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Stephen D. Holland
Iowa State University, sdh4@iastate.edu

Junho Song
Iowa State University

Dale E. Chimenti
Iowa State University

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Residual Bias Phenomenon in Air-Coupled Ultrasonic Capacitive Film Transducers

Abstract

We discuss in this paper the underlying physics of a residual bias phenomenon, whereby the metalized Mylar films of air-coupled film transducers accept and retain a residual electrostatic charge. Experimental measurements to demonstrate and quantify this effect are reported here, along with a hypothesis of the mechanism of charge transfer and embedding. The measurements show the amplitude performance of the capacitive film transducers as a function of applied bias voltage and frequency. Factors such as humidity and decay time also play roles in the acquisition and holding of charge on a film. We hypothesize that charge transfers from the conductive backplate and collects on the non-metalized side of the film. The charged films therefore are electrostatically attracted to the transducer backplate even with no applied voltage bias. Typically, an externally applied bias voltage is needed to charge the capacitor. With a persistent residual bias effect, these air-coupled capacitive film transducers could be used like conventional piezoelectric transducers with no biasing required. This effect has substantial implications for the operation of air-coupled film transducers.

Keywords

ultrasonic transducers, capacitive sensors, nondestructive evaluation, nondestructive testing

Disciplines

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HTML ABSTRACT + LINKS

RESIDUAL BIAS PHENOMENON IN AIR-COUPLED ULTRASONIC CAPACITIVE FILM TRANSDUCERS

Stephen D. Holland[1], Jun-Ho Song[2], and D. E. Chimenti[2]
[1]Center for NDE, Iowa State Univ, Ames, Iowa 50011
[2]Center for NDE and Aerospace Eng Dept, Iowa State Univ, Ames, Iowa 50011

ABSTRACT. We discuss in this paper the underlying physics of a residual bias phenomenon, whereby the metalized Mylar films of air-coupled film transducers accept and retain a residual electrostatic charge. Experimental measurements to demonstrate and quantify this effect are reported here, along with a hypothesis of the mechanism of charge transfer and embedding. The measurements show the amplitude performance of the capacitive film transducers as a function of applied bias voltage and frequency. Factors such as humidity and decay time also play roles in the acquisition and holding of charge on a film. We hypothesize that charge transfers from the conductive backplate and collects on the non-metalized side of the film. The charged films therefore are electrostatically attracted to the transducer backplate even with no applied voltage bias. Typically, an externally applied bias voltage is needed to charge the capacitor. With a persistent residual bias effect, these air-coupled capacitive film transducers could be used like conventional piezoelectric transducers with no biasing required. This effect has substantial implications for the operation of air-coupled film transducers.

Keywords: Capacitive foil transducer, air-coupled ultrasound, residual bias, surface charges, electret microphone, charge transfer.
PACS: 43.38.Bs

INTRODUCTION

We have been developing new and improved air-coupled capacitive foil transducers [1] to enhance the detection and resolution of air-coupled ultrasonics. In the process of conducting these investigations, we have found that the measured sensitivity of these transducers was not consistently reproducible. Eventually, we were led to the conclusion that electrostatic charges can collect in the metalized polymer film (used as a dielectric and outer electrode in these transducers), thereby changing the electromechanical properties and affecting the transducer's sensitivity.

Figure 1 illustrates schematically the construction of an air-coupled capacitive film transducer. A polymer film, metalized on one side, is placed on a micromachined copper or silicon backplate. The film metalization is grounded, and a DC bias voltage (0 to 400 V) is applied to the backplate. The bias voltage causes an electrostatic attraction between the metalized film and the backplate. The metalization and backplate form two plates of a capacitor. An incident sound wave sets the film into vibration, modulating the capacitance and thereby inducing a measurable AC voltage or current across the capacitor. This signal is detected with a sensitive low-noise amplifier.

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FIGURE 1. Operation of a capacitive film air-coupled transducer. Movement of the film by a sound wave induces an AC voltage or current summed with the DC bias.

(a) (b)

FIGURE 2. (a) Bias-voltage-induced charge transfer across the air gap between film and substrate. (b) Resulting positive charge on polymer film causes attraction even with no bias voltage applied.

