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A flat piezoelectric polymer film loudspeaker as a multi-resonance system

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A flat diaphragm full-range loudspeaker utilizing a piezoelectric polymer is described. This loudspeaker is characterized by an excellently simple constitution and multi-resonance response characteristics. Since the fundamental resonant frequency of a loudspeaker should be as low as possible, it is convenient to utilize the flexural vibration of a bimorph diaphragm. The input-output relation of a bimorph diaphragm radiator in a multi-resonance frequency region is studied theoretically, and the formula for estimating output sound pressure level for the resonant peak is given. This is also examined experimentally.

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1. INTRODUCTION

This paper reports on both a conceptualization for a simple loudspeaker construction that utilizes a sheet of composite piezoelectric polymer,[1] and a procedure for estimating the response of its multi-resonance sound radiator diaphragm.

A direct radiator loudspeaker with a flat diaphragm, whose radiation is caused by the flexural mode vibration of the diaphragm, is attractive due to its simple structure. However, its rugged frequency response due to multi-resonant vibration of the diaphragm seemed to be a disadvantage.

Subjective tests reported by Wakita and Saito show that 10 dB frequency response irregularity is allowable for speech signals and 20 dB is for music.[2] Refering to this work, some moving coil flat loudspeaker with a multi-resonance characteristics were developed.[3] However, the loudspeaker construction was still as complicated as that for a conventional loudspeaker.

As was reported as a result of a previous study on telephone receiver structures,[4] piezoelectric devices are characterized by simple construction. There was a proposition about a simple loudspeaker using piezoelectric ceramic wafers,[5] and a few samples are commercially available now. However, they still have had fatal disadvantages due to brittleness of the conventional ceramic.

Recently, certain piezoelectric polymers, made from polyvinylidenefluoride (PVDF), were studied. They are soft, flexible and easily rollable into a wide film.[6–8] Especially, the composite piezoelectric polymer,[9,10] which is a system of lead-titanate-zirconate (PZT) ceramic powder and PVDF and/or fluorinated rubber (FR), not only shows piezoelectricity as large as that for a heavily elongated pure PVDF film,[6] but also has a Young's modulus that is widely controllable through variation in the ratio between PVDF and FR. This material is suitable for making a molded sheet. As a whole, it is useful for a full-frequency-range loudspeaker with a simple flat diaphragm.

In this paper, a flat loudspeaker made of a large plane bimorph diaphragm is proposed. A flat bimorph is suitable for use as a full-range loudspeaker, which needs a very low fundamental resonant frequency. However, it is still difficult to estimate practical sensitivity of a flat diaphragm having a low fundamental resonant frequency because of its tendency to show many resonant peaks and dips in its middle or high working frequency range. This paper also describes the formula for estimating loudspeaker response at a resonant peak in the multi-resonance frequency region, comparing the estimated output sound pressure level with the measured level.

2. FLAT LOUDSPEAKER CONSTRUCTION AND A DEMONSTRATION

To let the fundamental resonant frequency of the loudspeaker diaphragm be as low as possible, a laminated structure, i.e., a "bimorph" structure as shown in Fig. 1, was selected. Its radiator function is caused by its transversal mode vibration.

As indicated in Table 1, Young's modulus for the composite piezoelectric polymer is as large as that for general polymer materials. Therefore, a plastic sheet is convenient for the base material. A polyethylene-telephtalate film was used because of its mechanical reliability.

Figure 2 shows a flat piezoelectric loudspeaker model for a demonstration. A diaphragm sheet is supported at its upper and lower edges. Its electrical impedance (2.3 kΩ for 1 kHz) is purely capacitive (0.07 μF). Figure 3 shows its output sound pressure.

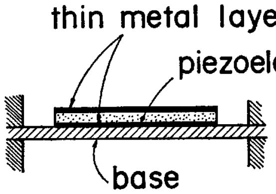

Fig. 1 Bimorph structure for the piezoelectric diaphragm.

