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AUDIO AND ULTRASONIC TRANSDUCERS BASED ON ELCTROTHERMOMECHANICAL FILM (ETMF)

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ABSTRACT

A transducer material consisting of foamized plastic, called electrothermomechanical film (ETMF) is introduced. The film has conductive electrodes on at least one side, so it can be used with either an electrostatic or electrodynamic driving force. The film can be used both as a transmitter and a receiver at audio and ultrasonic frequencies, also in hydroacoustical applications. Lumped-component and one-dimensional distributed-parameter models are developed to examine the behaviour of the film. Frequency responses and sensitivities predicted by the models are compared against measured data.

Audio applications of the film as a loudspeaker (tweeter and full-range) are introduced with data collected from prototypes. Means of controlling radiation pattern and frequency response are shortly discussed. Also, applications of the film as a microphone, hydrophone and hydroacoustic source for audio and ultrasonic frequencies are mentioned.

1. Structure of the film

Electrothermomechanical film[1,2] (from hereon abbreviated as ETMF) is an approximately 20 µm thick film of full-cell type foamized plastic, with small, very flat biaxially oriented gas bubbles, which make up typically 50% of the volume. Bubbles are about 1 µm thick and more than 30 µm wide so that the compressibility of the film is mainly controlled by the filling gas not by the bending stiffness of the plastic material. Due to the configuration of the bubbles the film has a high breakdown voltage in electrostatic applications. ETMF is used as laminated multi-layer structures when large displacements are needed because of its thinness.

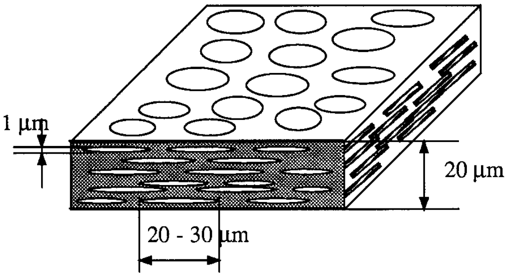

Figure 1. *The basic structure of ETMF*

The film is manufactured by injecting the filling gas bubbles into molten plastic and then extracting a tube of this gas-plastic mixture in which the bubbles are spherical. By expanding this tube by blowing it into a thin film results in biaxially oriented bubbles. The plastic materials can be selected according to the application considering the temperature range and other environmental factors and applicability of adhesives needed for mounting the film. Plastic materials used in the experiments included polyethylene, polypropylene and Teflon, which can be used if the film is required to have electret properties. Because of this simple manufacturing process and the inexpensive materials the manufacturing cost of the film can be also kept quite low.

In addition to substances that stay gaseous over the entire usable temperature range, liquids that have their boiling point within this temperature range have been experimented with. Using boiling liquids gives very strong temperature-dependent properties to the film.

The electrode structure can also be selected relatively freely according to the application. If low weight is essential (e.g. a wide frequency range is needed), and the electrodes can have some surface resistance, then they can be made of thin metal film sputtered onto the surface(s) of the film. If low resistances or high current capacity is needed the electrodes should be then made of thin metal foil. The electrodes can be divided into separate regions in order to control the directional pattern or to separate the surface into transmitter and receiver regions.

2. Operating principles of ETMF transducers

The thickness and thus also the capacitance of the film can be varied by applying an external force to it. The force can take on many forms: "pure" mechanical force, (sound) pressure, thermal expansion of the filling gas, electrostatic force between two electrodes, electromagnetic force between two conductors or between a conductor and a ferromagnetic plate or an electromagnetic force on a conductor in an external magnetic field. The application of ETMF to electroacoustic transducers does not actually introduce any essentially new principle of electroacoustic conversion but rather enables a set of new implementations of established conversion methods. To avoid any confusion, it must be emphasized that the film does not in itself possess any piezoelectric properties rather the conversion relies completely on the presence of externally caused forces.

The film can be used as a force-sensitive variable capacitance in various sensor applications, ranging from mechanical sensors to microphones and hydrophones. The film can tolerate relatively high pressures (at least up to several MPa) without damage or significant hysteresis effects as long as the force is evenly distributed on its surface. It is also relatively easy to seal the film against a humid or corrosive environment. Thus the film can be used in several applications where previously piezoelectric transducers were required. The disadvantage of ETMF in sensor applications is that its voltage/pressure sensitivity changes more rapidly than in normal condenser microphones to variations in temperature or static pressure.

