made thin. Low bias is generally preferable for reasons of safety and simplicity of the driving electronics. On the other hand, very thin films are less

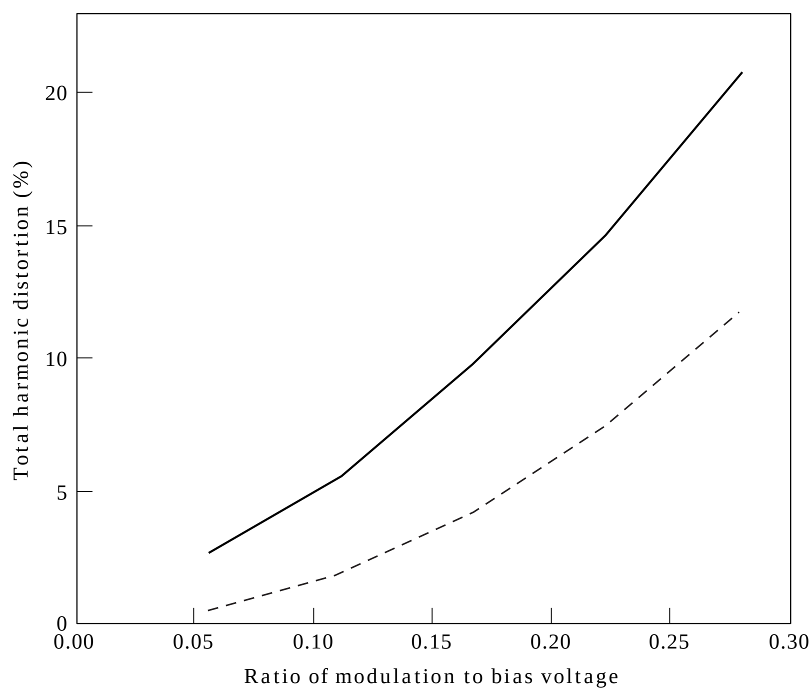

Figure 12. Measured (—) and predicted (- - -) effect of modulation voltage on total harmonic distortion; bias = 700 V.

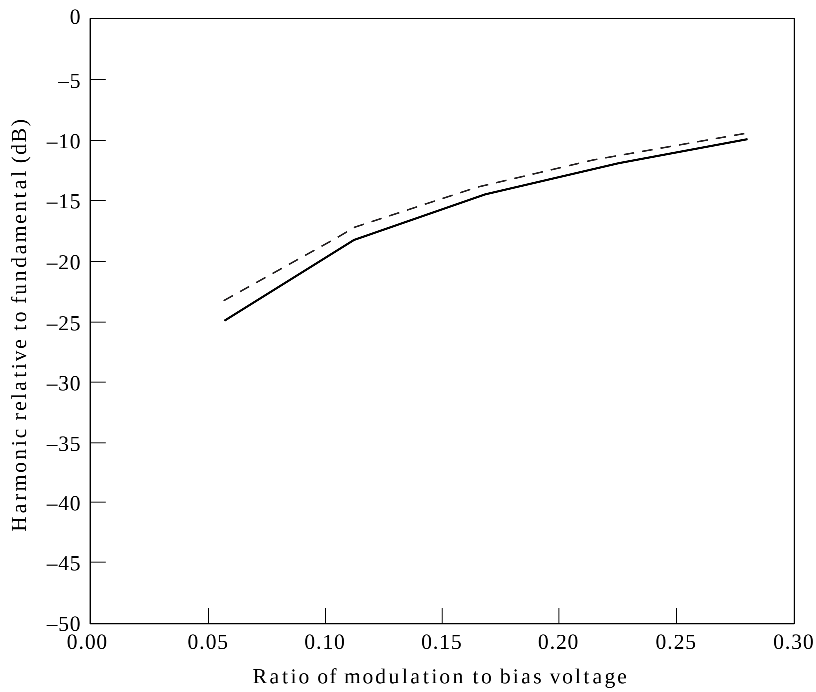

Figure 13. Measured (—) and predicted (- - -) effect of modulation voltage on second-harmonic power (relative to fundamental).

durable and more difficult to fabricate. One way to gain the toughness of a thick film with the greater voltage sensitivity of a thin film is to fabricate a multilayer stack of thin films.