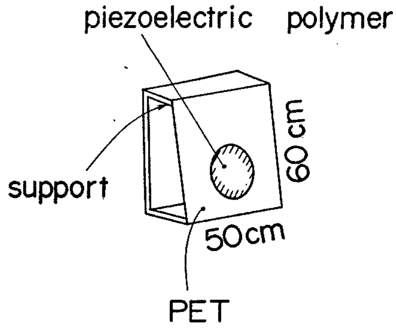

Fig. 2 Example of flat piezoelectric loudspeaker with bimorph diaphragm.
PVDF-PZT composite film (about 200 mm diameter, about 0.2 mm thickness) was pasted on polyethylene-telephtalate film (0.19 mm thickness).

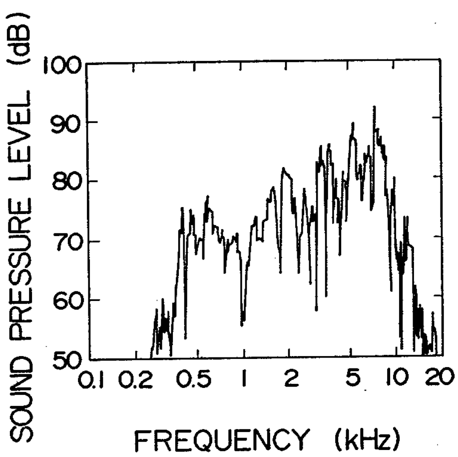

Fig. 3 Output sound pressure from flat loudspeaker shown in Fig. 2.
Two volts rms input was fed through a 4 Ω: 8 kΩ step-up transformer. Measurement was made 50 cm from the diaphragm.

Table 1 Physical quantities of some piezoelectric materials.

Materials	Constants				
	Relative dielectric constant (ϵ/ϵ_0)*	Young's modulus (10^9 N/m^2)	Density (10^3 kg/m^3)	Piezoelectric d-constant (10^{-12} m/V)	Author(s)
Composite piezoelectric polymer	40–140	0.5–6	less than 6	10–45	Shirai *et al.*[9]
PVDF (elongated)	12	3.6	1.8	27	Tamura *et al.*[6]
Quartz	4.5	78	2.65	2.3	Mason[11]
PZT ceramic	1700	53	7.75	170	Mason[11]
Collagen	8	2	1.2	2.7	Fukada[12]
PMG (elongated)	10	2	1.3	5	Fukada[12]
Nylon 11	3.7	3	1.2	0.5	Fukada[12]

* ϵ_0, dielectric constant for vacuum.

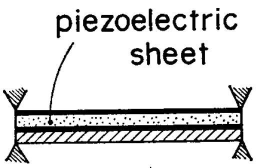

Fig. 4 Simplified model for calculation.

A level of 0.1 Pa (1 μbar) can be produced by an apparent input power of about 3.5 volt-amperes.

From experiments of this sort, it was concluded that:

(1) Its sensitivity is, though less than that for a moving-coil loudspeaker, as high as that for an electrostatic one.

(2) Irregularity in its sensitivity frequency characteristics is less than 20 dB.

As a whole, its performance attains a sufficiently practical level.

3. OUTPUT LEVEL ESTIMATION

As the next stage, a bimorph diaphragm model response for its multi-resonance frequency region was calculated. For calculation simplicity, the following assumptions were introduced.

(1) The simplest bimorph diaphragm model, shown in Fig. 4, is used.
It is simply supported at its boundary. The piezoelectric sheet diameter is equal to that for the base. We denote that;

h_1 and h_2: thickness,
ρ_1 and ρ_2: density,
Y_1 and Y_2: Young's modulus,
σ_1 and σ_2: Poisson's ratio.

Where suffix 1 means for the piezoelectric sheet and 2 for the base. Additionally, it was designated that;

$$\left.\begin{aligned} \alpha &= Y_1/Y_2 \text{ (complex number)}, \\ \beta &= h_1/h_2 \text{ (real number)}. \end{aligned}\right\} \qquad (1)$$

and diaphragm radius is a.

(2) Young's modulus, including the mechanical resistance term, can be denoted so that;

$$Y_{1 \text{ or } 2} = Y'_{1 \text{ or } 2}(1 + j \tan \delta_{1 \text{ or } 2}), \qquad (2)$$

where $j=\sqrt{-1}$ and $\tan\delta$ is the loss factor. Here, it is assumed that mechanical loss is due to internal energy loss in the diaphragm materials only, i.e., energy dissipation due to sound radiation is neglected. Accuracy for this assumption will be checked later by several experiments.

