INTRODUCTION

A loudspeaker is a transducer which transforms electrical signals into acoustic sound. Conventional speakers usually consist of a vibrating surface (called a diaphragm) and a driving units which is, in most cases, a voice coil driven by a magnetomotive force or a piezoelectric ceramic actuator. In piezoelectric polymer speakers, the active driving element and the air-pushing diaphragm are combined into a single unit. Utilizing the piezoelectric effect of polyvinylidene fluoride (PVDF) material and the flexibility of the polymer film, a unique speaker can be formed from PVDF which vibrates under the stimulus of an AC electric field applied to the surface electrodes on the film.

There are two principal types of loudspeakers. The first uses a vibrating surface to radiate sound directly into the air. The second uses an acoustic element (a horn, e.g.) which is inserted between the diaphragm and the air. The direct radiator type is used most often in small radios, residential, and automotive stereo systems. The horn type is used in high fidelity systems, large sound systems for auditoriums and theaters, and outdoor music and PA systems. Here we will only discuss piezo polymer speakers for direct radiating systems. The uses and effects will be discussed in a separate application note.

SPEAKER STRUCTURE

An extremely crude speaker element can be created by simply hanging a sheet of piezo polymer film in air and applying an AC electrical signal. Sound will emanate from the film and its audio characteristics will vary as you flex and bend the film in different directions. Although this demonstrates basic operation, the performance is marginal and unpredictable at best. By controlling the shape of the film and the support structure of the mounting, a very acceptable speaker can be created.

Please refer to Figure 1. A simple speaker design consists of two parts. The first is the vibrating PVDF diaphragm and the second is the speaker enclosure and support structure. Because PVDF film is anisotropic in its surface piezoelectric parameters, it is important to orient the film properly in this design. The maximum displacement per volt applied is along the machine direction (or "1" direction) of the film. As such, the highest acoustic output is achieved when the machine direction is oriented in the length L direction. The width W is perpendicular to the machine direction and the total height of the speaker consists of the enclosure depth H_2 and the film height H_1.

The function of the enclosure is to isolate the front side of the film from the rear side. The film is curved in one direction (the direction of highest piezoelectric activity) and clamped rigidly onto each end of the enclosure. The curvature of the film is maintained by the sides of the enclosure. When a voltage is applied to the film electrodes, it creates a mechanical strain in the film in both the normal direction and in-plane active direction. Because the film is very thin, the strain in the normal direction is negligible. However, the larger displacement caused by in-plane strains is converted to radial motion along the radius of curvature and perpendicular to the film surface. Because of the curvature, the film surface basically moves in and out of the enclosure. The large film area effectively couples acoustic energy into the surrounding air. This speaker design has very good high frequency characteristics. The acoustic output is constant for frequencies up to 20 kHz.

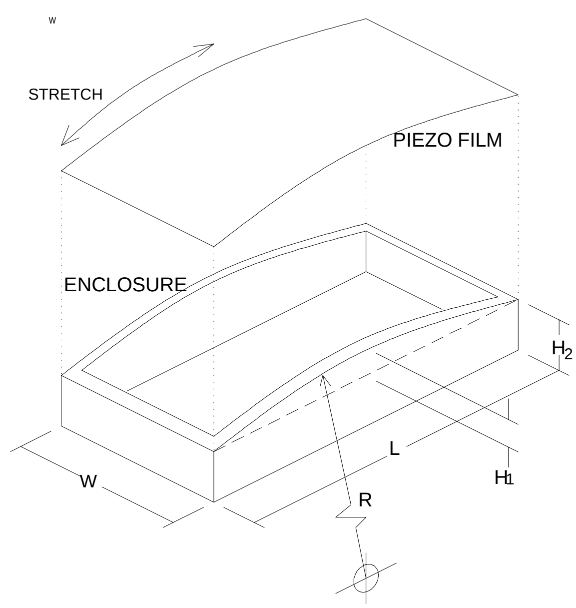

Figure 1

Sound pressure levels at a specified distance, and the frequency response curves of a piezoelectric polymer

speaker can be analytically calculated by solving the wave equation for a curved plate in conjunction with the electro-mechanical equations of piezoelectricity.
The calculations involve the size and shape of the film element, amplitude of the driving signal, piezoelectric properties and dielectric and mechanical loss properties of PVDF film materials, radiation impedance effects, and the mass loading effects of the electrode materials, among other parameters. MSI has developed a computer program to obtain numerical results from a wide variety of parameters. Because of the complexities, the details of these calculations will not be presented here. Discussed below, however, are the effects of key structure parameters on the acoustic performance of a typical speaker design.

