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Improvement of low frequency signal radiation performance for piezoelectric loudspeakers

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Piezoelectric loudspeaker is characterized by their very simple constructions, but their radiation performance at low frequency region is poor because their diaphragms are too stiff for large amplitude vibration. This paper proposes two innovative methods for improvement of low frequency radiation performance of piezoelectric direct-radiator loudspeakers. One is a flat-shape loudspeaker unit with a tuck-shaped flexible diaphragm by a sheet of PVDF piezoelectric film. The other is a paper cone loudspeaker unit with a large radiator driven by continuous revolution of piezoelectric ultrasonic motors. A loudspeaker system with satisfactorily wide frequency range for music can be constructed by combination of these two sorts of loudspeaker units.

1 Introduction

The lowest frequency of sound signal from a direct radiator loudspeaker is limited by the lowest resonant frequency (f_0). The vibration displacement of its diaphragm is inversely proportional to the square of signal frequency. Therefore, size of a loudspeaker diaphragm for radiation of low frequency signal shall be large and its amplitude shall also be large. This handicaps piezoelectric loudspeakers whose ordinary diaphragm is unavoidably small and stiff.

This paper proposes two sorts of new piezoelectric direct-radiator loudspeaker constructions suitable for low frequency sound radiation. One is a flat-shape loudspeaker unit with a tuck-shaped diaphragm by a sheet of PVDF piezoelectric film. The flexible PVDF polymer film is suitable to construct large diaphragm with low resonant frequency. The other is a paper cone loudspeaker unit driven by an ultrasonic motor(USM). The USM is characterized by very high driving mechanical impedance because its rotor contacts its stator tightly. This type of loudspeaker is, therefore, expected to operate with large amplitude in low frequency region.

2 Loudspeaker in low frequency region

The simplest form for output sound pressure of an omnidirectional direct radiator loudspeaker is given by the following formula:

$$P = j\omega\rho \frac{VS}{4\pi l} e^{-jkl} \tag{1}$$

where, ω is signal angular frequency, ρ is density of air, S and V are effective area and vibrating velocity of the diaphragm, l is distance between radiator and measuring point and k is wave constant, ratio of ω and sound velocity. We notice VS is volume velocity of the source. This formula shows that the acceleration of diaphragm $j\omega V$ should be constant against frequency for a flat frequency response. The diaphragm velocity is given by the following formula:

$$V = \frac{F}{z} = \frac{F}{j\omega m + r + \dfrac{s}{j\omega}} \tag{2}$$

where, F is driving force. *z, m, r* and s are mechanical impedance, effective mass, mechanical resistance and stiffness of the diaphragm. We see that only the region where:

$$V \approx \frac{F}{j\omega m} \tag{3}$$

meets the constant acceleration condition . This region is called as *mass controlled*. Its lower limit is given by resonant frequency of the diaphragm. Therefore, ordinary direct radiator loudspeakers cannot radiate the signal whose frequency is lower than the diaphragm resonant frequency effectively. This means the diaphragm resonant frequency shall be as low as possible to radiate satisfactorily low frequency signal.

It results that larger diaphragm mass or smaller support.stiffness is necessary. But, a heavy radiator is difficult to be supported by a soft stiffness. Moreover, a loudspeaker for low frequency region requires a large volume displacement, because it must be inversely proportional the frequency.

3 Piezoelectric rectangular loudspeaker using a tuck shape PVDF bimorph

3.1 Construction

Shape of the first new loudspeaker idea is illustrated in **Fig. 1**. A folded zigzag-tack shaped bimorph sheet of PVDF (polyvinylidenfluoride) film is applied to a flat rectangular loudspeaker diaphragm whose size is, for example, 260 mm X 144mm with various depths.

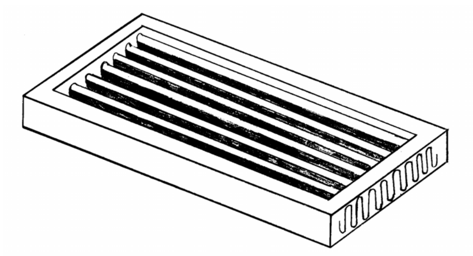


Fig. 1: Shape of loudspeaker with a tuck-shape diaphragm

Electrical impedances of four samples with different tuck depths, 10 mm, 16 mm, 20 mm, and 24.5 mm, are 3.2 kiloohm, 2.1 kiloohm, 1.6 kiloohm and 1.8 kiloohm, respectively, at 1000 Hz.

