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The Development of Ultra Thin Speakers for Mobile Phones

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ABSTRACT

In this paper we describe the design of novel, ultra-thin piezoelectric speakers for mobile phones. Due to the expansion of the slim mobile phone market, ultra-thin speakers providing high-quality sound are in strong demand. Piezoelectric speakers are much thinner than the electrodynamic speakers generally used in mobile phones. However, to achieve high-quality sound, the rigid structure and low internal friction of piezoelectric speakers must be improved. In this study, we have successfully developed highly reliable 0.9-mm-thick piezoelectric speakers that consist of a piezoelectric bimorph transducer and an elastic support structure and that provide high-quality sound. We have also successfully used these ultra thin speakers in a slim mobile phone.

INTRODUCTION

The demand for slim mobile phones is currently increasing, as shown in Figure 1. The thickness of mobile phones has been decreasing steadily over the past several years without affecting the performance. This has led to a rise in demand for ultra-thin speakers that provide high-quality sound.

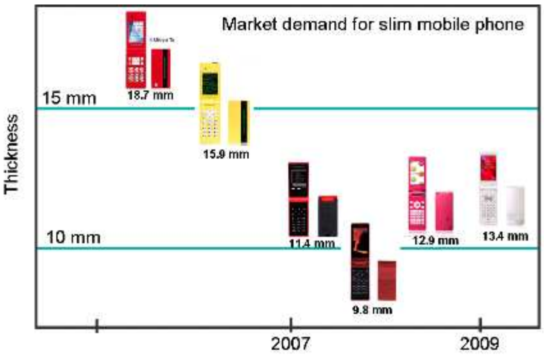


Figure 1 Increase in demand for slim 3G mobile phones

Piezoelectric speakers are much thinner than the electrodynamic speakers generally used in mobile phones [1-7].

However, the rigid structure and low internal friction of piezoelectric speakers must be improved in order to achieve the high sound quality required for mobile phones.

Electrodynamic speakers are the speakers generally used in mobile phones. Electrodynamic speakers consist of a magnet circuit and a vibratory diaphragm, and have the advantage of a low quality factor (*Qm*) and a low resonant frequency. Electrodynamic speakers can therefore achieve a high sound pressure level in a low frequency range and a smooth sound pressure level frequency response. On the other hand, electrodynamic speakers tend to be thicker (2.0 mm or more) because they contain a magnetic circuit. A high magnetic flux density is therefore required to achieve a suitable sound pressure level. It is therefore difficult to reduce the magnetic thickness because the magnetic flux density depends on the magnetic volume.

Piezoelectric speakers have the advantage of thinness (1.0 mm or less). Piezoelectric speakers consist of piezoceramics and shim (metal materials), and the self-bending vibration of the piezoceramics is what is used for the driving force of the speaker. However, because piezoelectric speakers have a high quality factor (*Qm*) and a high resonant frequency, the sound pressure level in the low frequency bandwidth and the non-smooth sound pressure level frequency response (piezoelectric speakers have a steep sound pressure peak in the resonance frequency area) must be improved to achieve the high sound quality required for mobile phones [8-19]. Moreover, because piezoceramics are brittle, their drop impact resistance has to be improved before they can be used in a mobile phone.

Table 1 Features of piezoelectric speakers compared with electrodynamic speakers

acoustic property	fundamental resonant frequency	600～800 Hz	>1kHz
	quality factor Q_m	2～8	> 50
	sound pressure level in low frequencies	high	low
feature	thickness	> 2 mm	< 1 mm
	issues	thickness reducing	sound quality drop impact resistance

Piezoelectric speakers generally consist of multi-layer ceramics. Multi-layer ceramics can be driven on a lower voltage than single-layer ceramics because they have a stronger field strength. On the other hand, multi-layer ceramics are difficult and expensive to manufacture, meaning that issues such as reliability and cost must be resolved before multi-layer ceramics can be used in mobile phones.