DESIGN PARAMETERS

PVDF FILM THICKNESS - Piezoelectric film is available in various thickness'. Standard thickness' from MSI are 28 µM, 52 µM, and 110 µM. Other thickness' are available on a special order basis. The sound pressure level produced by a piezo polymer speaker at a certain distance is directly proportional to the applied electric field strength. Therefore, for a given voltage, in principle, the thinner the film, the higher the sound pressure produced. Sound Pressure Level (SPL) is usually used to measure the output performance of a speaker and is defined by the following equation:

$$\mathrm{SPL} = 20\,\log_{10}\frac{P}{P_{ref}}\ (\mathrm{dB})$$

P is sound pressure at a certain distance from the speaker and $P_{ref} = 2 \times 10^{-5}$ Pascal. Reducing the film thickness by half will generate a 6 dB increase in SPL. However, reducing film thickness will increase the capacitance of the speaker element, resulting in a higher current draw form the power amplifier (this will be discussed later). The use of thinner films can also cause deformation of the film curvature especially for speakers requiring large area of PVDF film. This deformation of curvature can cause irregularities in the frequency response curve.

CURVATURE OF PIEZOELECTRIC POLYMER FILM - The curvature radius of a film speaker is an important parameter for determining the frequency range of the speaker. For a rough estimation, the low frequency cutoff of a speaker is proportional to the square root of the ratio of Young's modulus of PVDF film to its density, and inversely proportional to the radius of curvature. Substituting the material property parameters, this low frequency can be estimated by the following equation:

$$f \sim \frac{21}{R\,(\mathrm{cm})}\ \mathrm{kHz} = \frac{53}{R(\mathrm{inch})}\ \mathrm{kHz}$$

R is the radius of curvature and f is the low frequency corner. See Figure 2. Note that the above equation does not take the mass loading effect of the electrodes into consideration. When the PVDF film is thin and heavy electrode materials such as silver ink are used, the above equation should be modified.

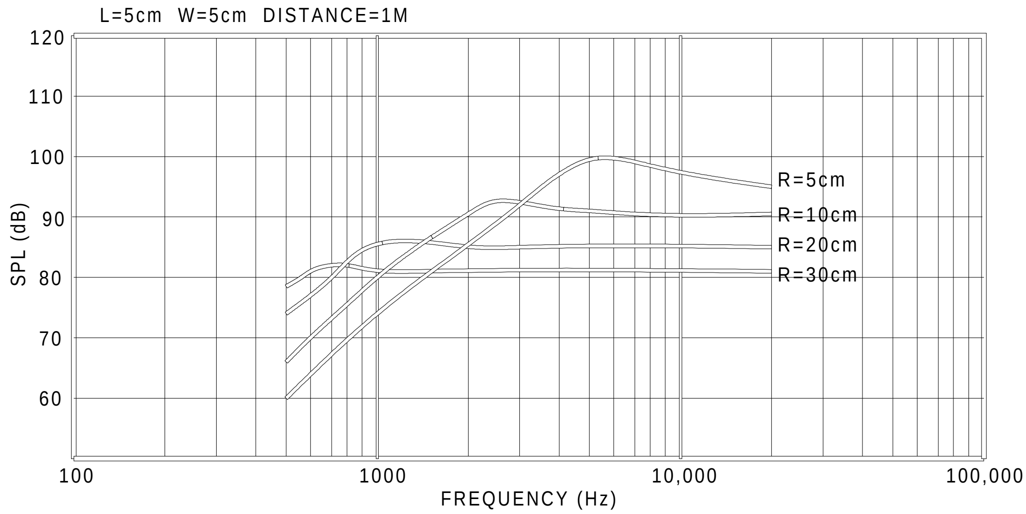

Figure 2

In the design of a piezo polymer speaker, the curvature of the film needs to be considered along with other structural parameters. For example, for a small area speaker, especially with a short length L, a large radius makes the film close to a flat plane, resulting in a lower acoustic output. On the other hand, for a large area speaker, a small radius makes the speaker deeper which requires a larger space.