Cross-sectional construction of the diaphragm is shown in **Fig. 2**.

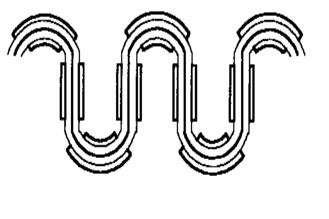


Fig.2: Cross-sectional construction of diaphragm

The surface electrodes are shaped so as to deform the diaphragm for breath of air as shown in **Fig. 3.**

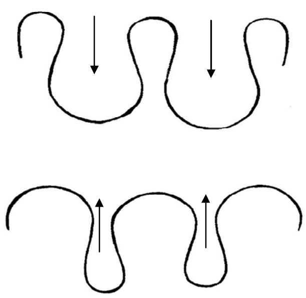


Fig. 3: Diaphragm breathes air by deformation

3.2 Resonant frequency and sensitivity

Acoustical angular resonant frequency ω_0 is given by stiffness of the diaphragm s and total mass m of the diaphragm and air load as、

$$\omega_0 = \sqrt{\frac{s}{m}} \tag{4}$$

Acoustical stiffness s can be estimated by examining the microphone operation as:

$$s = \frac{P}{Q} \tag{5}$$

because this loudspeaker is reversible. Q, volume displacement of the diaphragm by input sound pressure, is calculated by size and Young's modulus of the diaphragm material. As explained in **Fig. 4**.

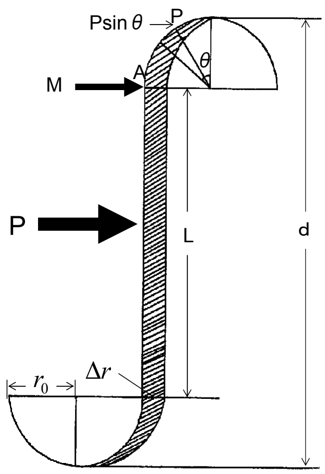


Fig. 4: Diaphragm displacement at microphone operation

The calculated resonant frequency is compared in **Fig. 5** as a function of tuck depth. As is seen in this result, calculation is effective for prediction of the resonant frequency. We see that this type of piezoelectric loudspeaker shows very low resonant frequency, even less than 100 Hz., and that deeper tuck size results lower resonance.

Next, we examine the output sound pressure level as a function of the tuck depth. We put width and thickness of the diaphragm as b and h, and radius of the curved tuck part as r_0, respectively. Radius increment of the diaphragm Δr by piezoelectric effect is given by the following equation.

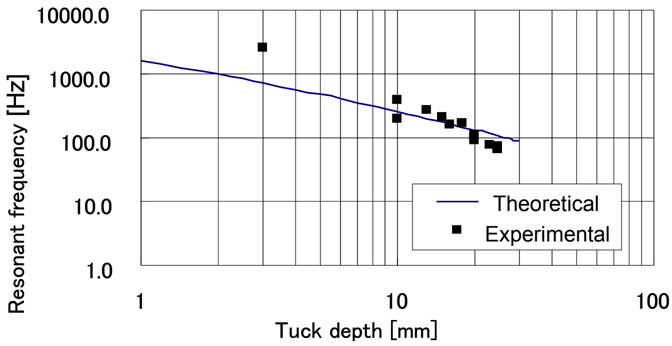


Fig. 5: Calculated and measured resonant frequency

$$\frac{1}{r_0 + \Delta r} - \frac{1}{r_0} = \frac{12 M_V}{E b h^3} \tag{6}$$

Where E is Young's modulus and, M_V is bending moment due to the piezoelectric force, which is given as

$$M_V = \frac{E h d_{31} V e^{j\omega t}}{2} \tag{7}$$

Where d_{31} are piezoelectric coefficient and V the input voltage. We calculate static volume displacement ($\omega = 0$) and estimate the output sound pressure at the mass controlled frequency region.