The electrostatic principle can be used in a sound source as well. Due to the structure of the film it requires no support structure to maintain the electrode separation and thus only needs some structure to maintain the shape of the film, e.g. a rigid back plate. The main difference between an ordinary electrostatic sound source (e.g. a loudspeaker) and ETMF is that it forms a "sealed enclosure", having at least theoretically at low frequencies omnidirectional characteristics, whereas an ordinary electrostatic source is usually a dipole. Of course, it is possible to use multiple ETMFs to build dipoles or gradient sources of higher order.

With regard to sound source applications an important property of ETMF is that the film layers can be stacked to form multi-layered transducers thus increasing both the sensitivity and the maximum linear displacement. An especially attractive feature of ETMF regarding the electrostatic applications is that according to Paschen's law the dielectric strength in bubbles increases with decreasing bubble size. Thus a single bubble, no matter how thin it is, has a breakdown voltage of around 100 V. A typical film has about ten layers of bubbles, which can be regarded to act as independent insulators, and so the breakdown voltage of the film should be around 1 kV, which has been obtained with samples free from impurities.
It has been also noticed that structures made with sufficiently thin electrodes (e.g. 5 μm aluminium foil) are when subjected to electric breakdown voltage self-repairing, that is, the electrodes vaporize around the breakdown location. If the use of an external polarization voltage needs to be avoided, the film can be made of an electret material, such as Teflon as was mentioned earlier. With electret materials, however, the effective polarization voltage is limited to a small fraction of that achievable with an external source and this naturally reduces the sensitivity of the transducer.

Transducers can also be constructed electrodynamically thus eliminating the need for polarization voltage and a possible step-up transformer, but using ETMF has not provided any significant advantages so far to the design of electrodynamical transducers. Therefore, the experiments have been limited to electrostatic transducers, where significant advantages can be obtained.

3. The behaviour of ETMF as an electroacoustical transducer

There are four different cases which are of interest when examining the behaviour of ETMF as an electroacoustical transducer: sound transmission to air, sound reception from air, sound transmission to water and sound reception from water.

To gain a deeper understanding of the behaviour of ETMF it can be described by a dynamic analogue circuit using lumped circuit elements[3]. (As is later shown this model is strictly valid only for the audio frequency range.)

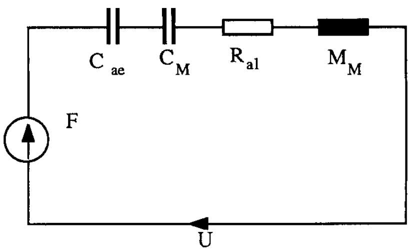

Figure 2. *Lumped-circuit model of ETMF*

Symbols used in the diagram are:

F = force on the film
C_{ae} = acoustical capacitance caused by the polarization field (only in electrostatic transducers)
C_M = acoustical capacitance caused by the mechanical structure of the film
R_{al} = acoustical resistance from the acoustical load
M_M = acoustical inductance caused by the mechanical
structure of the film
U = velocity of the surface of the film

It is assumed that the film is sufficiently large to enable radiation reactance to be ignored and that the internal losses of the film are negligible when compared to the acoustical load.

The first interesting case is the behaviour of the film as a sound source when used as an electrostatic transducer with constant-voltage drive. If it is assumed that the signal voltage is significantly lower than the polarization voltage, then the following expression can be derived for the velocity of the surface of the film:

$$U = \frac{V_{AC} V_{pol} \varepsilon}{d^2 \cdot \left(\omega i \left(\frac{\rho_f d}{2} + \sigma_s \right) + \frac{\rho_0 c^2}{\omega i a d} + \rho_0 c \right)} \qquad (1)$$

where

V_{AC} = signal voltage
V_{pol} = polarization voltage
ε = dielectric constant of the film
d = thickness of the film
a = relative gas contents of the film
ω = angular frequency
ρ_0 = density of the filling gas
ρ_f = density of the film
c = speed of sound in the loading medium
i = $\sqrt{-1}$

If instead of constant-voltage polarization the source is operated with a constant-charge polarization to reduce distortion (in the same way as in conventional electrostatic loudspeakers), the expression 1 can still be applied by using the open-circuit output voltage of the polarization charge source as the effective polarization voltage.

In this case it is most illustrative to describe the transducer as a filter which can be described with a resonant frequency and a Q-value:

$$f_{res} = \frac{c}{2\pi d\sqrt{\frac{\rho_f a}{2\rho_0}}} \tag{2}$$

$$Q = \frac{c}{\rho_m c_m}\sqrt{\frac{\rho_f \rho_0}{2a}} \tag{3}$$

where ρ_m is the density of the loading medium and c_m the speed of sound in the loading medium.