Changing the radius not only controls the cutoff frequency, but also affects the sound pressure level at certain distances from the speaker. Figure 3a shows the relationship between low frequency corner and radius of curvature. Figure 3b shows the relationship between SPL at 10 kHz and radius of curvature for the same speaker. As seen from the graphs, the cutoff frequency and SPL are both inversely proportional to the radius.

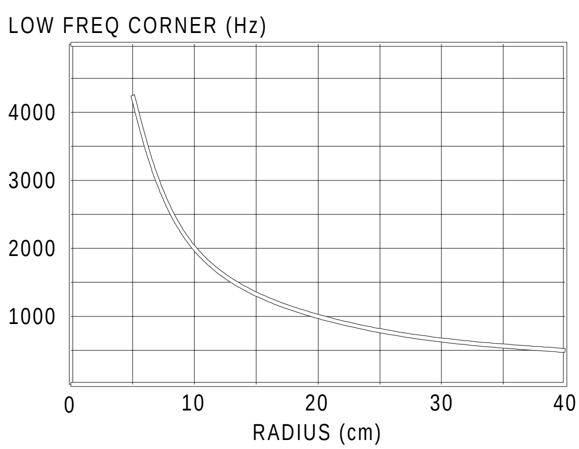

Figure 3a

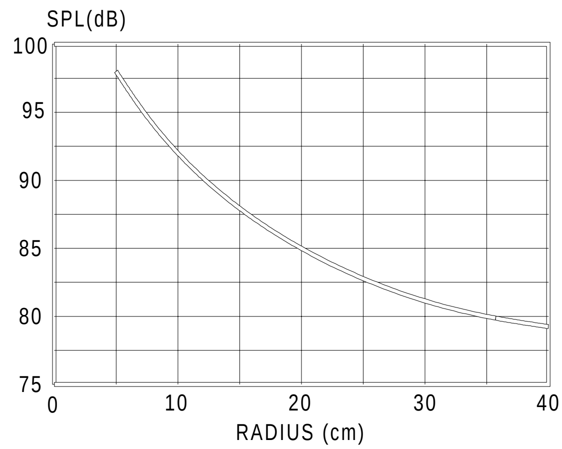

Figure 3b

LENGTH AND WIDTH OF SPEAKER FILMS - The acoustic output of a PVDF speaker is directly related to the length and width dimensions which are, in turn, determined by each different application. The sound pressure generated by a speaker at a certain distance is linearly proportional to the active area of PVDF film. Therefore, SPL is a logarithmic function of the PVDF film dimensions if the speaker area is rectangular. Figures 4a & 4b show the relation between SPL and film length and width respectively at 10 kHz.