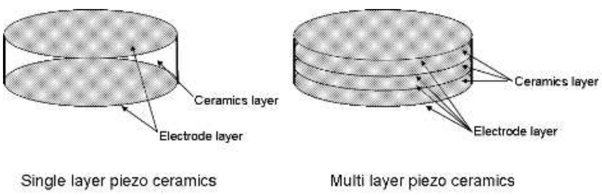


Figure 2 Structure of single-layer and multi-layer ceramics

Therefore, in order to use piezoelectric speakers as ultra-thin speakers in mobile phones, we need to improve the sound quality by developing highly efficient and reliable ceramic transducers with a low quality factor (*Qm*) and low resonant frequency.

We have achieved this by using a high-power piezoelectric bimorph transducer that consists of a single layer to develop 0.9-mm-thick piezoelectric speakers with high-quality sound.

We will subsequently describe how we developed these speakers.

EXPERIMENT

Preparations

Our ultra-thin piezoelectric speakers consist of single-layer piezoceramics and shim materials and an elastic polymer and frame. Lead-zirconate-titanate (PZT) ceramics with a thickness of 40 μm were used as the piezoceramics [20-21]. Both principal surfaces of the ceramics were covered by a silver electrode.

Phosphorate with a thickness of 0.5 μm was used as the shim material, and both principal surfaces of the phosphorate plate were covered by the piezoceramics. This was then used to construct a bimorph transducer.

An elastic polymer film was placed between the 0.9-mm-thick frame and shim, and the bimorph transducer was then attached to the frame. A 30-μm-thick polymer film was used as the elastic supporting material. All of the materials were connected by an adhesive and arranged in a concentric circle to create an ultra-thin speaker with a thickness of 0.9 mm.

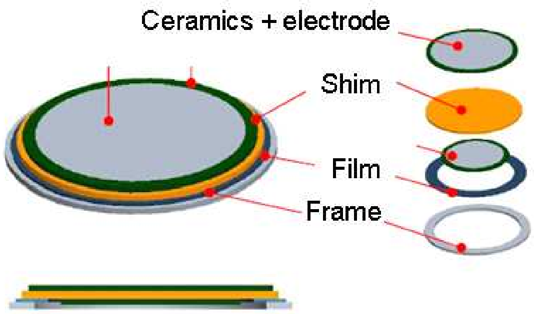


Figure 3 Structure of ultra thin speaker

Measurements

・**Electrical properties**

The electric properties of the speaker, such as the resonant frequency and electrostatic capacity (Cp), were measured by using a Hewlett-Packard impedance analyzer (4194A).

The values of Q_m and the equivalent circuit constants for the transducers were measured at a low vibration level by measuring the impedance-frequency responses by using a Hewlett-Packard impedance analyzer (4194A). The Q_m of the transducers was defined by equation (1) below [22].

$$Qm = \frac{Fs}{f_2 - f_1} \qquad (1)$$

Where fs represents the resonant frequency and f_1 and f_2 represent the quadrantal frequencies.

- **Acoustic properties**

The acoustic properties of the speakers were measured by using an audio analyzer. The distance between the sound hole centre in the mobile phone and the microphone was 10 cm. A driving voltage of 5 Vrms was input to the speakers. The frequency bandwidth was 100 Hz to 20 kHz. The acoustic properties were measured in an anechoic room.

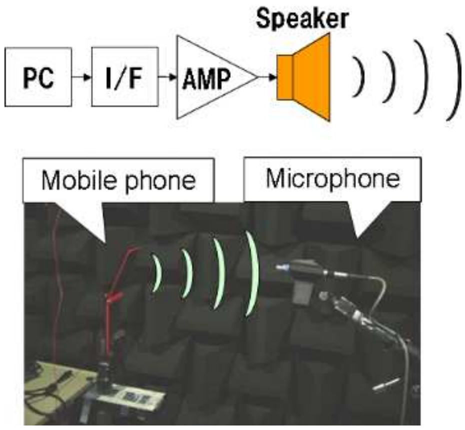


Figure 4 Method used to measure the acoustic properties of the speakers

RESULTS AND DISCUSSION

Bimorph transducer

In this study, we investigated using a 40-µm-thick bimorph transducer that was made using single-layer ceramics.