The following expression can be derived for the sound pressure of the planar wave generated at the resonant frequency by the film:

$$p = \frac{V_{AC} V_{pol}\,\varepsilon}{d^2} \tag{4}$$

If the reference level for the sound pressure is 20 μPa then the following approximate expression can be used for the sound pressure level (L_p) at the resonant frequency:

$$(5)\quad L_p \approx 20\cdot\log V_{AC} + 20\cdot\log V_{pol} + 20\cdot\log \varepsilon/d^2 + 93.98$$

Using typical parameters for the materials employed in the prototypes it can be seen that a single layer of the film radiating to air behaves as a narrow-band bandpass filter with a resonance frequency around a few hundred kHz and a Q around 10 - 30 when the film is assumed to be lossless.

These values which correlate reasonably well with measured data show that the frequency response of the film has a rising 6 dB/octave-slope through the audio frequency range and a similar falling slope at higher ultrasonic frequencies (around and above 1 MHz). The asymptotic behaviour at these frequencies can be best characterized with two auxiliary variables which can be described as corner frequencies of high-pass and low-pass filters defined only by either the film mass or the film compliance (fig. 3).

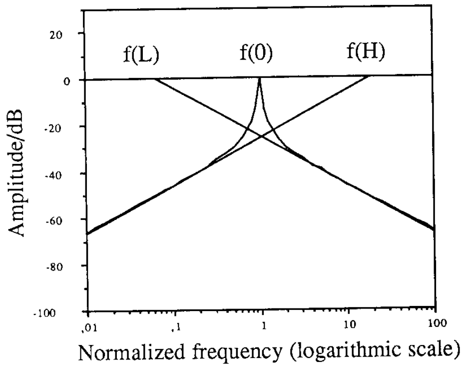

Figure 3. *Computed frequency response of ETFM radiating to air*

For the frequencies f_H and f_L the following expressions can be derived:

$$f_L = \frac{1}{2\pi}\cdot\frac{c}{ad} \tag{6}$$

$$f_H = \frac{1}{4\pi}\cdot\frac{\rho_m c_m}{\rho_f d} \tag{7}$$

By combining expressions 5 and 6 an approximate expression can be derived for the sound pressure in a planar wave generated by a large ETMF source:

$$(8)\quad L_p(f) \approx 20\cdot\log V_{AC} + 20\cdot\log V_{pol} + 20\cdot\log \varepsilon/d^2 + 93.98 + 20\cdot\log f/f_H$$

The computed response agrees quite well with practice, as can seen from measured response of a five-layered ETMF source with 5 μm aluminium electrodes (fig. 4). The measurement shows that the Q-value is lower than predicted, but this can be explained by the losses caused by the multi-layer structure.

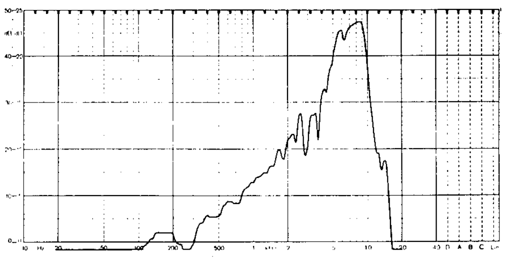

Figure 4. *Measured near-field response of a ETMF source, 200 Hz - 200 kHz. Vertical scale 50 dB, zero level 60 dB SPL, polarization voltage 100 V, signal voltage 10 V (RMS).Notice that the high-frequency cutoff is caused by the microphone, which had an upper limit of 170 kHz.*

Using the lumped-component model other cases can also be examined. For hydroacoustic sources the model shows that the matching of the film to water is good over a wide frequency range from a few kHz up to 20 - 80 MHz. However, at higher ultrasonic frequencies the possibility of standing wave modes in the film arises since it can be assumed that the speed of sound is relatively low in the film. To examine the behaviour of the film at higher frequencies a one-dimensional model describing the film as a transmission line consisting of alternate layers of plastic and air (and the possible metal electrodes) is currently being developed.

4. Audio applications of ETMF

One of the characteristic properties of ETMF when used as a loudspeaker is that practically no waves are transmitted transversally across the surface. This makes the film probably one of the closest approximations to the ideal piston source. Large radiating surfaces (about 1 - 2 m^2), which can also be curved in one direction can be easily constructed. Also important design factor is that the displacement that can be obtained using a single layer of the film is very small and thus to obtain reasonable sound pressures it is necessary to use 10 - 100 layers of the film, depending on the required frequency range. To estimate the amount of layers needed it can be assumed that the maximum displacement with low distortion is about 5% of the thickness of the film which is typically 20 µm. Thus 1 m^2 of the film yields a volume displacement of ±1 cm^3. Of course, at very low frequencies the audibility of the distortion is smaller, and so at bottom end of the audio range larger displacements can be allowed thus reducing the need for additional layers.

