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The Acoustical Design of Slim size Piezoelectric Speakers for Mobile Phones

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Abstract

Recently, market demand for slim mobile phones has been increasing. Speakers are an important device in mobile phones because they create an interface with the phone user. However, due to the thickness of conventional electrodynamic speakers, designers have been restricted in how they design the mobile phone case. Piezoelectric speakers could solve this problem, because they are no more than 1.0 mm thick. We therefore developed an ultra-thin piezoelectric speaker with a thickness of less than 0.9 mm. Piezoelectric speakers, however, differ from electrodynamic speakers in certain ways, requiring the formulation of guidelines for optimum design. In this study, we examined the relationship between design factors such as the acoustic structure, damping of phone case vibration, and electrical pass design and the acoustic characteristics in order to achieve high-quality sound in a slim mobile phone that uses our piezoelectric speaker.

1. Introduction

Recently, market demand for slim mobile phones has been increasing. The device and mounting technologies required to achieve slim mobile phone design have also been evolving at a rapid pace. The acoustic devices in mobile phones, such as the speaker, microphone, and earpiece speakers, are very important because they create an interface with the phone user. The speaker is one of the largest devices used in a mobile phone. It is therefore often an obstacle to slim design.

Electrodynamic speakers are the speakers most commonly used in mobile phones. Electrodynamic speakers have magnetic circuits that are driven by a system consisting of permanent magnets, yokes, and voice coils. It is therefore not easy to make an electrodynamic speaker that is less than 2.0 mm thick. When designing a slim mobile phone, the speaker must be thinner than 1.0 mm, which cannot be achieved with an electrodynamic speaker.

Piezoelectric speakers on the other hand utilize the elastic effect of piezoelectric ceramics to enable a thin design of less than 1.0 mm. Piezoelectric speakers are a valid candidate for use in slim mobile phones. We therefore developed an original ultra-thin piezoelectric speaker with a thickness of 0.9 mm. The features of piezoelectric speakers differ from those of electrodynamic speakers in the following ways:

(1) Piezoelectric speakers have a high mechanical stiffness, so the sound pressure level at low to medium frequencies is not as good as that of electrodynamic speakers. On the hand, piezoelectric speakers have a excess sound pressure level in the high frequency region.

(2) Piezoelectric speakers have a strong driving force, causing the thin mobile phone case to vibrate. In the low frequency region, the pressure of the sound radiating from the piezoelectric speakers is low. Therefore, if the fundamental resonance frequency of the mobile phone case is in the low to medium frequency region, the sound pressure level of the speakers may attenuate due to phone case vibration.

(3) Piezoelectric speakers have static capacitive immittance, so the power consumption of electrical driving system increases as the input signal frequency becomes higher.

To achieve a high sound quality by using piezoelectric speakers, the problems above must be examined and solved, which might not be easy because it is difficult to use piezoelectric speakers efficiently.

In this paper, we studied the relationship between the acoustic characteristics and design factors such as the acoustic structure, damping of phone case vibration, and electrical design in order to achieve high-quality sound in a slim mobile phone that uses our piezoelectric speaker.

As a result, we were able to formulate guidelines for optimum sound quality design and succeeded in producing a market-ready slim mobile phone. This study is described in detail below.

2. Experiment

2-1. Preparation of piezoelectric speaker

Figure 1 shows an outline of the driving part of the piezoelectric speaker that we used in our mobile phone.

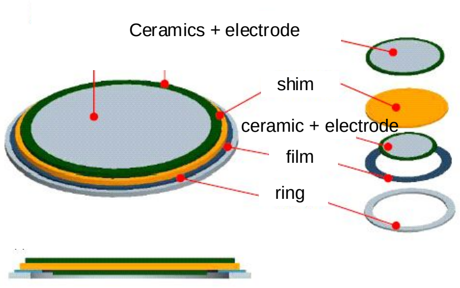


Figure 1. Outline of piezoelectric speaker

The diaphragm consists of a 42-alloy metal shim, a polyethylene terephthalate (PET) film, and two piezoelectric ceramic plates. The metal shim and film were placed between the two piezoelectric ceramic plates, whose diameters were 17 mm and 18 mm, and adhered with an appropriate binder.