In most piezoelectric speakers, multi-layer piezoceramics are used. Multi-layer piezoelectric ceramics have an electric field strength that is higher than single-layer ceramics, and can therefore be driven on a lower voltage. On the other hand, because multi-layer ceramics are formed by laminating multiple thin ceramics layers, the manufacturing process is complex and expensive, and there are problems with electrode wiring and reliability.

Multi-layer ceramics also have an electrostatic capacity that is higher than that of single-layer ceramics. The power consumption of multi-layer piezoelectric ceramics therefore tends to be higher than that of single-layer ceramics, even though the driving voltage is low.

Cost is also an important consideration when developing an acoustic device for mobile phones. Moreover, because mobile phones are portable devices, high speaker quality is a must.

Table 2 Features of single-layer piezoelectric ceramics compared with multi-layer ceramics

	Single Layer	Multi Layer
Electro field strength	Low	High (Better)
Electrostatic capacity	Low (better)	High
Power consumption	Nearly equal or less	Nearly equal or more
Productivity	Low (better)	High
Cost	Low (better)	High

Considering these issues, we decided to investigate using single-layer piezoelectric ceramics, and evaluated the correlation between the acoustic properties and the ceramic structure (such as the layer type and thickness). Table 3 shows the results of our evaluation.

Table 3 Correlation between acoustic properties and ceramic structure (single layer or multi-layer)

Piezo ceramics type			Acoustic Properties	
Type	Thickness	Number of layers	Fs (Hz)	SPL at Fs (dB)
Multi-layer	100 μm	3	1750	95
Single-layer	40 μm	1	1100	93
Single-layer	50 μm	1	1250	90
Single-layer	75 μm	1	1450	89
Single-layer	100 μm	1	1600	88

Fs: Fundamental resonant frequency
SPL: Sound Pressure level (5Vrms input)

By reducing the ceramic thickness in the single-layer type, the fundamental resonant frequency (Fs) decreased and the sound pressure level at Fs increased. We considered that this was the effect of a decrease in the rigidity and an increase in the electro field strength.

It is also important to note that we could obtain a sound pressure level equal to the level of a multi-layer ceramic with a 40-µm-thick single-layer ceramic. This indicates that the same acoustic properties as those of a multi-layer ceramic could be achieved by reducing the ceramic thickness in the single layer. We therefore proved that we could develop a low-cost transducer.

However, taking into account issues such as warping and cracking, it has commonly been held that the thinnest single-layer ceramic that could be mass-produced was 70 µm.

It was therefore necessary to optimize the ceramic manufacturing process and verify that thin single-layer ceramics could be mass produced. In this study, we successfully manufactured a single-layer ceramic with a thickness of 40 μm, and used it to create a transducer.

We then looked at how we could improve the vibration displacement of the bimorph structure. The bimorph structure is shown in Figure 5.

A bimorph structure is a structure in which two piezoelectric ceramics are stuck together with opposite polarization. The piezoelectric elements on one side extend radially while the elements on the other side contract. This makes it possible to obtain high displacement and power—twice the driving performance of a unimorph structure.

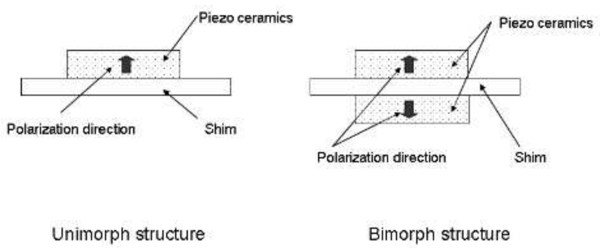


Figure 5 Bimorph and unimorph structures

The results of comparing the acoustic properties of unimorph and bimorph ceramic structures with a thickness of 40 μm are shown in Table 4.