(3) The output sound pressure at only a distant point on the principal axis of the diaphragm is calculated. The distance between that point and the diaphragm center is denoted r', which is regarded to be satisfactorily larger than the diaphragm radius a.

(4) Only symmetrical vibration modes are noticed in calculation, because any asymmetrical modes, which have diametrical nodal lines, brings no output sound pressure except at a point near the diaphragm.

Flexural mode vibration displacement, ξ, for the diaphragm due to input voltage, E, is given by the equation[4)]

$$(D_1+D_2)\nabla^4\xi+(\rho_1 h_1+\rho_2 h_2)\frac{d^2\xi}{dt^2}=0, \qquad (3)$$

and also two equations for the boundary condition. One of them is inhomogeneous, including the bending moment term due to the piezoelectric effect. The bending moment is given by

$$M_v \equiv Y_2 h_2 \frac{d_{31}E}{2(1-\sigma_1)} \frac{\alpha(1+\beta)}{1+\alpha\beta}, \qquad (4)$$

where D values are flexural rigidities, such that

$$D_1 \equiv \frac{Y_2 h_2}{3(1-\sigma_1^2)}\left[\alpha\beta^3+\frac{3}{2}\alpha\beta^2\left(\frac{1-\alpha\beta^2}{1+\alpha\beta}\right)+\frac{3}{4}\alpha\beta\left(\frac{1-\alpha\beta}{1+\alpha\beta}\right)\right],$$

$$D_2 \equiv \frac{Y_2 h_2}{3(1-\sigma_2^2)}\left[1-\frac{3}{2}\left(\frac{1-\alpha\beta^2}{1+\alpha\beta}\right)+\frac{3}{4}\left(\frac{1-\alpha\beta}{1+\alpha\beta}\right)\right], \qquad (5)$$

and where d_{31} is the piezoelectric d-constant for the piezoelectric sheet. It is assumed that d_{31} is real. The solution at the point on the diaphragm (radius r from its center, $0 \le r \le a$) is

$$\xi = M_v[J_0(ka)I_0(kr)-I_0(ka)J_0(kr)]/\Delta_0, \qquad (6)$$

where $J_0(ka)$ and $I_0(ka)$ are Bessel functions. The determinant, Δ_0, is

$$\Delta_0 \equiv \begin{vmatrix} J_0(ka) & I_0(ka) \\ [D_1(1-\sigma_1)+D_2(1-\sigma_2)]\frac{k}{a}J_1(ka) & \\ -(D_1+D_2)k^2 J_0(ka) & -[D_1(1-\sigma_1)+D_2(1-\sigma_2)]\frac{k}{a}I_1(ka) \\ & -(D_1+D_2)k^2 I_0(ka) \end{vmatrix}, \qquad (7)$$

and the complex wave number, $\underset{\cdot}{k}$, is given by

$$\underset{\cdot}{k}^4 \equiv \frac{\rho_1 h_1 + \rho_2 h_2}{\underset{\cdot}{D}_1 + \underset{\cdot}{D}_2}\omega^2 . \qquad (8)$$

Here ω is the angular driving frequency.

Assuming that the diaphragm is mounted on an infinitely large baffle board, and that the diaphragm size is smaller than the wave length of the sound in air, then the velocity potential, $\underset{\cdot}{\Psi}$, for the output field at a point located at distance r' from the diaphragm center, is given by Rayleigh's formula. This is such that

$$\underset{\cdot}{\Psi} = \frac{1}{2\pi}\iint_S \frac{\partial \xi}{\partial t}\cdot\frac{\exp(-jk'r')}{r'}dS$$
$$\simeq \frac{j\omega}{2\pi}\frac{\exp(-jk'r')}{r'}\iint_S \underset{\cdot}{\xi} dS . \qquad (9)$$

Here k' is the wave number in air, and integration extends over all areas of the diaphragm. We can calculate the output sound pressure, $\underset{\cdot}{p}$, by using Ψ and the formula

$$\underset{\cdot}{p} = j\omega\rho_a\underset{\cdot}{\Psi} . \qquad (10)$$

Here, ρ_a is density of air (1.21 kg/m^3).

It is necessary to calculate output sound pressure for the resonant condition. Considering that both the piezoelectric material and base material are polymer plastics, we make some assumptions.