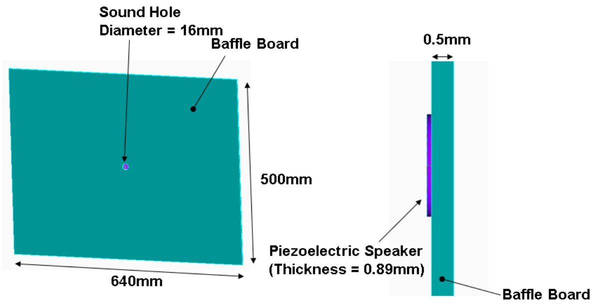


Figure 2. Baffle board used to measure sound pressure level

The diaphragm was adhered to a PPA (polypropanolamine) frame, completing the configuration of the driving part of the speaker. The driving part of the speaker has a diameter of 23 mm and a thickness of 0.89 mm. The maximum input voltage that can be applied to the speaker is 8 Vrms. The design of this piezoelectric speaker is described in detail by Onishi et al.

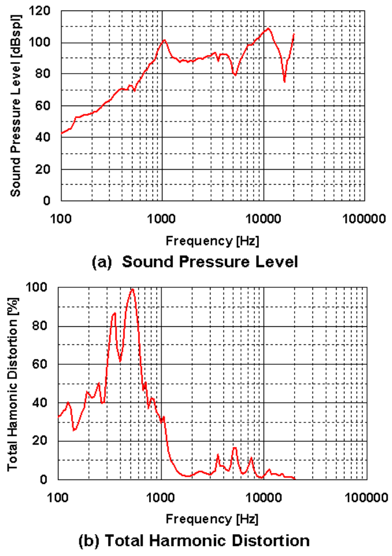


Figure3. Sound pressure/frequency response characteristic of piezoelectric speaker

Figure 3 shows the frequency response in the acoustic characteristics. Figure 3 (a) shows the sound pressure level and Figure 3 (b) shows the total harmonic distortion of our piezoelectric speaker. The piezoelectric speaker is fixed with a baffle board made of acrylic. The dimensions of this board are shown in Figure 2. The input voltage is 8 Vrms and the frequency range is 100 Hz to 20 kHz. The distance between the speaker sound hole and the microphone used to measure the acoustic characteristics is 10 cm.

From Figure 3 (a), the fundamental resonance frequency is 1.1 kHz. There are large and sharp positive peaks caused by mechanical resonance (including radiation impedance) at 1.1 kHz and 11.2 kHz and negative peaks caused by anti-resonance at 5.3 kHz and 16 kHz. Therefore, the sound pressure/frequency response characteristic is not flat. This is because a piezoelectric speaker consists of ceramics and a metal shim, which have a high mechanical stiffness and a low damping factor, giving the speaker a high mechanical quality factor.

For a speaker to achieve high-quality sound, the most important feature is flatness of the sound pressure/frequency response characteristic. As described in section 3, it is very important to suppress the large positive and negative peaks in the sound pressure level by designing an appropriate sound structure in the mobile phone.

From Figure 3 (b), the total harmonic distortion (THD) is larger than 50% in the frequency region lower than 1.1 kHz. This is because the piezoelectric speaker has a high mechanical stiffness. The reason why THD is close to 100% at 500 Hz is because the second harmonic frequency of 500 Hz is close to the fundamental resonance frequency of 1.1 kHz.

2-2. Method of mounting the speaker

We mounted piezoelectric speakers in slim mobiles phone using the method described below.

Figure 4 shows an outline and the outer dimensions of the mobile phones that we used. Figure 5 shows the general internal structure of the phone case behind the LCD.

The slim mobile phones mentioned in this paper are clamshell type mobile phones. Their cases are made either from resin that includes glass fibers or from metal. The piezoelectric speakers are adhered to the phone case behind the LCD.

The approximate dimensions of LCD side of the slim size mobile phones are as follows: total thickness of between 4.0 mm and 5.5 mm, length of about 100 mm, and width of about 50 mm. To make total thickness when folded less than 15 mm, the cases cannot be too thick. However, mobile phones are used in many different environments and their cases must therefore have sufficient stiffness. We therefore used resin that includes glass fibers or metals as the case materials because these materials are sufficiently stiff. The resin case is about 1.0 mm thick and the metal case is about 0.3 mm thick. Figure 6 shows an outline of the internal structure of the area around the piezoelectric speaker.