The output sound pressure of the ordinary loudspeakers at distance r is given by the following formula:

$$P = j\omega\rho \frac{j\omega Q}{4\pi r} e^{j(\omega t - kr)} \tag{8}$$

Where ρ is density of air and Q is the volume displacement. Output sound pressure can be estimated by the static volume displacement and the resonant frequency as explained by **Fig. 6**.

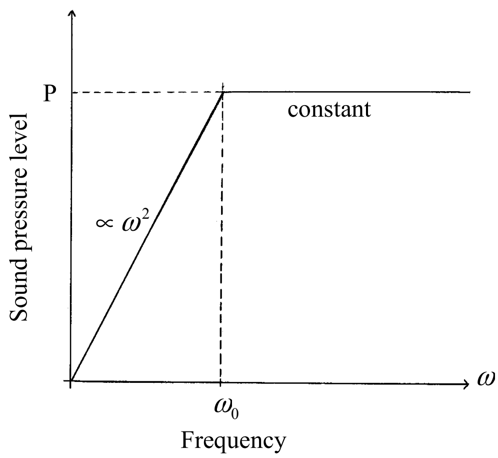


Fig. 6. Explanation of output level

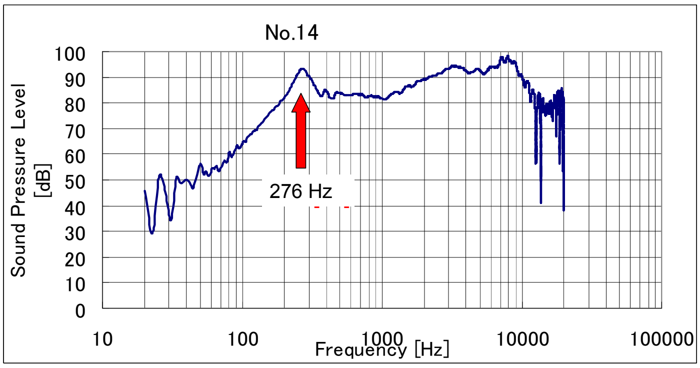
The diaphragm of our loudspeaker is assumed to be a single resonance system. We divide the frequency region into two parts. One is lower than the resonance frequency and another higher than it. In the lower region (stiffness controlled region), the output sound pressure is proportional to the square of frequency, because the diaphragm volume displacement is constant. In the upper region (mass controlled region), the output sound pressure is constant because the diaphragm volume acceleration is constant. Therefore, we can estimate the sound pressure difference in the upper region, i.e. the working frequency region of the loudspeaker by using static displacement. **Table 1** compares relative output levels for 3 samples with rather regular frequency responses. The estimations fit to the experimental results. We see deeper tuck size , i. e., lower resonant frequency, brings less sensitivity.

Table 1. Output sound pressure and tuck depth

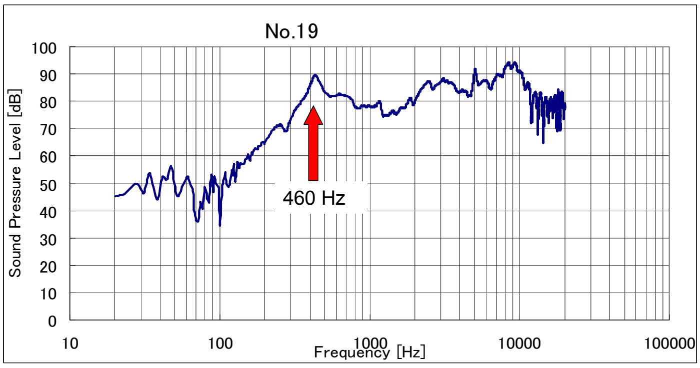
Depth	Sensitivity	
	Measured	Estimated (relative)
16mm (reference)	0dB	0dB
20mm	-6dB	-8.3dB
24.5mm	-11dB	-13.6dB

3.3 Performance of experimental models

Fig. 7 shows the frequency response of two experimental unit models with moderate resonant frequencies and rather flat responses by using flat baffle of 1200 X 840 X 20 mm.