(a) Poisson's ratio for both materials are equal:

$$\sigma \equiv \sigma_1 = \sigma_2 (\simeq 1/3) . \qquad (11)$$

(b) The ratio between real and imaginary parts of $\underset{\cdot}{Y}_1$ is equal to that for $\underset{\cdot}{Y}_2$; we call this ratio $\tan\delta$, as shown in Eq. (1). This means that the mechanical Q factor of the piezoelectric polymer is assumed to be equal to that for the base material.

(c) Factor $\tan\delta$ is satisfactorily smaller than unity (for example, 0.01 ~ 0.03).

Then, we can estimate output sound pressure for resonant peaks. The conditions for resonance are given by the solution of

$$\underset{\cdot}{\Delta}_0 = 0 . \qquad (12)$$

From this, eigenvalues, α_m, are determined as

$$\underset{\cdot}{k}a = \alpha_m$$
$$\alpha_1 = 2.2325, \quad \alpha_2 = 5.4551, \quad \alpha_3 = 8.6135, \quad \cdots$$
$$\alpha_m \simeq (4m-1)\pi/4 \text{ (for a large } m) . \qquad (13)$$

If we designate

$$\underset{\cdot}{D} \equiv D' + jD'' \equiv \underset{\cdot}{D}_1 + \underset{\cdot}{D}_2 , \qquad (14)$$

then the complex angular frequency, $\underset{\cdot}{\omega}_m$, for α_m is given by

$$\underset{\cdot}{\omega}_m \equiv \omega_m' + j\omega_m''$$
$$\simeq \sqrt{\frac{D'}{\rho_1 h_1 + \rho_2 h_2}}\cdot\frac{\alpha_m^2}{a^2}\left[1 + j\frac{\tan\delta}{2}\right] . \qquad (15)$$

The diaphragm shows resonant peak vibration when driving frequency is ω_m'.

When α_m is not so large, Bessel functions are modified so that[13]

$$\left.\begin{aligned} J_0(\underset{\cdot}{k}a) &\simeq J_0(\alpha_m) + j\frac{\tan\delta}{4}\alpha_m J_1(\alpha_m) \\ J_1(\underset{\cdot}{k}a) &\simeq J_1(\alpha_m) - j\frac{\tan\delta}{4}[J_1(\alpha_m) - \alpha_m J_2(\alpha_m)] \\ I_0(\underset{\cdot}{k}a) &\simeq I_0(\alpha_m) - j\frac{\tan\delta}{4}\alpha_m I_1(\alpha_m) \\ I_1(\underset{\cdot}{k}a) &\simeq I_1(\alpha_m) - j\frac{\tan\delta}{4}[I_1(\alpha_m) + \alpha_m I_2(\alpha_m)] \end{aligned}\right\} . \qquad (16)$$

Then, Ψ at resonant peak vibration can be given by

$$\underset{\cdot}{\Psi}_{0m} = \frac{\exp(-jk'r')}{r'}\omega_m\frac{a^2}{\underset{\cdot}{k}^2}\frac{\underset{\cdot}{M}_v}{\underset{\cdot}{D}}\frac{4}{\tan\delta}$$
$$\cdot\frac{\begin{pmatrix} J_0 I_1 - J_1 I_0 + j(\tan\delta)/4 \\ \cdot[2\alpha_m J_1 I_1 + (J_0 I_1 - J_1 I_0)] \end{pmatrix}}{-2\alpha_m[(1+\sigma)J_0 I_0 + \alpha_m(J_0 I_1 - J_1 I_0)]} , \qquad (17)$$

where J_0, etc., means $J_0(\alpha_m)$, etc.

To estimate a typical response for the piezoelectric flat loudspeaker, consider

$$\left.\begin{aligned} &\underset{\cdot}{Y}_1 = \underset{\cdot}{Y}_2 \equiv \underset{\cdot}{Y} \equiv Y'(1 + j\tan\delta) \\ &h_1 = h_2 = h \\ &\rho_1 = \rho_2 = \rho \\ &\therefore\ \underset{\cdot}{\alpha} = 1 \text{ and } \beta = 1 \end{aligned}\right\} . \qquad (18)$$