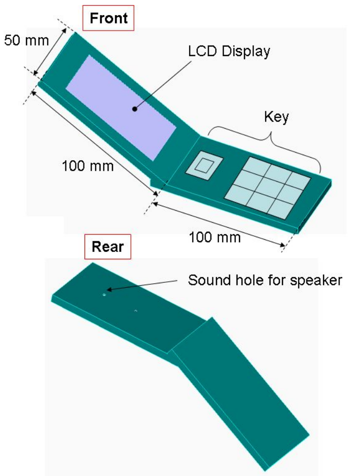


Figure 4. Outline of slim mobile phone

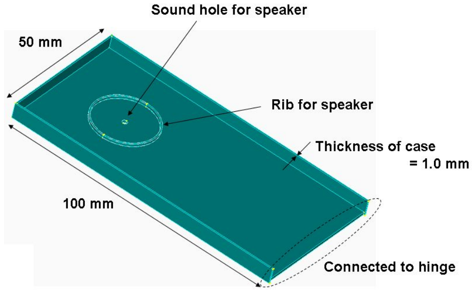


Figure 5. Outline of internal structure of phone case behind LCD

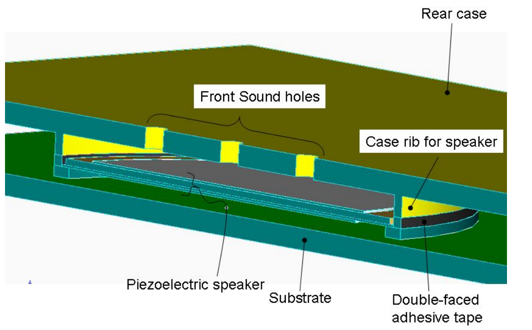


Figure 6. Outline of acoustic structure of area around

2-3. Designing the acoustic structure by using an equivalent acoustic circuit

Figure 7 shows the acoustic equivalent circuit derived from the acoustic structure of the area around the speaker shown in Figure 6 [1]. We calculated and estimated the relationship between the sound pressure/frequency response characteristic and the dimensions of the acoustic structure before finalizing the design of the mobile phone.

The size of all the acoustic components is restricted by the overall mobile phone design. The area of the sound hole must be smaller than 20 mm^2, the length of the sound hole must be shorter than 1.0 mm, the front cavity must be smaller than 500 mm^3, and the clearance between the speaker frame and printed circuit board (PCB) is restricted to 0.1 mm. The mobile phone design and the calculation equation are described in detail later.

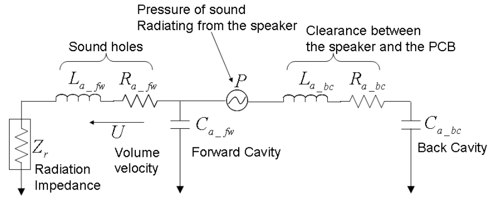


Figure 7. Acoustic equivalent circuit

2-4. Vibration of mobile phone case

To analyze the effect of mobile phone vibration on the acoustic characteristics of the speaker, we attached a vibration damper and evaluated changes in the sound pressure level. We measured the sound pressure level at a distance of 10 cm from the center of the LCD of the mobile phone. We used a free field microphone (B&K Type 4133), microphone conditioning amplifier (B&K 2690-A-OS2), and audio analyzer (Listen, Inc. SoundCheck).

2-5. Electrical design

Figure 8 shows the electrical design used to compress the dynamic range of the high band component of the signal. The problems mentioned above can be solved by limiting the dynamic range of the high band component separated by a high pass filter.