A problem with ETMF as a loudspeaker is that its impedance at audio frequencies is almost purely capacitive. Thus even if a single multi-layer transducer can in principle be used to cover the entire audio frequency range it is sensible to drive only a smaller part of the layers with high-frequency signals so as to increase the modulus of the impedance at higher frequencies.

The unique possibility of constructing large curved surfaces enables constructing loudspeakers in which the radiating pattern stays relatively constant over a wide frequency range and can be designed according to the application by varying the geometry of the source. An experimental midrange/tweeter unit constructed according to these principles has a large radius of curvature in the middle part and a much smaller radius in the ends (fig. 5). Measurements from this structure (fig. 6) indicated that the output stays relatively constant in the angle defined by the center portion of the speaker and then falls to a smaller almost constant value when measurements are made in the arc defined by the area of larger curvature. Thus ETMF enables one of the long pursued goals of audio transducer design to be reached. The only limitations to designing curved transducers are that they must be large compared to the wavelength and the curvature can be only in one direction since the film is not very stretchable.

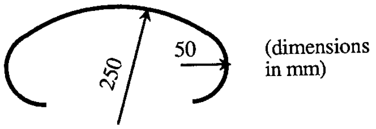

Figure 5. *The structure of the prototype loudspeaker*

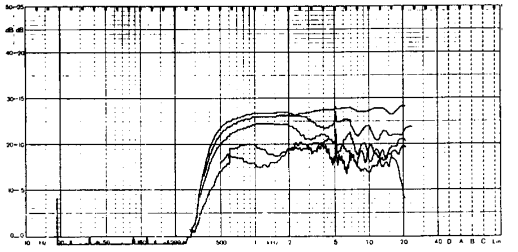

Figure 6. *Frequency response of the prototype speaker at 15˚ intervals from 0˚ to 90˚.*

ETMF can also be used for condenser microphones. ETMF microphones have a little lower sensitivity than usual condenser microphones due to their lower compliance but this is partially compensated by the fact that higher polarization voltages can be used. The particular advantage of ETMF as a microphone is that it can tolerate very high pressures, up to several MPa if no shear is involved. An interesting property of ETMF as a microphone is that its sensitivity is independent of the microphone area and neither does high-frequency on-axis response vary with transducer size (disregarding diffraction effects).

5. Ultrasonic applications of ETMF

As indicated earlier ETMF transducers radiating to air have a significant peak in their output around 100 - 200 kHz. At the resonant frequency an excellent efficiency can be obtained especially if the electrical circuit is tuned to a resonance at that frequency by connecting an inductor in series with the film. The signal source must naturally be able to handle such a low load impedance. In high-level ultrasonic applications the film can be driven without polarization voltage at a frequency that is half of the desired output frequency. In this way large sources emitting a homogenous plane wave at a high level can be constructed.

Advantages of ETMF as an ultrasonic source are very much the same as those of a loudspeaker: ability to construct large radiating surfaces and the ability to control the radiation pattern by varying the geometry of the source. In ultrasonic applications these advantages are even more explicit, since the wavelengths are inevitably much smaller than the transducer dimensions. This has been used for example in a prototype of an ultrasonic cleaner in which the source is a semi-circle (radius appr. 25 cm) that focuses the sound to the center of the cleaning fluid (in this case water). The sound level in the center region is about 20 dB higher than at the surface of the source and thus there is no risk of cavitation at the source surface where any cavitation would decrease the output power and cause corrosion of the source.

When used in hydroacoustical applications, the behaviour of the film is characterised by the much larger acoustical load presented by water. The simple lumped-component model predicts a flat frequency response from a few kHz to tens of MHz, but this kind of behaviour does not occur in practice, since the standing waves in the film start to alter the response above a few hundred kHz. However, the film should have significant output at even very high ultrasonic frequencies, and the response at lower frequencies is very flat, thus ensuring also good transient response.

6. Summary

It has been shown that the new material introduced, ETMF, has many attractive applications both as an audio and an ultrasonic transducer on which many previously unrealisable systems can be built. ETMF should not be regarded as a substitute for established technologies (not at least in all respects), but rather as means to avoid the limitations of older transducers.

7. Aknowledgements

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