Loudspeakers for flexible displays

Takehiro Sugimoto^{1,*}, Kazuho Ono¹, Akio Ando¹, Kohichi Kurozumi²,
Akira Hara³, Yuichi Morita³ and Akito Miura³

¹NHK Science & Technical Research Laboratories,
1-10-11 Kinuta, Setagaya-ku, Tokyo, 157-8510 Japan

²NHK Engineering Services, Inc.,
1-10-11 Kinuta, Setagaya-ku, Tokyo, 157-8540 Japan

³Foster Electric Co., Ltd.,
512 Miyazawa-cho, Akishima, Tokyo, 196-8550 Japan

(Received 25 August 2008, Accepted for publication 28 August 2008)

Keywords: Loudspeaker, PVDF, Electrodynamic actuator, Display
PACS number: 43.38.Ja [doi:10.1250/ast.30.151]

1. Introduction

The increasingly widespread use of mobile appliances, such as 1-Seg [1,2], is changing the way we live, and a continuous development of new devices is essential for fuelling this growth. Conventional loudspeakers, however, still have a stiff enclosure and mechanical drivers, and this construction is not suitable for evolving mobile environments. Hence, concerns with loudspeaker improvements are growing.

In 2003, NHK Science & Technical Research Laboratories (NHK STRL) started to develop flexible displays for advanced mobile televisions. These flexible displays were conceptualized as thin, lightweight and flexible enough to be rolled up and carried around. The displays were fabricated with organic electroluminescence [3] or liquid crystal displays driven by organic thin-film transistors [4].

For these displays, we have developed two types of flexible and transparent loudspeakers [5,6]. The first type uses piezoelectric polyvinylidene fluoride (PVDF) with electrodes made of a transparent conducting polymer. We pasted the PVDF film on a plastic substrate used in the flexible display—this structure was intended to simulate assembly with the flexible display. The second type uses electrodynamic actuators, which are the mechanical components of conventional dynamic loudspeakers. We fabricated twenty-four miniature (4 g) electrodynamic actuators for this loudspeaker and installed them on the lateral sides of the plastic substrate. To radiate sound efficiently, these actuators push/pull the edge of the display, parallel to the surface.

Some companies already have loudspeakers that generate sound from the surfaces of TVs or PC displays [7,8], and others have developed ultra-thin loudspeakers for flat panel displays [7,9]; however, these sound-generating techniques are only suitable for solid materials or hard devices. Therefore, they are not applicable for flexible displays.

In this letter, we report on the structure of two proposed loudspeakers and their frequency response. These loudspeakers are not only for flexible televisions but also useful for various kinds of applications, e.g. other mobile terminals, because they can be also used as transparent loudspeakers.

2. Structure of the PVDF loudspeaker

Figure 1 outlines the structure of the PVDF loudspeaker and the principles underlying its vibration. The loudspeaker is A4 (210 × 297 mm) size and transparent. The PVDF adopted in this study was first processed by uniaxial extension, and its polarization was controlled to attain piezoelectricity. As shown in the left side of Fig. 1, applying voltage changes the device thickness, and reduced thickness converts into lateral stretching along its length. The whole loudspeaker vibrates according to that motion, as illustrated in the right side of Fig. 1.

For electrodes on the PVDF, we chose a conductive paint made of a polythiophene, which is a transparent conducting polymer, because conducting polymer can expand and shrink with the motion of the PVDF. On the other hand, the conventional metal electrodes used in a previous study [10] cannot easily move this way. The electric conductivity of polythiophene is not high compared with metal; thus we made terminals of silver along the edges of the electrodes to apply voltage from all sides.

After the electrodes were formed on both PVDF surfaces, the PVDF was pasted over the whole polyethersulfone (PES) film, which is a pliable and transparent plastic. The PES film was A4 size and 200 μm thick, and is used as a substrate for flexible displays. Assembly with the PES film was intended to simulate practical conditions, in which the loudspeakers are installed on the flexible displays.

A previous study on a sound generator using a composite piezoelectric polymer can be found in the literature [10]. The generator used a piezoelectric composite polymer, based on PVDF, with metal electrodes and was set up on a plastic base for mechanical reliability. It focused on the theoretical estimation of sound pressure level (SPL) and the development of a flat loudspeaker. In contrast, the present paper describes a flexible and transparent loudspeaker that can be bent, or even rolled up.

3. Structure of a loudspeaker with electrodynamic actuators

The left side of Fig. 2 outlines the sound generating mechanism using electrodynamic actuators. We designed new

*e-mail: sugimoto.t-fg@nhk.or.jp

Fig. 1 Structure of PVDF loudspeaker for flexible display.

Fig. 2 Structure and a photograph of loudspeaker for flexible displays with electrodynamic actuators.

miniature actuators that would preserve the mobility of the end device. The actuators consist of coils and neodymium magnets with a magnetic flux density of 0.45 T. The actuator's impedance was $4\ \Omega$, and it weighed 4 g.

In the case of a solid plate or board, we can generate sound by pushing and pulling it vertically, because the force on a single point can be conveyed throughout the whole area [7,8]. However, flexible displays are soft. A vertical force applied to a limited number of points on the surface cannot move the whole display efficiently. Therefore, we installed the actuators on the lateral edges of the PES, rather than on the surface, arranging them as densely as possible to obtain sufficient SPL. In practice, this was twelve per side. The actuator characteristics do not vary widely, because electrodynamic actuators have been used for a long time and are well understood. Therefore, it was not necessary to sort them.

The actuators pushed/pulled the PES parallel to its surface, generating bending waves, which travelled on the display, until at last the sound was emitted.