Then, output sound pressure at $\omega = \omega_1$ (fundamental resonant frequency), ω_2, ω_3, etc. is calculated as

$$|p_1| = 0.5644\frac{\rho_a}{\rho}\frac{Y'd_{31}E}{(1-\sigma)\tan\delta}\frac{1}{r'} , \qquad (19)$$

$$\left.\begin{aligned} &|p_2| = 0.9018|p_1| \\ &|p_3| = 0.8937|p_1| \\ &\cdots \end{aligned}\right\} . \qquad (20)$$

Subsequently, the sound pressure for a much larger m needs to be calculated. Values for functions J_0, I_0, J_1, and I_1 can be calculated using asymptotic series expansion, when α_m is larger than 10. However, $\alpha_m(\tan\delta)/4$ exceeds unity at α_m of 400, when

$\tan\delta$ is equal to 0.01, which is a typical value for most plastic materials. Thus it can be assumed that,

$$\left.\begin{aligned}&\alpha_m \gg 1\\&\alpha_m(\tan\delta)/4 \ll 1\end{aligned}\right\}, \tag{21}$$

and sound pressure can be calculated as,

$$|p_0| \simeq \frac{1}{2}\frac{\rho_a}{\rho}\frac{Y'd_{31}E}{(1-\sigma)\tan\delta}\frac{1}{r'} = 0.8858|p_1|. \tag{22}$$

This gives the resonant peak sound pressure for a flat piezoelectric loudspeaker in its multi-resonance frequency region.

The estimated $|p_0|$ is shown in Fig. 5, with an assumption having been made that

$$\left.\begin{aligned}&\rho=2.5\ [\mathrm{g/cm^3}]\\&Y'=5\times10^{10}\ [\mathrm{dyn/cm^2}]\\&\sigma=0.33\\&\tan\delta=1/40\end{aligned}\right\}, \tag{23}$$

which are typical values for polymer piezoelectric materials.

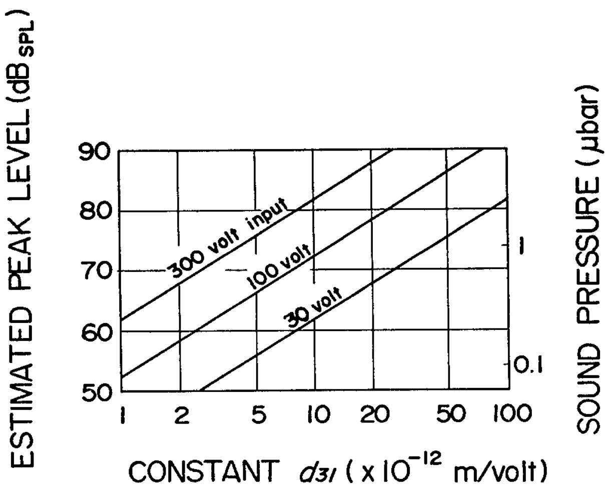

Fig. 5 Calculated output sound pressure peak level for flat loudspeaker.
It was assumed that $\rho=2.5\ \mathrm{g/cm^3}$, $E'=5\times10^{10}\ \mathrm{dyn/cm^2}$, $\sigma=0.33$, $\tan\delta=1/60$ and $r'=1$ m.

Finally, we check the case when the assumptions given by Eq. (18) are unsatisfied. Difference in ρ influences only the numerator of Eq. (8), which is independent from the influence of other parameters. Influences α and β can be determined by estimating the volume displacement at $\omega\rightarrow 0$,[4] in the manner

$$U_S = \pi a^2 \bar{\xi} = (\pi/4)a^4 M_v/[(1+\sigma_1)D_1+(1+\sigma_2)D_2]. \tag{24}$$

Where $\bar{\xi}$ is average displacement. Assuming Eq. (11),

$$U_S = \frac{3}{2}\pi a^4 \frac{d_{31}E}{h_2^2} \cdot \frac{\alpha(1+\beta)}{4(1+\alpha\beta)(1+\alpha\beta^3)-6(1-\alpha\beta^2)^2+3(1-\alpha\beta)^2}. \tag{25}$$

Through this formula, it can be seen that U_S varies only 12% (1 dB) when α varies 0.5 ~ 2, and β varies 0.5 ~ 1.5. Thus, estimation under the assumptions in Eq. (18) is practically possible.