Table 4 Acoustic properties of bimorph type and unimorph type transducers

Transducer Type		Acoustic Properties	
Type	Thickness	Fs (Hz)	SPL at Fs (dB)
Unimorph	40 μm	1100	93.2
Bimorph	40 μm	1180	98.9

The sound pressure level was about 6 dB higher in the unimorph type transducer, whereas the fundamental resonant frequency was about 100 Hz higher in the bimorph type transducer, proving the effect of the bimorph structure. We consider that the increase in this resonance frequency is due to an increased stiffness caused by the arrangement of the two piezoelectric elements in the bimorph structure.

Finally, we used the high-power 40-μm-thick single-layer bimorph transducer that we had developed as the driving source of an ultra thin speaker.

Elastic supporting structure

In this study we used an elastic structure in which a polymer film is inserted between the shim material and the frame. As a result, we were able to enhance the vibration displacement, decrease the mechanical quality factor (*Qm*), and improve durability against drop impact. These results are described in detail below.

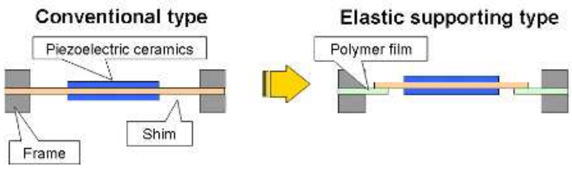


Figure 6 Elastic supporting structure

1. Enhancement of vibration displacement

The vibration displacement was increased by inserting a polymer film with a low rigidity between the frame and the shim materials, increasing the sound pressure level. In the conventional structure, the shim is connected directly to the frame, creating fixed ends in which the shim is strongly restrained.

On the other hand, with an elastic supporting structure, flexible free-edge-like ends are created because the shim material is supported by a polymer film. As a result, the range of the vibration expands, decreasing the resonance frequency.

In the elastic supporting structure, the driving force from the piezoelectric ceramic spreads to the polymer film through the shim material, achieving an impedance that matches the mechanical stiffness.

The equivalent stress concentrates on the polymer film with a low rigidity and the vibration at the speaker edge expands, strongly increasing the vibration displacement.

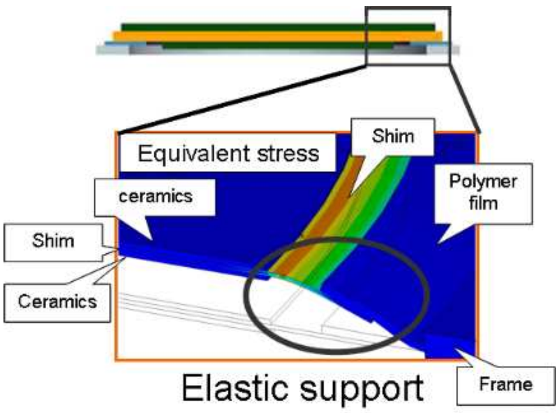
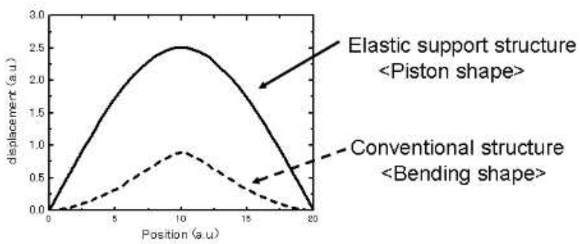


Figure 7 Mechanism of elastic support

Moreover, in the elastic supporting structure, the vibration shape becomes piston-like, whereas a bending vibration shape is formed in the conventional structure. Therefore, the sound pressure level increases in the elastic supporting structure because the volume exclusion of a piston shape is higher than that of a bending shape.

Figure 8 Vibration shape of elastic supporting structure compared with conventional structure



2. Quality factor *Qm*

The mechanical quality factor (*Qm*) can be decreased by inserting a polymer film between the shim material and the frame. This is due to mechanical dumping caused by the high internal friction that is a characteristic of the polymer material.

Table 5 shows the comparison of the mechanical quality factor *Qm* and the fundamental resonant frequency between elastic supporting structure and conventional structure. In the elastic supporting structure with the polymer film, *Qm* decreases strongly. And, *Qm* is overall attenuate by the insert of the polymer material though various materials were examined. Then, in a part of material, *Qm* decreased 50% or more, and the effect of the mechanical dumping with the polymer material was clarified.