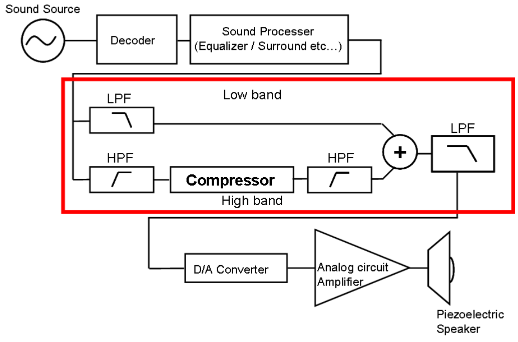


Figure 8. Block diagram of electrical path used to suppress power

In Figure 8, the area in the red box is the block used to solve the problems mentioned above. Signals processed by sound processors such as the surround processor and the equalizer are separated into low band and high band components by a low pass filter and a high pass filter. The separated high-band signal is input to a compressor. As shown in Figure 9, if the level of the signal input to the compressor is larger than the threshold level, the output signal is restricted according to the specified ratio. If the level of the signal input to the compressor is smaller than the threshold level, the output signal passes through the compressor. The high-band component processed by the compressor and the low band component are added and input to the low pass filter for final tuning of sound quality and electrical power consumption. After that, the signal is converted into an analog signal by the D/A converter and its electrical power is amplified to enable the audio amplifier to drive the piezoelectric speaker.

We examined the effectiveness of this electrical design by using sound processing simulation (Software: Matlab).

3. Results and discussion

We studied the relationship between the acoustic characteristics and the design factors so as to achieve high-quality sound in a slim mobile phone that uses a piezoelectric speaker.

First, to suppress the high sound pressure level in the high band, we studied the optimum design conditions for the acoustic structure (the acoustic components in front of the speaker).

Second, we analyzed the effect of phone case vibration on the sound pressure level of the speaker.

Finally, we investigated electrical design guidelines that would allow us to driving the piezoelectric speaker on low power. We proposed an electrical pass design and examined its effectiveness.

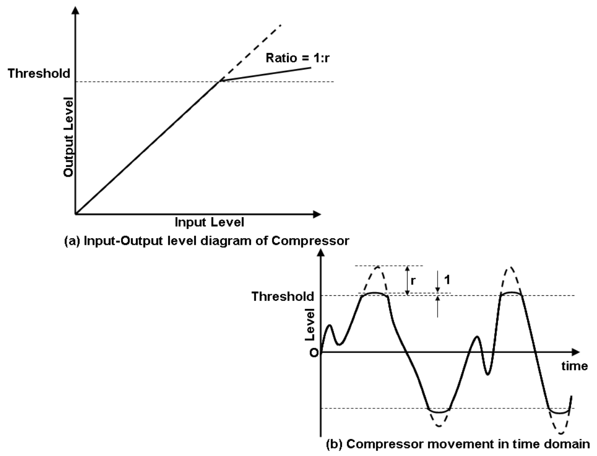


Figure 9. Concept of compressor in high band

3-1. Acoustic structure

3-1-1. Calculation of circuit coefficients

The equations for calculating acoustic inertia, acoustic compliance and radiation impedance are well known, so we have omitted them here. In this paper, we describe the process we used to calculate the pressure of the sound that radiates from the speaker (corresponding to the voltage source in an acoustic equivalent circuit), pressure loss caused by air friction, and the sound pressure level at certain distances from the mobile phone's sound hole.

The process for calculating the pressure of the sound that radiates from the piezoelectric speaker is described below. The balance equation used to calculate the electro-acoustic transformation that is arranged by the force factor is expressed by

$$A = \frac{I - Y_d E}{V} \qquad (1)$$

where $F\,[N]$ is the excited force on the diaphragm of the speaker, $Z_m\,[N \cdot s / m]$ is the mechanical impedance of the speaker, $V\,[m/s]$ is the vibration velocity of the diaphragm, $E\,[V]$ and $I[A]$ are the input voltage and current in speaker respectively, $A\,[N/V]$ is the force factor, and $Y\,[S]$ is the static admittance of the speaker.

To derive $P\,[N/m^2]$ (pressure of sound radiating from speaker) by using equation (1), the mechanical admittance and the force factor must be calculated from measurement data.

Figure 10 shows the electrical and mechanical circuit. The immittance of the speaker consists of the static electrical components $C_d\,[F]$ and $R_d\,[Ohm]$, and the motional mechanical components $L_{mn}[kg]$, $C_{mn}\,[N/m]$ and $R_{mn}\,[Ohm]$ (n is a natural number). The motional mechanical components are expressed by the parallel branches.

