A novel flexible electrodynamic planar loudspeaker

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Abstract—This paper proposed a flexible electrodynamic planar loudspeaker (FEPL) with limited thickness (<<10 mm). The structure is very simple such as a flexible thin film diaphragm (polyimide) electroplated traces of copper coil above a flexible magnetic placed in the bottom of cavity, thus forming a seamless integration of electromagnetic actuation and planar flexible structure. The advantage of this design is that it can be used in flexible electronics or can be deployed on the surface of any object easily. Compared with an equivalent cone type loudspeaker, the performance of FEPL infinite baffle was found to be better at high frequencies but lags slightly in the low frequency range. Three additional cases of the FEPL were investigated, i.e. the FEPL with enclosure and no vent (Case 1), the FEPL with enclosure and vented around the side walls (Case 2), and the FEPL with enclosure and vented on the diaphragm (Case 3). In general, the FEPLs with enclosure showed a better performance than the infinite baffle one. However, for the FEPL with enclosure and no vent (Case 1), the performance is only better in the high frequency region, and the operational range is 1.3 to 20 kHz. The FEPLs with enclosure and vents around the side walls (Case 2) showed a better sensitivity extending towards the lower frequency region, the operational range is 60Hz to 20 kHz and with a minimum average SPL of 50 dB in the lower frequency region and 90 dB in the higher frequency region. On the other hand, the performance Case 3 is between those of Cases 1 and 2. To optimize the performance, this study made a detailed analysis on the thickness of cavity, magnet and coil, magnet configuration and polarization, and diaphragm dimension, thus contributing to the scarce literature in this area of study.

Keywords—Electromagnetic actuation, flexible substrate, magnetic flux density, planar loudspeaker, sound pressure level.

I. INTRODUCTION

Flexible electronics has been a hot research and development topic in the electronics industry since the past few years. This is due to the rapid growth of flexible electronic technology [1]–[2]. The speaker is an important part of the electronics and has received many attentions [3]–[11]. Some progresses have been made towards the development of flexible loudspeaker, and most of them have failed for commercial production. In loudspeaker design, many different actuation mechanisms are employed for electro-acoustic transduction, such as electromagnetic [4], [12]–[16], piezoelectric [5]–[6], electrostatic [17, 8], and electro-thermal [18]–[19] actuation mechanism. The flexible and transparent loudspeakers using piezoelectric actuation mechanism were developed [3, 5] by using PVDF as the piezoelectric polymer as radiator. Results of their study showed that the PVDF driven flexible loudspeaker were able to produce 70 dB and 80 dB SPL within a frequency range of 1 to 20 KHz and 400 Hz to 10 KHz, respectively. However, PVDF material is very expensive due to the complex production process [6]. They are of high frequency speakers and difficult to produce sound in low frequency range. Industrial Technology Research Institute (ITRI) Taiwan in 2009 filed a patent [17] of an electrostatic actuated ultrathin flexible loudspeaker, it was able to produce sound within 200 Hz -20 KHz, and thus can be operated in medium and high frequency [11]. They combined arrays of tiny, bendable speakers to produce speaker systems of almost any size using standard inkjet printing on substrate of paper or plastic and a thin metal. Though suffers the same fate as PDVF loudspeaker in producing low frequency sound. Furthermore, other industrial based developed flexible loudspeakers include Yamaha Corporation [9] and Warwick audio technologies [10] that developed an electrostatic directional flexible loudspeaker capable of producing sound only in a specified direction. Fujifilm [8] also developed an electro-acoustic film which also operates using electrostatic mechanism. The inspired work of Xiao et al. [19] brought to light a flexible, stretchable, transparent loudspeaker designed using carbon nano-tubes (CNT). It operates using the electro-thermal mechanism. But this loudspeaker has a major drawback for the lack of industrial process to create thin films of CNTs. Until now electromagnetic actuation mechanism has not been explored in designing flat flexible loudspeaker that can be used in pop up banners, portable exhibition stands and other uses that require flat flexible loudspeaker.

This study has explored the possibility to develop a flexible electrodynamic planar loudspeaker using a finite element method (FEM) approach. Over the years, electromagnetic actuation has been proven to be the most efficient actuation mechanism to generate sound pressure [4]–[13]. In general the electrodynamic loudspeakers generate sound through the interaction of a magnetic field, usually created by a rigid
permanent magnet (neodymium magnet), with a coil of wire carrying an audio current and attached to a diaphragm. The proposed design adopts the structure of a single ended planar loudspeaker which is an electrodynamic loudspeaker [7, 14]. Therefore, the challenge is how to utilize this actuation mechanism and structure to achieve a flexible loudspeaker. A typical structure of the proposed design is shown in Fig. 1. The core structure is the substitution of the conventional rigid magnet with a flexible magnet made of mixture of polymer and neodymium (NdFeB) or ferrite material. According to [21] it is obtainable to have flexible magnets that have up to 1.8 MgOe (2730 gauss) or more. This is relatively good for flexible loudspeaker application when all other militating factors are put to check as will be shown later. Besides, an ultrathin flexible polyimide film was adopted as the diaphragm with a copper coil electroplated on one side of its surface. The proposed flexible loudspeaker is expected to have a thickness less than 10 mm.