From a practical standpoint, the size and thickness of the film element will be limited by the ability of the bubble to maintain its shape in the rest position, and to change shape uniformly under applied voltage. Note again the low-frequency assumption inherent to the model, i.e., the assumption that the film bubble contracts and expands in its lowest order mode. The frequency at which node lines appear on the film depends on film tension, which is not a parameter in the present model.

6. EXPERIMENT DESCRIPTION

Performance characterization measurements of the acoustic actuator were made in the anechoic chamber of the SRI Sound and Vibration Control Laboratory.

Figure 8 is a drawing of the acoustic actuator. The actuator consists of an acrylic-plastic holder with a 3×3-in. opening that exposes the film surface. The film is 1·5-mil silicone rubber (General Electric RTV112) and lies on top of a rigid acrylic matrix of 0·20-in-diameter circular holes. The holes of the matrix are densely packed and are made by numerically controlled machining.

Compliant electrodes are made by rubbing graphite powder on both sides of the film. There is no graphite on the region of film directly opposite each connector. This minimizes the chance of dielectric breakdown resulting from charge concentration at the edge of the connectors. Offset copper connectors are attached to each side of the film to provide the film excitation voltage.

Below the film and hole matrix is a plenum, which acts as a suspension cavity and allows application of suction to the film. Neoprene rubber gaskets seal the film and hole matrix to the plenum. The plenum was maintained at a slight negative pressure (via a suction hose attached to a small pump) to draw the film into the holes of the grid. The height of the film bubble elements could be changed by varying the suction, although during the measurements plenum suction was held at approximately 0·08 psi.

The film-actuator fixture was clamped to a test stand in the anechoic chamber, with a microphone positioned 1 m directly above the film. At the start of each measurement session the microphone was calibrated with a 94-dB SPL source at 1 kHz. High-voltage leads were connected to the electrodes for film excitation. Figure 9 shows the excitation and measurement circuits. Data were acquired with an HP 35670A Dynamic Signal Analyzer.

7. EXPERIMENTAL RESULTS

7.1. RADIATED PRESSURE

The experimental results in this section are limited to the frequency band 50–2000 Hz, which is a range of significant interest for both active noise control and general audio applications. The acoustic pressure measured at the microphone is plotted as an electric-to-acoustic transfer function. The transfer function, measured in pascals per volt (dB), represents the acoustic pressure at 1 m from the film divided by the modulation-voltage amplitude. Since the input voltage for these measurements is constant with frequency, the absolute acoustic pressure (in dB Pa) is simply a translation of the transfer-function curves shown.

Figures 10 and 11 show measured electric-to-acoustic transfer functions plotted as functions of frequency for different levels of modulation and bias voltage, respectively. Note that below about 200 Hz the actuator output is masked by background noise.

