A New Design of Thin and Flexible Loudspeaker

School of Engineering, University of Warwick, Coventry, CV4 7AL

Abstract - Loudspeakers are required whenever there is a need to reproduce sound. Utilising the technology behind ultrasonic capacitance transducers, a radically new loudspeaker concept has been developed, which has resulted in the creation of an ultra-thin loudspeaker. This speaker design, which is less than 1mm thick, is also flexible, being comprised of several thin sheets. Such a device would render it suitable to a wide range of applications, including those where space is at a premium, for example mobile telephones and notebook computers. An accurate mathematical model relating the material properties of the speaker to the expected resonant frequency has been developed, by analysing the fundamental characteristics and operation of the speaker. This has been used to improve the acoustical characteristics of the speaker. By utilising different loudspeaker geometries, there is a possibility of increasing the sound pressure level and bandwidth of the speaker such that a relatively flat response across the audible range can be achieved. This paper will report the work towards achieving this aim, and will discuss the need to fully understand the fundamental characteristics of the device.

I. Introduction

In recent years there has been rapid growth in the design, fabrication and manufacture of flat panel loudspeakers. However the idea of creating a flat panel loudspeaker is not a new one and the patents for flat speaker designs have actually been around for decades [1]. It is only relatively recently with the advancement of science and technology that flat-panel loudspeakers have been able to move out of the laboratory and into mainstream use. Today there are a number of manufacturers, of flat panel loudspeakers at various stages of development. However a number have reached commercial exploitation, an example being New Transducer Limited (NXT limited). This is now well established within the loudspeaker market.

The technology behind many existing flat panel designs uses a traditional method of excitation (such as a moving coil loudspeaker), which is used to excite vibrations within a thin panel. The diaphragm of the speaker is often excited in a way that produces the maximum number of bending resonances, evenly distributed in frequency, such that the panel vibrates as randomly as possible [2]. Close to the diaphragm this produces a complex sound field, although a short distance away it takes on far field characteristics.

In this work a new loudspeaker concept is described, which has resulted in the creation of an ultra-thin and flexible loudspeaker. Together with a mathematical model, which relates the material properties of the speaker to the expected resonant frequencies. It will be shown that the model accurately predicts the behaviour of the device, and that this is dominated by the material properties of the speaker.

II. The novel loudspeaker

Utilising the technology behind ultrasonic capacitance transducers, a new flat panel loudspeaker has been developed. In basic form the speaker consists of three or more layers of thin, flexible, materials, which on construction are sandwiched together to form the loudspeaker. This is shown schematically in figure 1, where it can be seen that a typical device has an insulating layer between two further electrically conducting layers.

As with the electrostatic loudspeaker the conducting membranes are held at constant charge using a bias voltage, which creates an electric field across the
thickness of the device. Because the foils are so close together, the application of a modest AC voltage signal creates a large electric field, which is highly efficient at moving the foils in the thickness direction, generating sound. With the benefits of flexibility and slender profile the loudspeaker has a clear difference in properties to other flat panel technologies. Therefore the potential applications of such a device are wide ranging, for example, a loudspeaker may be in the form of a large area sheet which can be mounted directly onto a wall to provide sound reproduction in the home without the need for bulky enclosures or external excitation devices. Furthermore such a speaker would be particularly suitable for use in applications where space is at a premium, for example, mobile telephones or notebook computers. In addition, the radiating surface could be replaced with transparent polymers, thus displays could be modified to radiate sound as well as optical images.

### III. Modelling of loudspeakers resonant frequency

From previous work carried out into air coupled ultrasonic transducers, it has been found that their mechanical response can be generally be modelled as a frictionless piston constrained by an air gap. The construction of the speaker is very similar to such devices, and therefore as a first approximation, when a charge is applied to the electrodes, the membrane can be considered to move as a simple frictionless piston resonator [3]. With this assumption, the speaker can be modelled as a simple mass spring system, with two resonant modes, where the mass is that of the membrane and insulator and the spring is provided by the air gap between the layers. Therefore the first mode resonant frequency of the system can be equated to:

\[
f = \frac{1}{2\pi} \sqrt{\frac{k}{m_1}} \quad [1]
\]

Where \(k\) is the spring stiffness and \(m_1\) is the mass of the membrane. Within this model the spring actually represents the air trapped between the layers, which we have assumed to follow adiabatic compression laws. Application of the laws of thermodynamics to the air gap results in the following expression for the stiffness, \(k\), of the structure:

\[
k = \frac{\gamma PA}{d_a} \quad [2]
\]

Where, \(\gamma\) is the adiabatic constant, and \(d_a\) is the thickness of the air gap between the layers of the structure. Substituting this equation into equation 1 and letting \(m_1 = \rho_m d_m A\) gives:

\[
f = \frac{1}{2\pi} \sqrt{\frac{PA}{d_m^2 \rho_m}} \quad [3]
\]

### VI. Model improvements

The above model neglects any mechanical properties of the vibrating membrane, which can be assumed to influence the behaviour of the system. This however can be rectified by considering the resonant frequency model for a flat plate, the formulas of which are given for common configurations in [4]. The resonant frequency for a flat plate whose edges are fixed is given as:

\[
f = \frac{K}{2\pi} \sqrt{\frac{Dg}{ma^4}} \quad [4]
\]

Where \(K\) is a constant, \(m\) is the mass of the membrane, \(a\) is the length of a side and \(D\) is the flexural rigidity per unit length. By substituting equation [1] into equation [4] the spring constant of the plate can be equated to:

\[
k_{plate} = \frac{K^2 Dg}{a^4} \quad [5]
\]

In order to substitute this into the developed resonant frequency equation, the initial model must be adapted to include a second “plate” spring to account for the mechanical properties of the device, see figure 2.
where \( \omega_d \) and \( \omega_n \) are the damped and undamped natural frequencies respectively and \( \zeta \) is the critical damping factor, which is given by:

\[
\zeta = \frac{b}{2A} \sqrt{\frac{\gamma \rho_m d_m}{d_a}}
\]

where \( b \) is the damping coefficient.

**V. Experimental apparatus**

In order to validate the predicted results from the model a loudspeaker was constructed such that the distance between the layers of the speaker could be altered, see figure 3.

![Figure 3: Showing the apparatus used to vary the structure of the loudspeaker.](image)

The loudspeaker was placed within an anechoic chamber and driven with a bias voltage 300V and a sinusoidal waveform with a peak-to-peak voltage of 2.8V from 20Hz to 20kHz. The resulting sound was received by a Brue and Kjaer 1/8th inch pressure field microphone (type 4138), which was connected to a Brue and Kjaer Nexus™ conditioning amplifier (type 2690). The results of which were recorded using a user defined computer program, see figure 4.
V. Comparison of theoretical and experimental results

A series of experiments were conducted to establish the validity of the model, where the frequency response of the loudspeaker was taken using the apparatus as in figure 4, the results of which can be seen in figures 5 and 6.

VI. Conclusion

A new and novel loudspeaker has been presented together with a model to predict the resonant frequency of the loudspeaker construction using the material properties of the device. The results of which have shown to correlate well with the experimental results obtained.

VII. References