DISCUSSION

In the construction and testing of several of these transducers, we have observed two phenomena that were initially difficult to explain: 1) measured amplitude sensitivity did not seem to be entirely consistent from one experiment to the next, and 2) the film seemed to sometimes be attracted to the backplate, even when no bias voltage was applied. After substantial experimentation and observation in the laboratory, we hypothesized that electrostatic charges might be crossing between the film and backplate and collecting on the film, as illustrated in Fig. 2(a). When a high bias voltage is applied, electronic charge from the nonmetalized surface of the film transfers across the gap to the backplate, leaving a net positive charge on the polymer film after the bias voltage is removed, shown in Fig. 2(b). It is important to note that a typical bias voltage of 200V across the dielectric and small air gap produced by the surface roughness of the backplate (typ. 20 μm) creates an electric field an order of magnitude larger than the classical breakdown voltage of air. The effect of this transferred charge is to electrostatically attract the film to the backplate even with no externally applied bias. Moreover, mechanical motion of the film will induce a current or voltage in the backplate just as if a bias voltage were applied. We call this effect the “residual bias”.

The residual bias is equivalent to the ultrasonic analog of the ‘electret microphone’ developed by Sessler and West in 1962 [2]. The charged film can be considered to be the electrostatic analog of a permanent magnet – an electret. Because the charging voltage is

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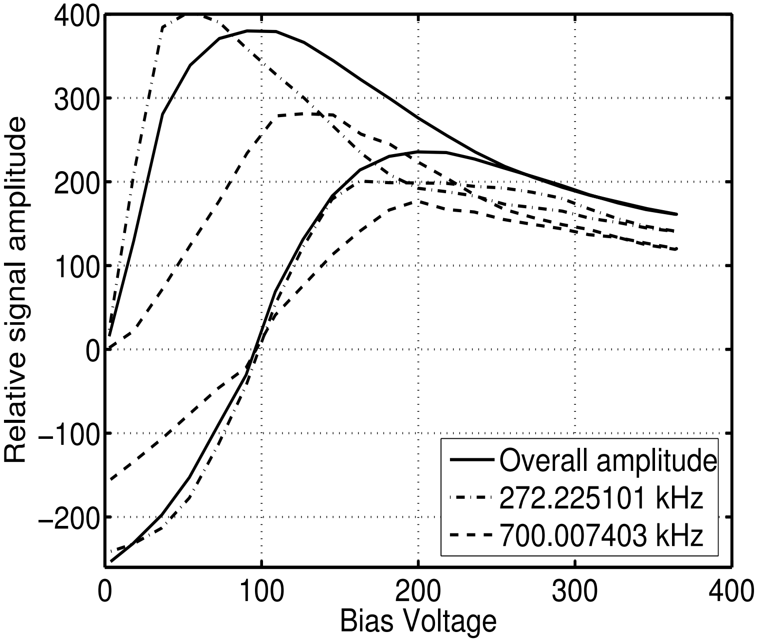

FIGURE 3. Variation of receive sensitivity of transducer as a function of applied bias voltage. Read clockwise, starting at (0,0).

much lower in our case it is likely that our films develop only surface charges [3] not the embedded charges discussed by Sessler and West [2].

EXPERIMENTS

To evaluate the residual bias phenomenon, we performed a series of experiments in which the receiver sensitivity of a capacitive film transducer was monitored as the applied DC bias voltage was increased from zero to a maximum and then decreased. Figure 3 shows the sensitivity of a transducer, with a new Mylar (polyethylene terephthalate) film, as the applied bias voltage is increased from 0 to 360 V and then reduced back to 0 volts. The plot should be interpreted clockwise starting at (0,0). The transducer is initially not sensitive at the starting bias voltage of 0 V. As the bias voltage is increased, the sensitivity first increases proportionally for all frequencies. The sensitivity to lower frequencies (270 kHz) peaks at a bias voltage of 60 volts. The overall sensitivity peaks at 100 volts, and the high frequency sensitivity (700 kHz) peaks at 120 volts bias. As the bias voltage is increased further to 360 volts the sensitivity decreases at all frequencies. The bias voltage is then decreased, leading to increasing sensitivity. As the bias voltage is decreased past 200 volts the sensitivity begins to drop and reaches zero at a bias voltage of 100 volts. As the bias voltage is lowered from 100 volts to 0 volts, the sensitivity increases again, but with a 180° phase shift that is recorded on Fig. 3 as a negative sensitivity. The transducer operates therefore with no external bias! Positive charges (missing electrons), which accumulated on the film while the bias was applied, generate a residual bias of -100 volts that allows the transducer to operate without an externally applied DC bias. An externally applied bias of +100 volts applied to the film in Fig. 3 exactly balances the charge on the film, causing the sensitivity to drop to