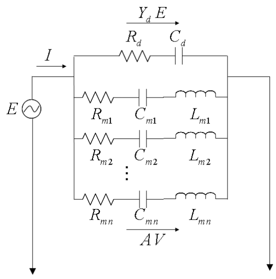


Figure 10. Mechanical equivalent circuit of piezoelectric speaker

Hereby, the static resistance R_d is negligible when analyzing the acoustic structure because the dielectric loss tangent $\tan\delta$ is 2% at most.

Figure 11 shows the system used to evaluate the force factor A.

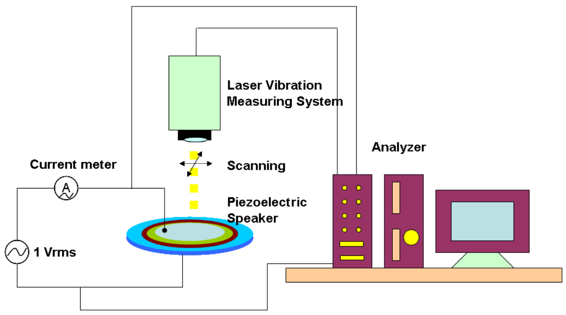


Figure 11. System used to measure force factor

The input current is measured by using a digital multimeter in which an input voltage with a 1 Vrms sweep tone (from 100 Hz to 20 kHz) is input. The static admittance $Y_d = j\omega C_d [S]$ is measured by using an impedance analyzer. The static capacitance of our piezoelectric speaker is $C_d = 260 [nF]$. The vibration velocity of the diaphragm of the piezoelectric speaker is evaluated by using a laser scanning system. To calculate the force factor, we used the sum of the complex vibration velocity of the diaphragm as the vibration velocity V.

The pressure of the sound radiating from the piezoelectric speaker is expressed by

$$P = A \cdot S \cdot E \tag{2}$$

where $S\ [m^2]$ is the area of the diaphragm.

The pressure loss caused by air friction in the sound hole is derived as shown below. Using the Darcy-Weisbach equation, the head loss is expressed by

$$\Delta h = \sum \lambda \frac{L}{d} \cdot \frac{V^2}{2g} + \sum \zeta \frac{V^2}{2g} \tag{3}$$

where $\Delta h\ [m]$ is the head loss, $L\ [m]$ is the length of pipe (sound hole), $V\ [m/s]$ is the average speed of the air flow, $d\ [m]$ is the diameter of the pipe, $g\ [m/s^2]$ is the gravitational acceleration, ζ is the loss coefficient for each element, and λ is the coefficient of the pipe loss [3].

The pipe loss coefficient λ is defined by a Reynolds number. To calculate the loss head, we defined the kinematic viscosity as $\nu = 1.49 \times 10^{-5}\ [m^2/s]$, and the critical Reynolds number as 2000. Hagen-Poiseuille's law and the Blasius equation can be used to calculate the laminar flow and turbulent flow, respectively.

Based on the information in the references and fluid simulation in a narrow space, we defined the loss coefficient for the sound hole as $\zeta = 2.6$.

Finally, the resistance in an acoustic equivalent circuit is expressed by

$$R = \frac{(\rho g)\left[\lambda \cdot \left(\frac{L}{d}\right) + (\xi + 1.5)\right]\left(\frac{v^2}{2g}\right)}{U} \tag{4}$$

where $U\ [m^3/\sec]$ is the volume velocity of the air.

We used the equation shown below to calculate the sound pressure level at the specified distance from the sound hole[2].

$$P_{meas} = \frac{\rho f U}{r} \tag{5}$$

Where $P_{meas}\ [Pa]$ is the sound pressure level to be calculated, $\rho\ [kg/m^3]$ is the mass density of the air, $f\ [Hz]$ is the frequency, and $r\ [m]$ is the distance between the speaker sound hole and the measurement point. Equation (5) is an approximate equation based on the supposition that the distance between the sound hole and the measurement point is larger than the diameter of the speaker and the acoustic wave radiating from the speaker can be regarded as a spherical wave embedded in the rigid wall. To calculate the transmission capability between the sound hole and the measurement point more accurately, FEM (finite element method) or BEM (boundary element method) simulation should be used. We used Matlab for calculation [4].