4. EXPERIMENTAL

In order to examine the peak sound pressure estimation formula, and to analyze the diaphragm behavior, the experimental model shown in Fig. 6 was constructed. It simulates the model for formulation shown in Fig. 1. The piezoelectric sheet was a

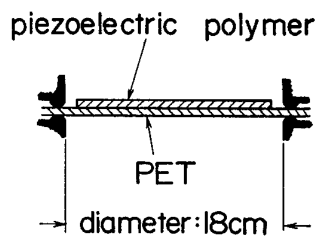

Fig. 6 Experimental circular bimorph diaphragm.
Piezoelectric material is PVDF-PZT composite 17 cm in diameter, 0.25 mm thick and 2.5×10^{-12} m/V d_{31}. Base material is similar to that shown in Fig. 2.

Table 2 Physical constants for sheets used in experimental model shown in Fig. 5.

		Base	Composite	Bimorph
Young's modulus	(N/m²)	5.4×10^9	3.7×10^9	4.8×10^9
Thickness	(10^{-3} m)	0.19	0.22	0.42–0.44
Density	(10^3 kg/m³)	1.4	3.6	2.5
$\tan\delta$	—	1/43	1/31	1/57

Measured by author using a small reed-shaped sample.

PVDF-PZT composite whose diameter was 17 cm, and whose measured piezoelectric constant, d_{31}, was 2.5×10^{12} m/V. The base sheet was a polyethylene-telephtalate film. Their physical constants are shown in Table 2.

Only the base was clamped at its boundary to realize a supported boundary condition. Due to the slight initial curvature of the bimorph sheet, it was difficult to clamp it without static tension. Therefore, the diaphragm behaved as a membrane at lower frequencies where the restoring force due to tension was dominant. It acted as a plate at higher regions. As is shown in Fig. 7, the transition into and out of both regions was at 360 Hz for this model.

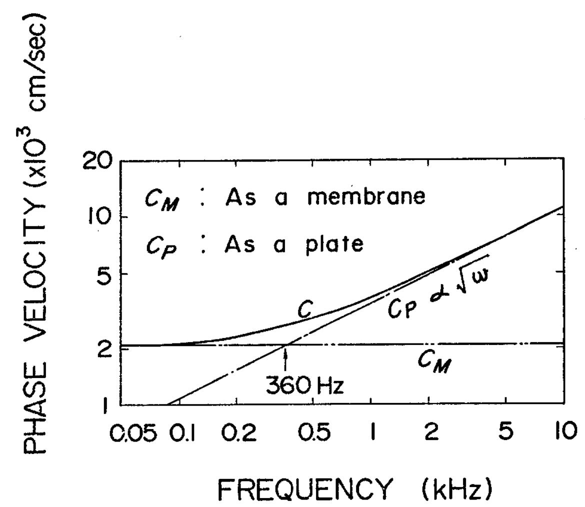

Fig. 7 Flexural wave phase velocity for diaphragm shown in Fig. 5.
C_M value is due to static tension measured using a strain-gauge. C_P value is given by using Eq. (8).

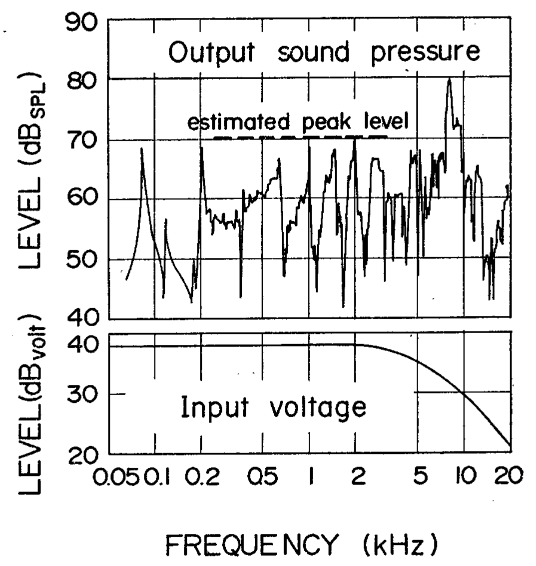

Fig. 8 Output sound pressure level, and input voltage.
Sound pressure was measured 20 cm from the diaphragm. Broken line represented peak level estimated using Eq. (22).