Table 5 Quality factor (*Qm*) of elastic supporting structure compared with conventional structure

Elastic Supporting Structure		Mechanical Properties	
Type	thickness	Q_m	Fs (Hz)
Polymer A	30 μm	9.8	1080
Polymer A	50 μm	10.4	1280
Polymer B	30 μm	12.5	1190
Polymer C	30 μm	14.9	1250
None	–	38.7	1650

Figure 9 shows a comparison of the acoustic properties of speakers that use elastic support, and those that do not. In the speakers that use an elastic supporting structure, the sound pressure level peak near the fundamental resonance frequency is attenuated by a decrease of *Qm*, achieving a smoother sound pressure level frequency response.

Moreover, as the rigidity of the polymer film decreases, the fundamental resonant frequency also decreases, and the sound pressure level in a low frequency bandwidth such as 300-1000 Hz increases.

In conventional piezoelectric speakers, the fundamental resonant frequency was high because the speakers used materials with a high rigidity, such as ceramics and metals. It was therefore necessary to improve the sound pressure level in the low frequency bandwidth to realize high-quality sound. Techniques such as decreasing the ceramic thickness and expanding the ceramic externals have been applied to decrease the fundamental resonant frequency in a conventional piezoelectric speaker. However, these steps led to a decrease in the reliability of the speaker, as well as an increase in cost and speaker size, making it difficult to installing the speakers in electric equipment such as mobile phones.

In an elastic supporting structure, the fundamental resonant frequency can be easily decreased without changing the ceramic shape, achieving a high sound quality.

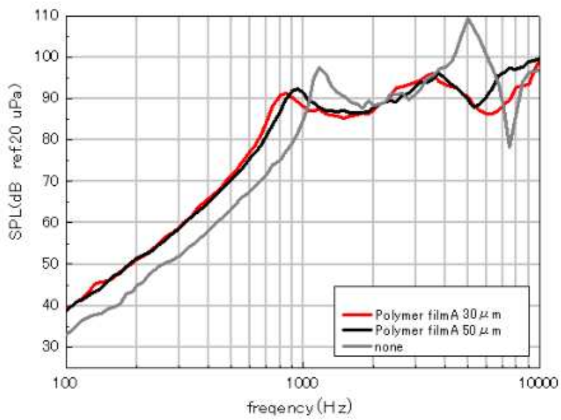


Figure 9 Acoustic properties of speakers

An elastic supporting structure also improves durability against drop impact. Drop tolerance was assumed to be a problem because the ceramics that were used in conventional piezoelectric speakers were brittle, making it difficult to use these speakers in portable electronic equipment such as mobile phones. However, the flexible polymer material used in the elastic supporting structure greatly improves the drop tolerance, helping to absorb impact upon falling

From these results, we proved that using an elastic supporting structure improved the acoustic properties and the reliability of the speakers.

Optimization method

In designing the speaker structure, we optimized the characteristics by developing an original calculation method. The calculation method we developed uses the finite element method (FEM). We established a highly accurate method to estimate speaker characteristics that combines experimental analysis and calculation analysis. Using this method, we were able to reduce the discrepancy between the measured value and the estimated value to just 10%.

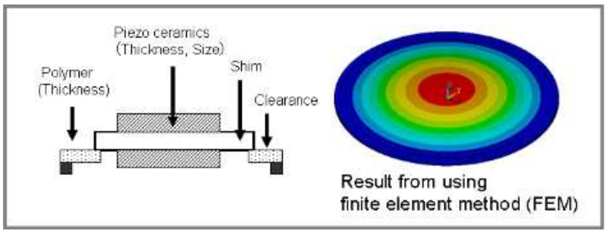


Figure 10 Analysis model of FEM

Table 6 Analysis of fundamental resonant frequency

	Experiment	Calculation
Mod1	1263 (Hz)	1327 (Hz)
Mod2	6263 (Hz)	6575 (Hz)
Mod2	14538 (Hz)	15127 (Hz)