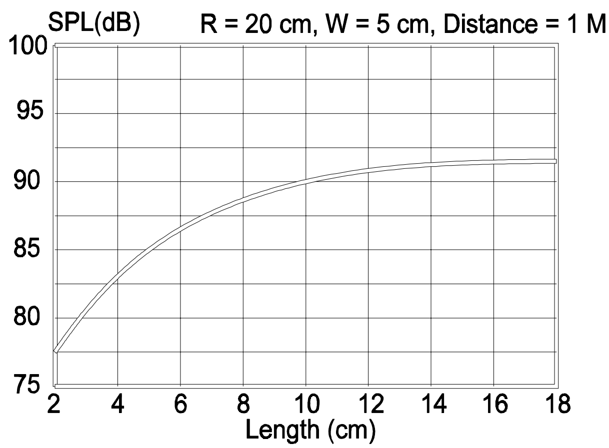

Figure 4a

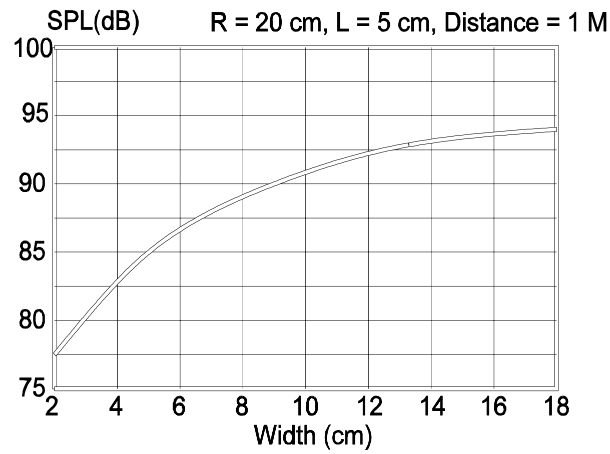

Figure 4b

POWER CONSIDERATIONS

In order to obtain a significant displacement from PVDF film to radiate sound, a high voltage is usually required. A step-up audio transformer can be used to increase the output voltage of an audio amplifier. The designer should give consideration to the electrical properties of the PVDF film speaker and the capabilities of the audio amplifier when selecting or designing the transformer. The input/output voltage ratio is directly proportional to the primary/secondary turns ratio of a transformer:

$$\frac{V_{sec}}{V_{pri}} = -\frac{N_{sec}}{N_{pri}}$$

The primary/secondary impedance ratio is proportional to the square of the turns ratio. The transformer must have an output impedance that is equal to or less than the PVDF film impedance at the highest specified frequency. If these impedances are not matched, significant distortion may result.

Conventional speakers present a resistive load to the power amplifier output while a PVDF film speaker presents a capacitive load to the output. Because of this the piezo film speaker impedance changes with frequency. For a 28 µm thick film with an area of 10 cm X 10 cm, the typical capacitance is about 35 nF. In the high frequency audio range, the impedance of such a speaker is quite low resulting in a high current draw from the amplifier. This current is about 90 degrees out of phase with the voltage applied to the PVDF film. With the high applied voltage and large current at higher frequencies, the apparent power, defined as the transformer output current times the voltage applied to the PVDF film, is somewhat higher when compared to conventional speakers. This power issue needs to be considered when choosing amplifiers and transformers. Because of the capacitive nature of a PVDF film speaker, an electrical resonance is introduced when using a transformer. This resonance should be avoided within the frequency range of interest or carefully damped.

PRACTICAL DESIGN TIPS FOR SPEAKERS

A reasonably good tweeter can be made using the basic design shown in Figure 1**.** Keeping the film smooth and wrinkle free will reduce distortion and provide an flat frequency response. The support should also be as rigid as possible to maximize the film surface displacement.

The lead attachment area should not be on the PVDF film radiating surface because any non-uniformity in the radiating element can be a source for distortion of air cavity. Filling the enclosure with a sound absorbing materials such as fiberglass or absorbing foams will reduce resonances and improve the sound quality**.** The enclosure should be made as rigid as possible to reduce structural resonances.

APPLICATIONS AND ADVANTAGES

Piezoelectric polymer speakers can be made in just about any imaginable shape or size. Square or rectangular elements can be sized to fit any available space. Wide horizontal or vertical dispersion angles can be obtained by wrapping the film in a 180 degree or 360 degree shape. The film can form a stand alone speaker element or can be laminated or attached to other structures to become an integrated speaker. A single film held in a shape with different curvatures in different areas of the film can provide unusual and unique frequency response characteristics. Piezo film speakers have the advantages of flat frequency response, high sound quality, low weight, flexible form factor, low cost, and ease of manufacturability. PVDF film speakers have a wide range of applications including home stereo, home theater, automotive, personal stereo, multi-media, and stereo headphones.

SAMPLE SPECIFICATION

PARAMETER	VALUE
Frequency Range	3.5 kHz - 20 kHz
SPL @ 40 cm	105 dB +/- 5 dB
Drive Voltage	125 V_{rms}
Enclosure Dimensions	13 cm X 11 cm X 6 cm
Radius of Curvature	7 cm
PVDF Thickness	52 µM
PVDF Capacitance	24 nF