Figure 8 shows the output sound pressure levels, and input voltage. Estimated peak level, using Eq. (22) for $\tan\delta=1/40$, is represented by the broken line. The estimate agrees satisfactorily with some peak levels, in spite of some formula simplification described in Section 3.

There is a marked peak at about 8 kHz. It is not shell resonance, the frequency for which is given by Eq. (2), but the resonance of the extensional vibration of the thick region at the diaphragm center. Resonant frequency for the extensional vibration for this diaphragm size is estimated to be 6 kHz for a free boundary, and 10 kHz for a clamped boundary.[14] Therefore, the peak seems due to some intermediate boundary condition between them.

As will be described in the Appendix, there is no output pressure level difference between circular and rectangular diaphragms. However, a rectangular shape is more favorable for construction of a boxy loudspeaker system or a plane panel loudspeaker unit. Figure 9 shows a flat loudspeaker of practical structure and sensitivity that uses a rectangular diaphragm. Figure 10 presents frequency characteristics for its output sound pressure. The estimated peak level, using Eq. (22), is also shown in this figure. It agrees with the measured level in the low and moderate frequency regions. At 1000 Hz,

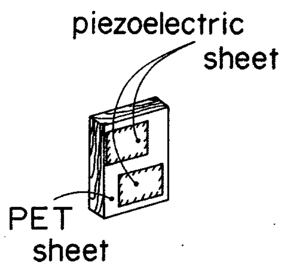

Fig. 9 Rectangular flat loudspeaker with practical structure and efficiency.
Base is 50 cm $\times$ 40 cm $\times$ 0.19 mm. Piezoelectric sheet is PVDF-PZT composite, whose d_{31} is 18×10^{-12} m/V, and 19 cm $\times$ 22 cm $\times$ 0.25 mm. Total capacitance of the sheets is 0.11 μF. Mechanical loss factor, $\tan\delta$, for the diaphragm is 1/23. Back of the box is closed.

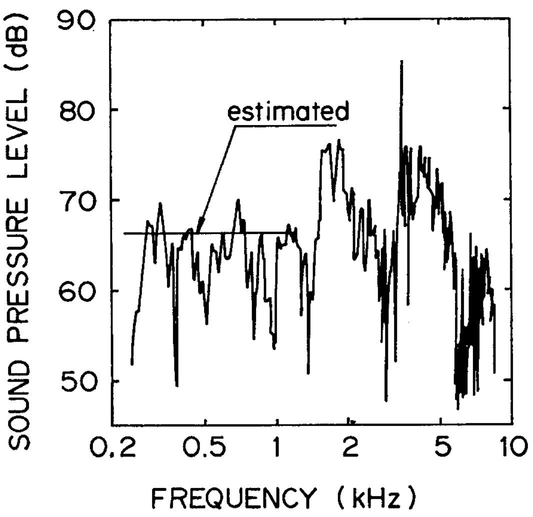

Fig. 10 Output sound pressure level for loudspeaker shown in Fig. 9. Apparent input power is 21.5 W at 1 kHz. Distance between diaphragm surface and microphone is 1 m.

apparent input power is 21.5 volt-ampares. Subsequently, the response of this loudspeaker is 53 dB (where 0 dB is 10 μPa (0.0002 μbar) output level from 1 volt-ampare input power). This is some 30 dB lower than that for a conventional cone-type electrodynamic loudspeaker.

5. ADDITIONAL DISCUSSION

The principal advantage of the flat loudspeaker described in this paper is its simple construction. However, it still has certain disadvantages.

(1) Frequency response irregularity

Its output sound pressure frequency characteristics are rugged. The irregularity is some 10~20 dB in peak-dip level difference. As has been described in Section 1, a cirtain amount of frequency response irregularity is allowable. Though there is some noticeable sound coloration due to the response irregularity of this loudspeaker, its performance is basically in the allowable region.

(2) Low efficiency

Its efficiency is still 30 dB below that for an electrodynamic loudspeaker.