Fig. 1 Exploded view of the basic design of the proposed FEPL

The main focus of this study is to design an optimum structure that will yield the maximum efficiency and still retains the desired properties of the proposed loudspeaker and also analyze its mechano-acoustic and electrodynamic properties using FEM. The finite element simulation was done in two parts; first the FEPL was simulated considering it having an infinite baffle, this is to extract the essential parameters of the FEPL. Secondly, using the essential parameters the FEPL was modelled having an enclosure, with and without perforations. The pressure exerted inside the enclosure (behind the flexible substrate) was solved for and its effect on the SPL depicted. The results of the analysis showed that when supplied with a one volt audio signal, the proposed speaker is capable of producing 50 dB\text{SPL} (for FEPL to be as an infinite baffle) and 90 dB\text{SPL} (for FEPL to be with enclosure) measured from one meter distance, and have operating frequency ranges of 170 Hz to 20 KHz and 1.2 KHz to 20 KHz, respectively. Compared with an equivalent cone type loudspeaker, the performance of FEPL infinite baffle was found to be on par with the one of cone type loudspeaker at high frequencies but lags slightly in the low frequency range. To optimize the FEPL performance, this study made a detailed distribution analyses on the thickness of cavity, magnet and coil, magnet configuration and polarization, and diaphragm dimension, thus contributing to the scarce literature in this area of study. The paper is organized as follows: the first section is an introduction; the next part illustrates the FEPL structure configuration and optimization; Section 3 is results and discussions; the last part is a conclusion.

II. FEPL STRUCTURE CONFIGURATION AND DESIGN

A. Speaker Cavity Design

Considering the proposed structure of the FEPL the factors responsible for the performance includes the FEPL cavity (i.e., the distance of the coil from the magnet), the magnet polarization and the magnet arrangement adopted. Fig. 2 shows the 2-D cross-section view of FEPL. Fig. 3a shows the measured magnetic flux density at (0.5 mm above the speaker surface) for four cases of speaker cavity height. As the cavity height increases, the magnetic flux density decreases according to the power law $B^n$ where $n = 1.0033, 1.00395, 1.0046$ and $1.00525$ respectively for cavity height as 2 mm, 3 mm, 4 mm and 5 mm. $n$ is found to be making a constant progression for every 1 mm cavity height increment thus making the magnetic flux diminish rapidly as the magnet moves farther away. However, the larger the size of speaker enclosure the better chances of having a low frequency sound production if the resonant frequencies are well controlled [24]. A trade-off was employed here considering the speaker size and the diaphragm excursion. While 2 mm cavity height might be more appealing considering $B$, it is not suitable for a large excursion of the flexible substrate and mitigates the chances of achieving a low frequency operation of the FEPL. Thus, 4mm was chosen to be the suitable height for this design.

Fig. 2 2-D cross-section view of FEPL

B. Magnet Thickness Design

Fig. 3b shows the magnitude of magnetic flux for different magnet thickness measured at a given distance (0.5 mm above coil surface) as depicted in Fig. 2. The magnitude of magnetic flux increases proportionally to the magnet thickness. However, while a 2 mm magnet thickness might not create enough magnetic fields, and the increase up to 5 mm would not be satisfactory because both the volume and weight are too larger. Thus, the thickness of magnet was chosen to be 4mm for the cost, packaging and sound quality trade-offs.

Fig. 3 Magnitude of $B$ for different (a) cavity height, and (b) magnet thickness
C. Magnet Configuration and Polarization Design

Two basic modes of magnet polarization as respectively shown in Figs. 4a (vertical) and 4b (horizontal) were adopted. Based on the physics of electromagnetism, the component of a magnetic flux responsible for actuating a vertical force in perpendicular with the flat surface of a coil is the radial flux, $B_r$, of a planar magnet irrespective of its polarization. However, because the loudspeaker under investigation is of square shape, two magnetic flux components are responsible for the vertical force actuation; the x-component $B_x$, and the y-component $B_y$. The dimensions of the planar magnets used for investigation are as shown in Figs. 4a and 4b. Figs. 5 and 6 show the magnetic flux distributions and magnitudes in the x and y axes of a single magnet which is vertically polarized or horizontally polarized in the x-axis. Note that the flux density is concentrated on the edges of the magnet and less on the center by using the vertical type in either the x- or y-axis (Figs. 5b, 5c, and Fig. 6); while the flux density is concentrated on the edges of the magnet in the y-axis (Fig. 5f and Fig. 6) and less on the center in the x-axis (Fig. 5e and Fig. 6) by using the magnet horizontally polarized in the x-axis. The asymmetric nature of the horizontally polarized magnet will cause distortions in the diaphragm and lead to poor sound quality. So the vertically polarized magnet was chosen for the FEPL design.