(a) diaphragm: 137 X 150 mm, tuck depth: 12-14 mm



(b) diaphragm: 100 X 91 mm, tuck depth: 10 mm

Fig. 7: Frequency response of experimental models

A loudspeaker system using both units were constructed. **Fig. 8** shows its frequency response. This is practical in the frequency region of more than 300 Hz and the low frequency response can be boosted by using an electro-dynamic subwoofer.

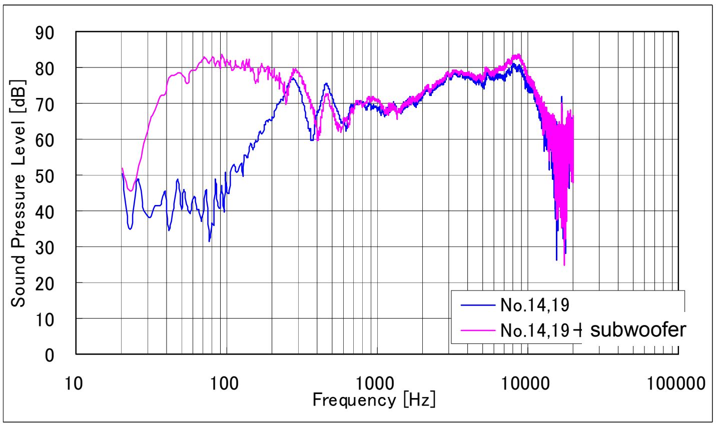


Fig. 8: frequency response of two-unit system

3.4 Conclusion

A flat piezoelectric loudspeaker using a tuck shape PVDF bimorph was proposed. Its resonant frequency and sensitivity were examined theoretically. The results suggest the wide frequency range and moderate directivity characteristics of this loudspeaker, which is practically useful.

4 Direct radiator loudspeaker by continuous revolution of ultrasonic motors

4.1 Ultrasonic motor

The second new loudspeaker idea uses continuous revolution of an ultrasonic motor (USM) as a driver. The USM is characterized by very high driving mechanical impedance because its rotor contacts its stator tightly. Therefore, this type of loudspeaker is expected to operate with large amplitude in low frequency region even by a heavy radiator.

Fig. 9 shows a cut model of USM and **Fig. 10** illustrates principle of USM. The USM is consisted by a circular metal ring rotor and a nicked metal ring stator. The stator is laminated by a thin piezoelectric ceramic ring. The feature of USM is that its rotor and stator is contacted each other. The rotor is driven by a frictional force. Therefore, USM shows larger driving force than the conventional electromagnetic motors.

Fig. 9: Structure of ultrasonic motor

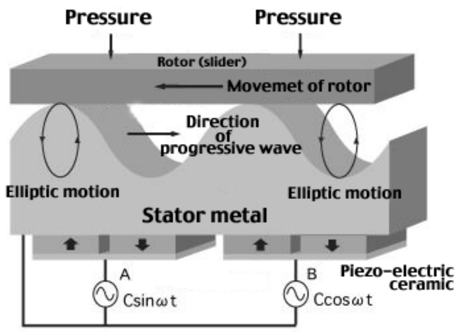


Fig. 10: Principle of ultrasonic motor operation

Rotational speed of the USM is controls by the frequency applied to a piezoelectric body of the stator. **Fig. 11** shows a relationship between measured input voltage and driving frequency.