If the dielectric constant for the piezoelectric material is designated as ϵ (shown in Table 1), apparent input electric power is given by

$$\left.\begin{aligned} P_e &= j\omega CE^2 \\ C &= \epsilon\pi a^2/h_1 \end{aligned}\right\}, \tag{26}$$

where C is the piezoelectric sheet capacitance. Using Eq. (22), the voltage response is given by

$$\begin{aligned} K_{ER} &\equiv |p_0|/E \\ &= \frac{1}{2}\frac{\rho_a}{r'}\frac{Y'd_{31}}{\rho(1-\sigma)\tan\delta}, \end{aligned} \tag{27}$$

which is independent from the diaphragm size. Power response is given by

$$\begin{aligned} K_{PR} &\equiv |p_0|/\sqrt{|P_e|} \\ &= K_{ER}/\sqrt{\omega C}. \end{aligned} \tag{28}$$

Therefore, improvement in the mechanical or piezoelectrical characteristics for the diaphragm material, such as increasing the Y/ρ or d_{31}, is valuable for improving both K_{ER} and K_{PR}. A decrease in C is also valuable for improving K_{PR}. The reason why the efficiency of the model shown in Figs. 2 and 3 is higher than that of the model shown in Figs. 9 and 10 seems to be that the piezoelectric sheet of the former is smaller, and therefore the C and equivalent ρ values are smaller. Thus, an analysis of the diaphragm on which a small piezoelectric sheet is partly mounted appears to be an interesting topic for future research.

To understand input-output characteristics of this loudspeaker, more precise analysis for a multi-resonant sound radiator is necessary. The next topics will be the effect of radiation loss in air and the directivity.

6. CONCLUSION

A conceptualization for a flat diaphragm loudspeaker utilizing piezoelectric polymer was given. The principal merit of the loudspeaker is its simple construction. When using it as a full-range loudspeaker, a bimorph diaphragm structure is suitable.

Output sound pressure for this loudspeaker in the multi-resonance frequency region was calculated and experimentally discussed. Its efficiency is proportional to the ratio of its Young's modulus and density, or piezoelectric constant, d_{31}. This is inversely proportional to the mechanical loss factor, $\tan\delta$, or electrical capacitance.

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APPENDIX

The model used for calculation in this work consists of a circular diaphragm, which is convenient for theoretical analysis as a multi-resonant vibrating system. A rectangular diaphragm is, however, more useful in practical terms than a circular one. To roughly compare output pressure level for the two shapes, the first term of the Green's function for both of them was calculated. The velocity potential is given by

$$\phi_0=\frac{1}{2\pi}\iint_S \frac{\Xi_0(x,y)\Xi_0(x',y')}{mS(\omega_0^2-\omega^2)}\frac{\exp(-jk'r')}{r'}dS\,, \tag{A1}$$

which is similar to Eq. (9), where Ξ_0 is a normalized characteristic function for the first mode.[15] For a circular diaphragm with radius a,

$$\Xi_0(r,\theta)=\left[\frac{J_0(\alpha_1 r/a)}{J_1(\alpha_1)}-\frac{I_0(\alpha_1 r/a)}{I_1(\alpha_1)}\right]\Big/ \left[2+\frac{J_1^2(\alpha_1)}{J_0^2(\alpha_1)}-\frac{I_1^2(\alpha_1)}{I_0^2(\alpha_1)}-\frac{4}{1-\sigma}\right]^{1/2}. \tag{A2}$$

The output sound pressure due to unit amplitude driving force at the center, and at the lowest resonant frequency, is then given by

$$p_{0c}=\frac{\exp[j(\omega t-k'r')]}{r'}\frac{\rho_a}{m}\frac{j0.2512}{\tan\delta}\,. \tag{A3}$$

For a rectangular diaphragm having sides l_a and l_b, Ξ_0 is

$$\Xi_0(x,y)=2\sin(\pi x/l_a)\sin(\pi y/l_b)\,. \tag{A4}$$

Therefore, similar output pressure due to unit driving force at the center is

$$p_{0r}=\frac{\exp[j(\omega t-k'r')]}{r'}\frac{\rho_a}{m}\frac{j0.2580}{\tan\delta}\,. \tag{A5}$$

The ratio of output levels is

$$p_{0c}/p_{0r}=0.974 \quad (-0.23\text{dB})\,. \tag{A6}$$

This difference appears to be negligible in actual practice.

It should be noted that this comparison is only for the fundamental modes of the circular and rectangular plates. However, it can be infered that there is no marked difference between p_{0c} and p_{0r} for their higher mode vibrations.

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