![Fig. 4 Polarization of B](image)

D. Diaphragm Dimension Design

Polyimide was chosen because its temperature is endurable to 200°C and lightweight. The density, coefficient of thermal expansion and thickness of the diaphragm are 1430 kg/m$^3$, 5.5x10$^{-5}$/K and 0.122 mm, respectively. Finally, the performance of SPL and the dimension of the diaphragm are to trade off. Fig. 7 shows the SPL of the speaker for four surface areas (S) as 60 mm x 60 mm, 70 mm x 70 mm, 80 mm x 80 mm, and 90 mm x 90 mm. Note that as S increases the SPL slightly decreases and has more distortion within the operational frequency range. When S is 60 mm x 60 mm (blue), then the SPL is maximum but with a large resonance peak at 1500Hz. In comparison, the case of 70 mm x 70 mm has a more flat SPL than the one of 60 mm x 60 mm. Given this, the surface area with 70 mm x 70 mm is found to be the better one of diaphragm dimension, and the calculated mass is 0.855g.

![Fig. 7 SPL for four cases of diaphragm surface area (S)](image)

E. Coil Thickness Design

The turn and pitch of the coil are set as 30 turns and 1mm, respectively. Copper was chosen as the coil material for good electric conductivity. Fig. 8 shows that the SPL increases as the thickness (T) of the coil increases, which holds true, because the wire cross-sectional area is a function of the current density. However, at higher frequencies the trend changes as the effect of the coil weight becomes noticeable. For T > 0.1 mm, additional coil thickness starts playing a more diminishing role on the SPL in the high frequency region. Because as the coil thickness increases, the coil mass starts contributing negatively to the speaker SPL.
The better case of T is 0.1 mm. If L and W are the length and width of the first coil turn respectively, p is the pitch of the coil, l is the total length of coil, and N0 is the number of coil turn. By (1) the total coil length was calculated to be 3.78 m. Consequently, the mass of the coil was calculated to be 1.6443 g given that copper has a density of 8700 kg/m$^3$ and the coil is a square coil with evenly distributed pitch.

\[2N_0(L + W) + 8p \sum_{i=1}^{N_0}(N_0 - 1) = l\] (1)

III. RESULTS AND DISCUSSIONS

Fig. 9 shows the SPLs for the FEPL to be as an infinite baffle and with enclosure. The operational frequency of the FEPL spans from 170 Hz to 20 kHz as an infinite baffle; this is considered the region where SPL curve is more flat and also to avoid the mechanical resonance which occurred at 157 Hz as shown in Fig. 10 for the maximum displacement plot of diaphragm over frequency. The operational frequency produces minimum and maximum SPLs of 40 dB and 110 dB respectively. Fig. 9 also shows the SPL of an equivalent electrodynamic cone speaker (conventional speaker), in which the parameters such as voltage applied, number of coil turns, coil cross-sectional area and the magnet remanent flux density of the speakers were set to equal values. But the radiating surface area of the conventional speaker is approx. 97% greater than that of the FEPL. The SPLs were measured from the same distance. Note that the conventional speaker has a better performance in the lower frequency range and produces a more stable sound within this region; because it can undergo a more space for linear motion (pistonic motion) within this frequency. While in the higher frequency region, the FEPL is seen to have a more stable sound.

Furthermore, the conventional speaker has its operational frequency within the low and middle frequency region while the FEPLs are better within the middle and high frequency region. In general, the conventional speaker (or FEPL) has the highest SPL in the low (or high) frequency region. Three additional cases of the FEPL as shown in Fig. 11 were investigated, i.e., the FEPL with enclosure and no vent (Case 1), the FEPL with enclosure and vented around the side walls (Case 2), and the FEPL with enclosure and vented on the diaphragm (Case 3). Fig. 12 shows the SPL performances of all the cases. Note that the FEPLs with enclosure showed a better performance than the infinite baffle one. However, for the FEPL with enclosure and no vent (Case 1), the performance is only effectual in the high frequency region, and the operational range is 1.3 to 20 kHz. The FEPLs with enclosure and vents around the side walls (Case 2) showed a better sensitivity extending towards the lower frequency region, the operational range is 60 Hz to 20 kHz and with a minimum average SPL of 50 dB in the lower frequency region and 90 dB in the higher frequency region. On the other hand, the performance Case 3 is between those of Cases 1 and 2.
IV. CONCLUSION

This paper proposed a novel flexible electrodynamic planar loudspeaker that can generate a good audible sound. Some factors of the structure and configuration that led to tradeoffs are also made, such as the thickness of the cavity, magnet and coil, magnet configuration and polarization, and diaphragm dimension. The comparison of the FEPLs with the conventional cone type loudspeaker convincingly proved that the FEPLs have a better performance than the cone type loudspeaker in the high frequency region. In addition, the FEPL have other advantages over the cone type speaker, e.g. its flexibility, simple structure, cost effectiveness, easy manufacturability and its application versatility. The idea behind this study is a novel one, and as such has remained unexplored.

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REFERENCES


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