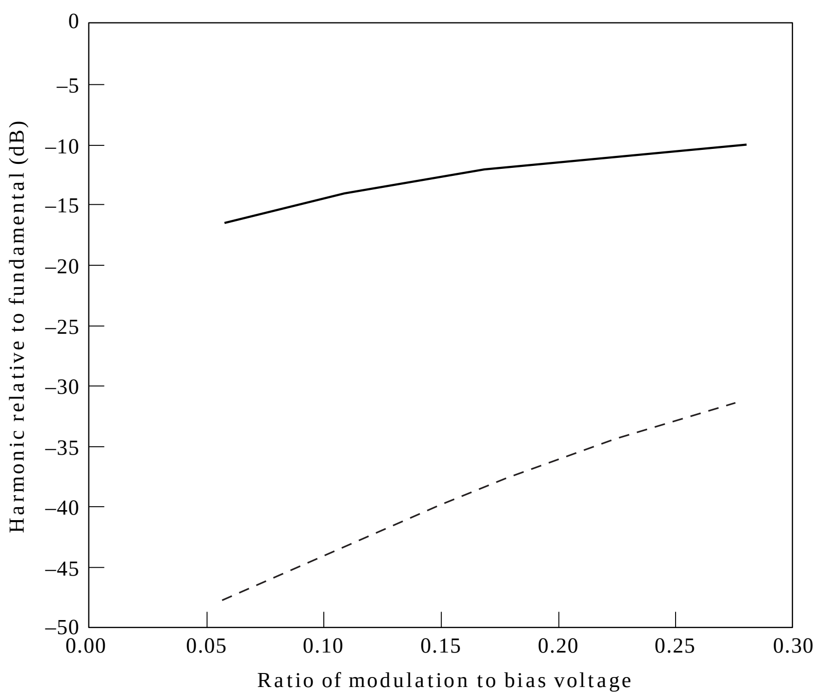

Figure 14. Measured (—) and predicted (- - -) effect of modulation voltage on third-harmonic power (relative to fundamental).

Also shown in Figures 10 and 11 are two sets of predictions based on the film-bubble radiation model. To predict radiation from a single element of the actuator, it is assumed in the model that the film thickness is 0·0375 mm, the base radius of the film bubble (i.e., the grid hole diameter) is 2·5 mm, and the bubble height is one-quarter of the base diameter.

The second set of theoretical curves is an estimate of the radiation from an array of elements. These curves are simple extrapolations of the single-element acoustic-pressure predictions, based on the number of elements in the real actuator. The active film surface area (3·0 by 2·4 in.) of the actuator has 140 film-bubble elements, counting area contributions of elements that are partially exposed. Adding the contributions from each element, the predicted acoustic pressure radiated by 140 film elements is 43 dB higher than the pressure radiated by a single film element.

For these extrapolations to be strictly valid, it is necessary that (1) the acoustic pressures from each element sum coherently at the microphone location, and (2) the acoustic output from a film element is unaffected by the other array elements. Condition (1) is a satisfactory assumption for radiation in the 50–2000 Hz range. Condition (2), however, is an approximation, as each element will see some near-field loading from adjacent elements. Furthermore, the implicit assumption is made that the single-element predictions are valid *quantitatively*, which has not been established. Therefore, the extrapolated model results are shown in the absence of a better predictive model, such as one based on finite-element simulation. *The purpose of the extrapolations is to provide a simple comparison for the experimental data*.

The experimental curves and the model predictions in Figures 11 and 12 agree qualitatively with respect to the effects of bias and modulation voltage on acoustic output. The model also reflects the observed rate of increase of acoustic pressure with frequency (12 dB per octave) over the range shown.

The experimental data are about 31 dB higher than the single-element predictions, and about 12 dB less than the extrapolated result for 140 film elements. Within the above-mentioned limitations of the model, therefore, this means that the acoustic pressure radiated by the actuator is equivalent to that of about 35 film-bubble elements.

Aside from the approximate method of extrapolation, there are other reasons why the actuator acoustic output may be below the predictions for 140 film elements. These include film non-uniformities, uncertainty in the bubble height, and modal behaviour on the film bubble elements. Some of the elements are only partially exposed and, because of electroding non-uniformities, some may not be fully excited. As shown in Figure 6, as the bubble height-to-base radius increases from 0·1 to 0·5, the acoustic pressure decreases by 6 dB. This is a potentially large source of error because during the experiments no attempt was made to accurately measure bubble height, and the height would change with any drift in plenum pressure. Since the film tension also was not controlled directly, it could not be guaranteed that the elements were oscillating in their lowest order vibrational mode. In future experimental work it is intended to measure both bubble height and modal behaviour of the actuator elements.