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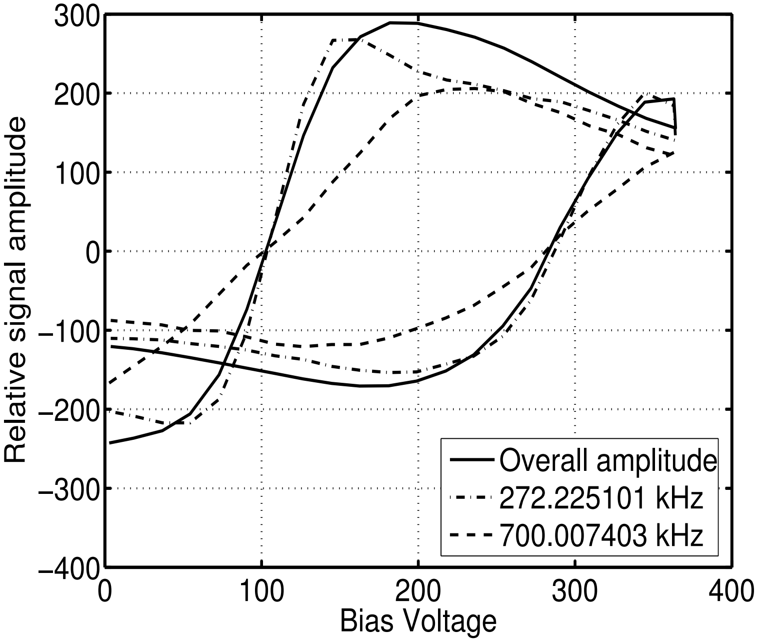

FIGURE 4. Effect of a 12 hour hold at 360 volts on receive sensitivity of transducer. Read clockwise, starting at (0V,-200) with 12 hour hold at (360V,150).

zero.

To evaluate the effect of time dependence on this charge deposition phenomenon, the above experiment was repeated on the same film with a 12 hour hold at the high voltage point of 360 volts. Figure 4 shows the hysteresis behavior. The curves begin at 0 V bias showing an ultrasonic detection amplitude near -200 (arbitrary sensitivity units), then increase past 0 sensitivity at 100 volts bias to a peak, then decrease as in Fig. 3. During the 12 hour hold at 360 volts bias the sensitivity increased slightly, and when the bias voltage is decreased, the sensitivity drops rapidly, crossing zero at 287 volts. The negative sensitivity peaks around 175 volts, then decreases slightly as the applied bias is reduced to zero. The 12 hour hold increases the residual bias from 100 volts to 287 volts.

Next, that same transducer is left with 0 volt bias for 80 hours and the cycle of increasing and decreasing bias is repeated, with the results shown in Fig. 5. Over the course of the hold time, the effective residual bias is reduced from 287 volts to 70 volts. To verify our hypothesis regarding charge transfer, we connected this transducer (with no external bias) to a sensitive electrometer configured in charge detection mode. We measured the induced charge on the backplate, after the film was mechanically removed from the transducer, and found it to be $Q = 40.7nC$. For comparison, from the measured 70 volt residual bias and transducer capacitance of $590pF$, we would expect $Q = CV = 41.3nC$, remarkably close to the measured value of $40.7nC$. We conclude from this observation that electrostatic charge build-up on the polymer film is the most likely cause of the residual bias phenomenon.

The results shown above were repeatable in the sense that different experiments with different films and different transducers gave similar curves. Nevertheless, a few weeks after the experiments shown above—specifically just as the summer heat and humidity began—we started to get some very different results. In particular, we noticed very rapid charge transfer across the film-backplate gap, illustrated in Fig. 6. A residual bias of almost 350