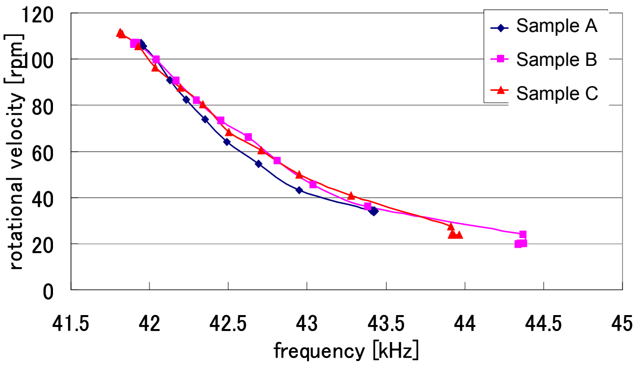


Fig. 11: Relationship of revolution velocity and input signal frequency

4.2 Construction and principle

Fig. 12 shows construction of the first model. Its shape is an ordinary direct radiator loudspeaker with a cone diaphragm, 25 cm in diameter, associated with a boxy enclosure of 100 litre. The driver including an USM is built in the enclosure. A coupling bar connects center shaft of the USM to the cone radiator via an flexible part to mitigate difference between circular and linear motions. A steel ring (inertia ring) of a few kilograms in weight is installed to outside of the stator of the motor. The stator with the inertia ring rotates continuously by electrical input applied via slip ring contacts. The rotor does not move because it is connected to the cone.

Revolution velocity of the motor is modulated by the input audio signal. The revolution velocity of the inertia ring is still kept constant, because its inertia is satisfactorily large. Therefore, driving force is applied to the rotor then sound is radiated by vibration of the cone diaphragm.

Output sound pressure can be calculated theoretically. The dynamic equation of rotatory motion is given as follows:

$$M = I\frac{d\Omega}{dt} \tag{9}$$

Where M is moment induced, Ω is angular velocity and I is moment of inertia of the stator with the ring.

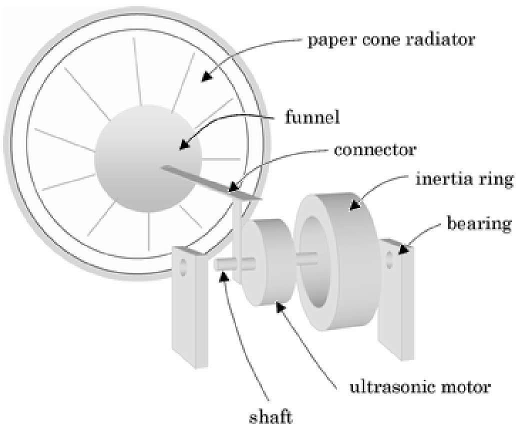


Fig. 12: First experimental model

If the radius of corn is a, I is given as follows:

$$I = m\frac{a^2}{2} \tag{10}$$

Driving force is given as follows, where b is radial length of connecting arm

$$F = \frac{M}{b} \tag{11}$$

And resonant frequency of this system is given by:

$$\omega_0 = \sqrt{\frac{sb^2}{I}} \tag{12}$$

Where s is stiffness of diaphragm support.

Assuming a as 25 cm, corn mass as 30 g, M as 5 kg, b as 5 cm and original resonant frequency of the cone radiator as 50 Hz, ω_0 is estimated to be 10 Hz. It means limiting frequency of this loudspeaker can be lower than it of conventional electrodynamic loudspeakers. And then assuming variation of revolution velocity as 20 rpm, output sound pressure is estimated to be 107 dB if mechanical efficiency is 100 %.

4.3 Improvements

Fig. 13 shows the structure of the improved model loudspeaker. Functions of the stator and the rotor were inversed to remove a slip-ring contactor. Two inertia rings were installed to the rotor via the shaft, and the corn radiator was connected to the stator..

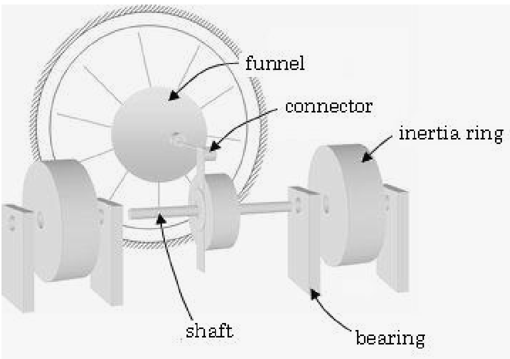


Fig. 13: Improved experimental model

The connecting mechanism between the motor and the cone radiator was also completed as shown in Fig. 14. Use of silicon rubber cushions decreases noise due to motor movement by more than 8 decibels.