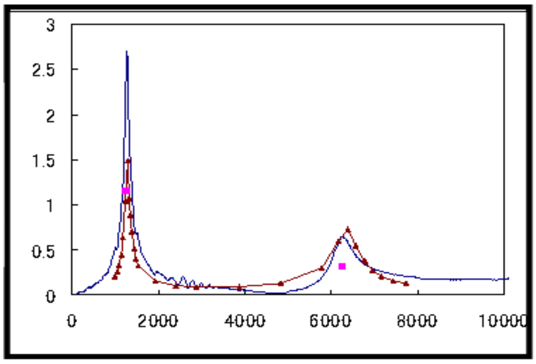


Figure 11 Analysis of vibration velocity

We carried out sensitivity analysis of our experimental design by using this optimization method. We developed this optimization method by using following process, based on which we designed the structure of the speaker.

1. Design of experimental orthogonal array measurement and simulation

2. Approximate equation

$$y = a_1x_1 + b_1x_2 + a_2x_1^2 + b_2x_2^2 + c_1x_1x_2 + \cdots$$

$a_i, b_i, c_i \cdots$: coefficients / x_i: design parameter

3. Optimum value search under constraints

To obtain the indicator of the structural design of the speaker, we carried out a correlational analysis of each design factor and the acoustic properties. We examined the correlation between the ceramic shape, elastic material shape, film shape, basic resonance frequency, and sound pressure level. The results of clarifying the design manual to obtain the desired acoustic properties are shown in Figure 12.

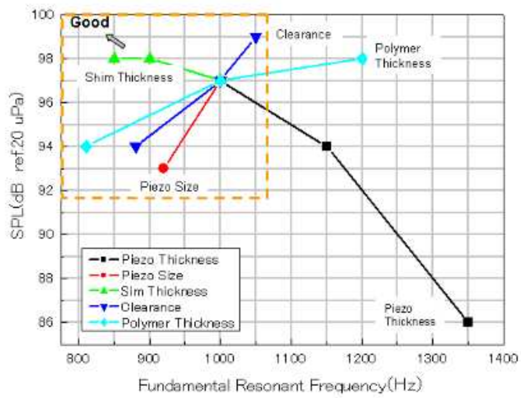


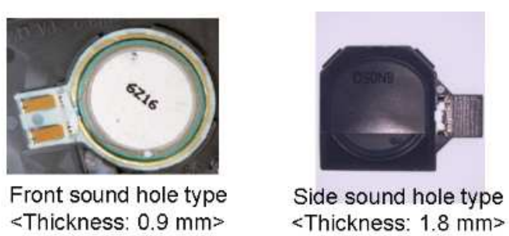
Figure 12 Correlation between structural factors

The feature of the piezoelectric speaker in the elastic supporting structure is that the fundamental resonant frequency is greatly affected by the film shape. In conventional piezoelectric speakers, it was necessary to change the shape of the piezoelectric ceramics and the shape of the shim material to control the fundamental resonance frequency, causing problematic design restrictions. However, in an elastic supporting structure, the characteristic can be controlled simply by changing the film thickness, creating a greater degree of design freedom.

Application in mobile phones

We prepared ultra thin piezoelectric speakers consisting of a bimorph transducer and an elastic support structure as prototypes. We made two kinds of speakers, one with a front sound hole and one with a side sound hole, and installed them in a mobile phone. The speakers are shown in Figure 13.

Figure 13 Prototype speakers



In the side sound hole type, the cover was placed on the speaker vibration side. With this configuration, the sound reverberates off the cover and radiates out from the side of the speaker. The thickness of the front sound hole was 0.9 mm and the thickness of the side sound hole type was 1.8 mm. Both of these speakers were thinner than an average electrodynamic speaker, which is about 3 mm thick .