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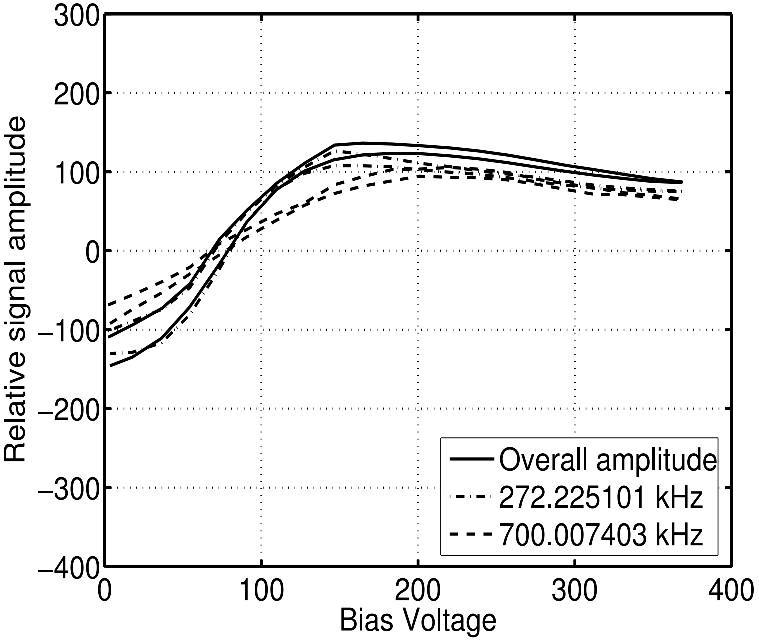

FIGURE 5. Result of an 80 hour hold at 0 volts on the receive sensitivity of transducer. The residual bias has been reduced to 80 volts.

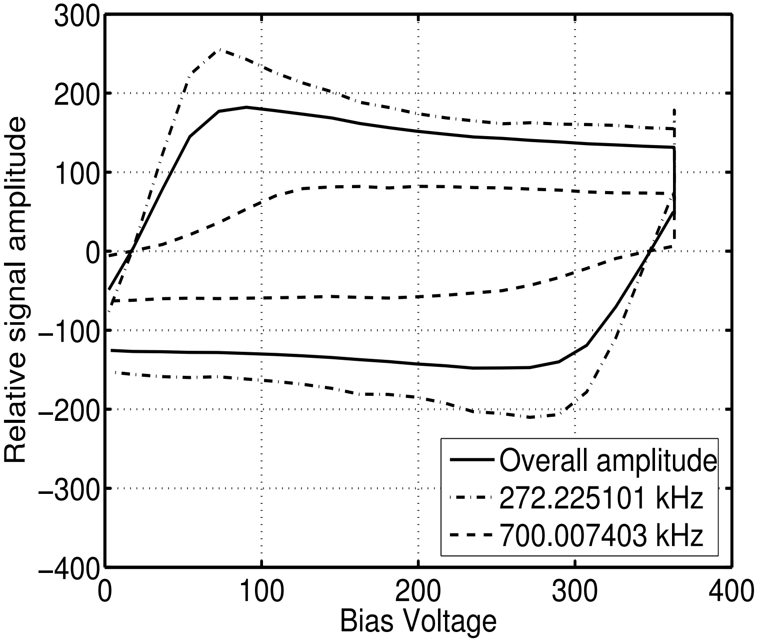

FIGURE 6. Rapid accumulation of residual bias, probably due to humidity. Read clockwise.

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volts accumulated very rapidly. Repeated experiments indicated that this bias also dissipated almost instantaneously. Our suspicion is that the high humidity caused a small amount of water to collect on our film samples, with the highly polar molecules of water (dielectric constant of about 79) greatly assisting the charge transfer process.

CONCLUSIONS

Electrostatic charge transfer can occur between the film and backplate of air-coupled capacitive ultrasonic transducers. This charge transfer creates a residual bias, allowing the transducer to operate in a manner similar to an electret microphone with no applied bias voltage. Because of this effect, the sensitivity of a capacitive film transducer is a function of the bias history, not just the bias voltage. When using air-coupled capacitive film transducers, it is very important to be aware of this effect. Depending on the bias and bias history of a transducer, its sensitivity can not only vary, but can drop to zero or change sign, as well.

FUTURE WORK

Substantial future investigations will be necessary to quantify, control, and exploit this phenomenon. In particular, the effect of different film materials needs to be investigated. Preliminary indications suggest that Kapton does not accept a residual bias so easily as Mylar. In addition, it would be very worthwhile to investigate the charging methods used in the electret microphone industry. By using higher voltages at very low currents it may be possible to embed the charges more deeply in the film, thereby reducing leakage. Sessler and West [2] reported very long lifetimes of embedded charges (but much shorter lifetimes for surface charges) in Mylar. Finally, the discharge time and the effect of humidity both need to be investigated. Eventually, it is possible that the use of long-life charged electret films can be eliminate entirely the need for biasing the newly developed, native, spherically focused transducers developed by Song *et al.* [1].

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