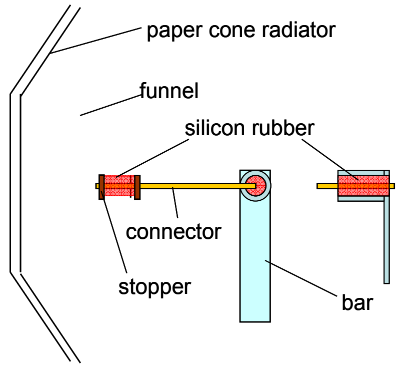


Fig. 14: Connecting mechanism of motor and radiator

The newest single-motor model has a large cone of 46 cm in diameter in an enclosure of 400 litre.

4.4 Dual-motor model

After experiments by a few single-motor models, authors invented a model using co-axial two ultrasonic motors shown in **Fig. 15**. Stator of one motor is fixed to the base and it of the other is connected to the cone radiator. Velocity modulation for any one motor, or for both motors in opposite phase, induces driving force. This construction increases effective mass of the inertia ring used in single motor models to be infinitive. This model will be suitable to decrease total mass of the USM driven loudspeakers.

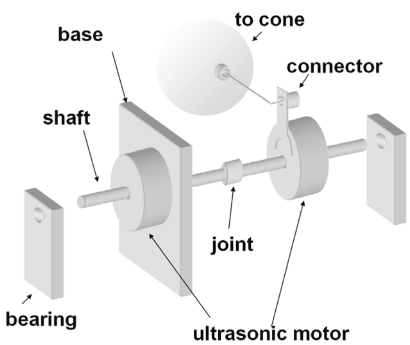


Fig. 15: Dual-motor model

The experimental model was given the same cone radiator and enclosure to the newest single-motor model for comparison.

4.5 Performance

Fig. 16 compares frequency responses of three single-motor models and a dual-motor model. The newer model radiates richer low frequency sound. Output sound pressure by the newest single-motor model and it by the dual-motor model, using the same cone radiator and enclosure, are similar, however, the dual-motor model shows smoother response.
Fig. 17 compares frequency responses of the dual-motor model and an ordinary electrodynamic loudspeaker using the same cone diaphragm and enclosure. The USM driven model radiates higher low frequency sound. This result shows even piezoelectric loudspeaker can radiate richer low frequency sound than conventional loudspeakers.

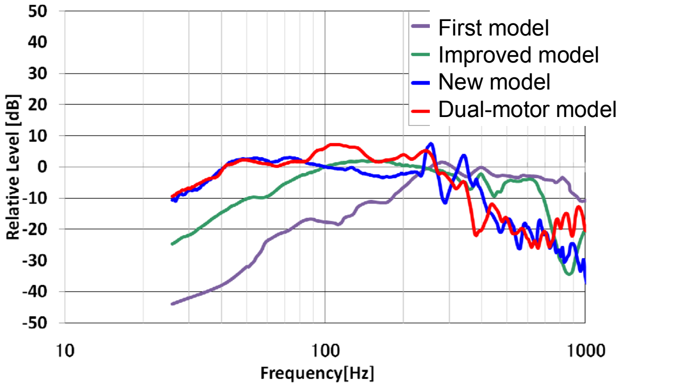


Fig. 16: Frequency response of experimental models

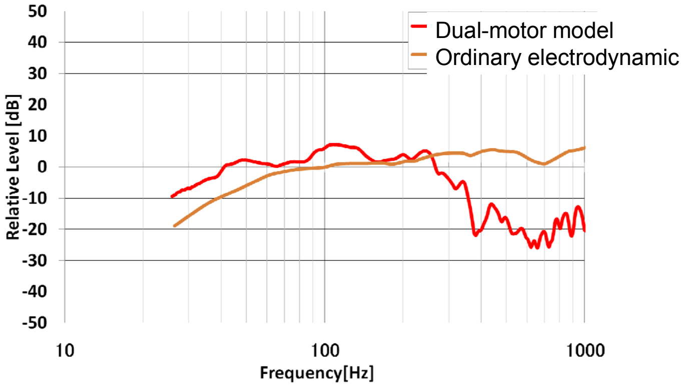


Fig. 17: Comparison of frequency response

4.6 Conclusion

The loudspeaker using continuous revolution of an ultrasonic motor (USM) is proposed. This is suitable to radiate sound of very low frequency. Because of high driving mechanical impedance of USM. The experimental models show satisfactorily large output sound pressure.!

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