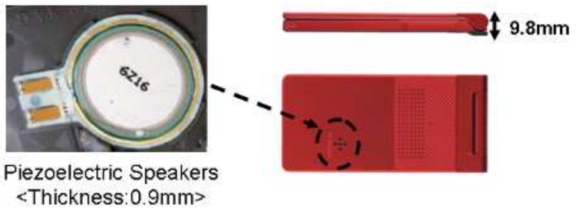


Figure 14 Mobile phone with front sound hole type spe aker

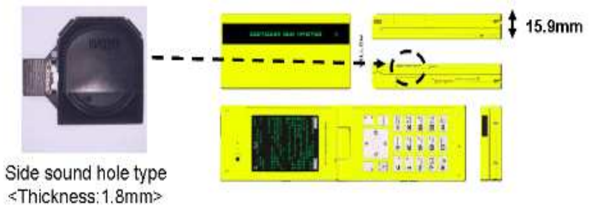


Figure 15 Mobile phone with side sound hole type speaker

The acoustic properties of the mobile phone with the front and side sound hole type speakers are shown in Figure 16.

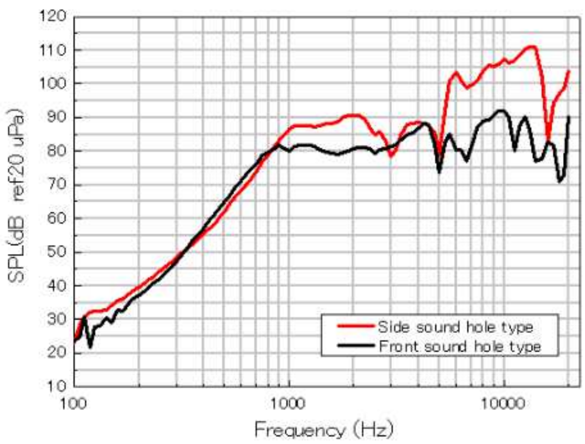


Figure 16 Acoustic properties of mobile phones with ultra-thin speakers

A sound pressure level of 90 dB or more could be achieved by both sound hole types at 1 kHz or more. Moreover, sound pressure level is about 65 dB in a low frequency bandwidth (500 Hz for example). We determined that this performance was sufficient for use in mobile phones.

The results of evaluating the reliability of the speakers for use as a acoustic devices in a mobile phone are shown in Table 7. These results show that the speakers we developed have sufficient structural quality for practical use in mobile phones.

Table 7 Reliability of ultra-thin speakers

Reliability	Result
Driving test (70℃ 1000 hr)	○ (Good)
Driving test (25℃ 1000 hr)	○ (Good)
Storage test	○ (Good)
Durability against drop impact	○ (Good)

○ : ±3dB (after test)

In this study, we were therefore able to develop an ultra-thin speaker that had both high sound quality and high reliability. We were also able to successfully use this speaker in an ultra-slim mobile phone.

SUMMARY

We developed an ultra-thin piezoelectric speaker that consisted of an elastic support structure and a bimorph transducer made of 40-µm-thick ceramic. The speaker was 0.9 mm thick, which is much thinner than the electrodynamic speakers used in conventional mobile phones .

We also developed a bimorph transducer made using a 40-µm-thick single-layer ceramic. This transducer was highly effective, and highly reliable, and enabled us to develop a speaker with a high sound pressure level.

We also developed an elastic supporting structure in which a polymer film was inserted between the shim material and the frame. This structure had the following effects and enabled us to create a highly reliable speaker with high sound quality.

- The equivalent stress was concentrated by decreasing the rigidity at the edge, enhancing the vibration and increasing the sound pressure level.
- Insertion of the polymer film decreased the rigidity, decreasing the fundamental resonant frequency. This served to improve the sound pressure level in the low frequency bandwidth.
- The polymer film improved the drop tolerance by absorbing impact upon falling, thereby improving the reliability.
- It was possible to control the resonant frequency by changing the film material and shape, improving the degree of design freedom.

CONCLUSION

We successfully developed an ultra-thin piezoelectric speaker with high quality sound and high reliability by developing a high-power bimorph transducer and an elastic supporting structure. High sound quality was exhibited when this speaker was installed in a mobile phone. We developed two types of speakers, one with a front sound hole and one with a side sound hole, and successfully used these speakers to produce and market an ultra-slim mobile phone.

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