7.2. HARMONIC DISTORTION

Figure 12 presents the measured and predicted total harmonic distortion for the film actuator as a function of the modulation-to-bias voltage ratio. Total harmonic distortion increases with increasing modulation amplitude. Although the experimental data and the predictions agree qualitatively, the measured harmonic distortion is much higher than the predictions.

The reason for the disparity is isolated in Figures 13 and 14. The data in these graphs correspond to the total distortion data of Figure 12, but specifically show the relative levels of the second and third harmonics in the acoustic pressure. These two harmonics are the primary contributors to the total harmonic distortion.

The model makes remarkably good predictions of second-harmonic power, which arises from the voltage-squared dependence of squeezing force on the film. On the other hand, the model is a bad predictor of third-harmonic power. The third harmonic is larger than the second harmonic over much of the parameter range, and is 20–30 dB higher than predicted. This is why total harmonic distortion is much larger than expected. It should be pointed out that our model predictions of harmonic distortion are not strongly dependent on the assumption that the bubble element has a spherical subsection shape (other shapes can be assumed).

8. CONCLUSIONS

In this research, a new electroacoustic actuator that is based on the electrostrictive response of a silicone film was developed and tested. The design described in this paper allows actuators of large or small spatial extent to be fabricated from a single section of electrostrictive film.

The acoustic pressure radiated by the actuator and the harmonic distortion were measured and compared to results extrapolated from a model developed for a single film element. The measured acoustic pressure in the band 50–2000 Hz was less than predicted by the model, but this can be attributed to both the simplified extrapolation method as well as to uncertainties in the bubble-element height and modal behaviour. With more uniform films and better control of element height and film tension, full advantage can be taken of the large film displacements that this actuator design allows. Although harmonic distortion is significant with the current actuator, we believe it can be reduced with design refinement. Also, because much of the second-harmonic distortion arises from the voltage-squared dependence of force on the film, it can be reduced electronically by tailoring the shape of the voltage waveform at the actuator input.

Electrostrictive polymer films have excellent potential to be developed for use as compact, conformal, lightweight acoustic actuators. With good actuator design, these films can produce very high acoustic power per unit weight and surface area. It should be mentioned that the measured acoustic output from the present actuator corresponds to a sensitivity (acoustic power output per 1 W of power input) of 100 dB SPL/W at 1 m in the mid-frequency range (above 1500 Hz).

In future work, methods of fabricating high-quality, thin polymer films will be investigated, as well as multilayer film stacks, which can potentially generate large acoustic power at low bias voltages. Also study tradeoffs among film thickness, film durability, and acoustic performance will be studied. Finally, the authors plan to investigate the sources of odd-harmonic distortion.

REFERENCES

1. S. Furuyama, K. Kojima, T. Nomura, K. Hasegawa and S. Mimura 1992 *Society of Automotive Engineers* (*SAE*) *Technical Paper* 920078. Light weight loudspeaker.
2. J. Scheinbeim and B. Newman 1993 *U.S. Patent* 5,229,979. Electrostrictive driving device, process for sonic wave projection and polymer materials for use therein.
3. J. Scheinbeim, B. Newman, Z. Ma and J. Lee 1992 *ACS Polymer Preprints* **33**, 385–386. Electrostrictive response of elastomeric polymers.

4. R. Kornbluh, R. Pelrine and J. Joseph 1995 *Proceedings of the Third IASTED International Conference on Robotics and Manufacturing, Cancun, Mexico*. Elastomeric dielectric artificial muscle for small robots.
5. R. Pelrine, J. Kornbluh, J. Joseph and J. Marlow 1995 *Sensors and Actuators*, accepted for publication. Analysis of the electrostriction of polymer dielectrics with compliant electrodes as a means of actuation.
6. R. Pelrine, J. Kornbluh, J. Joseph and S. Chiba 1997 *Proceedings of 10th Annual International Workshop on Micro Electro Mechanical Systems (MEMS 97), Nagoya, Japan*, 238–243. Electrostriction of polymer films for microactuators.