The right side of Fig. 2 shows a photograph of the loudspeaker with electrodynamic actuators. Each of the thin bars on the lateral edges of the loudspeaker contain twelve actuators. Some of these actuators are connected in series, and others in parallel, for a total loudspeaker impedance of $22\ \Omega$.

4. Experiments and results

All measurements were made in an anechoic chamber, at a distance of 1 m.

Fig. 3 Steady-state response of PVDF loudspeaker. Measurement distance was 1 m.

4.1. Frequency response of PVDF loudspeaker

Figure 3 plots the steady-state response of the PVDF loudspeaker. The loudspeaker was held by clips on its short sides. We bent it into a circular arc, which is an ordinary bent condition of flexible displays. The applied voltage was stepped up to 20 V (rms) by an output transformer.

The frequency response of the PVDF loudspeaker exhibited some dips and peaks, which might originate from the resonance structure of the PVDF, and it was found that this loudspeaker responded from some hundreds of Hertz to

Fig. 4 Steady-state response of loudspeaker with electrodynamic actuators. Measurement distance was 1 m.

20 kHz. PVDF has been used for generating high frequency sound (higher than several kilo Hertz) in audio equipment, however, this study reproduced sound lower than 1 kHz. This result will be discussed later in Sect. 5.

4.2. Frequency response of loudspeaker with electrodynamic actuators

Figure 4 plots the steady-state response of a loudspeaker with electrodynamic actuators. The loudspeaker was fixed to poles using clips as shown in Fig. 2. This is the same bent condition as the PVDF loudspeaker.

The response shows fewer peaks and dips than the PVDF loudspeaker. The lowest resonant frequency of this loudspeaker was around 500 Hz, because the frequency response fell rapidly below 500 Hz. This is similar to the behaviour of conventional loudspeakers using electrodynamic actuators.

5. Discussion

In our preliminary experiment, we used a small PVDF (4×4 cm) and its frequency response was insufficient to reproduce low frequency sound. It only radiated sounds higher than 2 kHz [11]. The PVDF loudspeaker in this study, however, generated sounds as low as 800 Hz. Generally, the directivity of a direct radiator is dependent on the size of the diaphragm [7,12], and a larger diaphragm has narrow directivity, even in a lower frequency range. This suggests that upper limit of the frequency range where mutual cancelation between the sound from the front and back occurs would fall with a larger diaphragm. Therefore, a larger diaphragm, i.e. the A4-size PVDF, would prevent interference between sound from the front and back, which might result in an extension of the frequency range, as observed in this study.

The frequency responses of the two loudspeakers are not flat; however, these loudspeakers were developed for mobile use, and high-fidelity reproduction is not mandatory. Their sound quality might to be acceptable enough to enjoy the content and understand speech in a mobile environment.

Making the sound louder requires a larger amplitude of vibration. However, too large an amplitude would disrupt the images on the display. We have not yet investigated the influence of vibration on images; however, we can say that the vibration was not visible under the conditions in this study.

The materials used in this study, i.e. the conducting polymer and the PES substrate, are not necessarily the best for acoustics. The search for good acoustic materials should continue.

Further research on the surface vibration of the flexible loudspeakers would clarify several parameters that control the sound quality, and improve various acoustic characteristics of the flexible loudspeakers.

6. Conclusion

We developed two loudspeakers for flexible displays. The first was made of PVDF and the second used electrodynamic actuators. The steady-state response indicated the possibility of extending the frequency range of the PVDF loudspeaker by enlarging its physical size. The loudspeaker with electrodynamic actuators had a better response than the PVDF loudspeaker.

We intend to improve the acoustic characteristics of the loudspeakers with the aim of assembling them with flexible displays into flexible televisions.

References

- [1] http://www.nhk.or.jp/digital/en/digitalbroad/04_3_mobile.html
- [2] <http://www.dpa.or.jp/english/about/index.html>
- [3] M. Suzuki, T. Tsuzuki, T. Komiyama, T. Yamaguchi, T. Furukawa and S. Tokito, "Flexible color OLED display based on phosphorescent materials fabricated by ink-jet printing," *Proc. 13th IDW, OLED3-3*, pp. 475–478 (2006).
- [4] Y. Fujisaki, H. Sato, T. Yamamoto, H. Fujikake, S. Tokito and T. Kurita, "Flexible color LCD panel driven by low-voltage-operation organic TFT," *J. SID*, **15**(7), 501–506 (2007).
- [5] T. Sugimoto, K. Ono, A. Ando, K. Kurozumi, A. Hara, Y. Morita and A. Miura, "Development of loudspeakers for flexible displays," *Proc. Autumn Meet. Acoust. Soc. Jpn.*, 2-7-6 (2007) (in Japanese).
- [6] T. Sugimoto, K. Ono, K. Kurozumi, A. Ando, A. Hara, Y. Morita and A. Miura, "Loudspeakers for flexible displays," *AES 123rd Convention*, 7303 (2007).
- [7] J. Borwick, *Loudspeaker and Headphone Handbook*, 3rd ed. (Focal Press, Oxford, 2001).
- [8] <http://www.nxtsound.com/>
- [9] <http://www.fps-inc.co.jp/english.html>
- [10] J. Ohga, "A flat piezoelectric polymer film loudspeaker as a multi-resonance system," *J. Acoust. Soc. Jpn. (E)*, **4**, 113–120 (1983).
- [11] T. Sugimoto and K. Kurozumi, "Acoustic characteristics of electro-active polymers," *Proc. Autumn Meet. Acoust. Soc. Jpn.*, 1-1-6 (2006) (in Japanese).
- [12] L. L. Beranek, *Acoustics* (The Acoustical Society of America, New York, 1996).