3-1-2. Experiment and simulation results

Because our piezoelectric speaker consists of ceramics and a metal shim, it has a high stiffness, and a high Q value. Therefore, the sound pressure level in the high band is high and the frequency response has some large positive and negative peaks. To achieve high-quality sound, the sound pressure/frequency response characteristic must be made flat and the high sound pressure level in the high band must be suppressed. To solve these problems, we formulated guidelines for designing the sound hole and the front cavity. In this paper, we describe phone model A, whose case is made from resin that includes glass fibers. The thickness of the case of model A is 1.0 mm. We determined that the total sound hole area should be 10.0 mm² based on the design of the mobile phone as a whole.

Figure 12 shows the simulation results when the total sound hole area is fixed to 10.0 mm², and the front cavity alternates between 50 mm³, 100 mm³, 300 mm³, 500 mm³, 1000 mm³, and 2000 mm³.

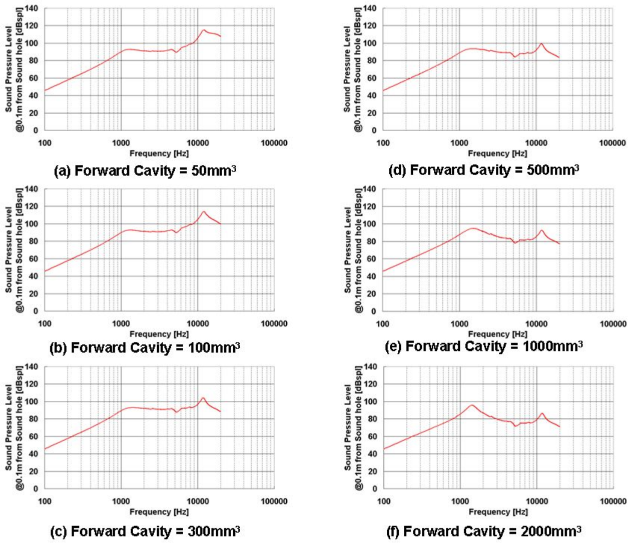


Figure 12. Results of simulation by using acoustic equivalent circuit (The front cavity alternates between 50 and 2000 mm³)

From Figure 12, the sound pressure level in the high band decreased gradually as the front cavity increased. This is because the front cavity works as a capacitor in parallel with the main radiation impedance path as shown in Figure 7. We judged that the optimum value for the front cavity is 300 mm³. Figure 13 shows the simulation data and measured data for a mobile phone designed using the optimum value for the front cavity indicated above.

From the data in Figure 13, the high sound pressure level was suppressed appropriately. Moreover, the positive and negative peaks of the sound pressure/frequency response characteristic were suppressed more than those in Figure 3. This is because appropriate air friction occurred in the narrow sound hole (10 mm²).

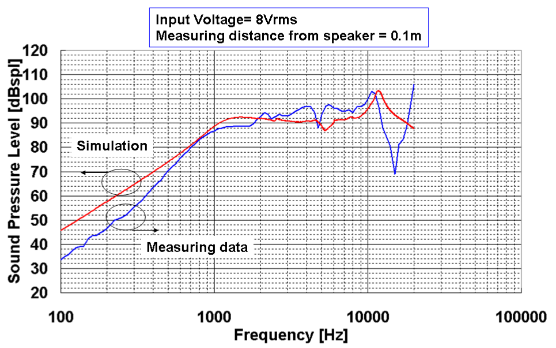


Figure 13. Results of experiment and simulation for sound pressure/frequency characteristic with fixed sound hole and forward cavity dimensions

3-2. Vibration damping

The cases of slim mobile phones are required to be thinner than those of usual mobile phones. Also, piezoelectric speakers have a strong driving force. Therefore, the piezoelectric speakers often cause the cases of slim mobile phones to vibrate, and the sound wave that radiates from the vibration of the mobile phone cases degrades the acoustic characteristics of the speaker.

We studied the vibration of a mobile phone case made from thin metal. To analyze the effect of phone case vibration on the sound pressure level of the speaker, we attached a damping material on the entire surface of the case behind the LCD and evaluated the effect of the damping material. The damping material was concrete.

Table 1 shows the results.

Table 1 Effect of phone case vibration

Frequency [Hz]	SPL without vibration damper [dBspl]	SPL with vibration damper [dBspl]	Deviation [dB]
500	64.9	68.8	3.9
1000	81.6	85.6	4
2000	80	79.8	-0.2
7500	85.6	84.4	-1.2

From Table 1, it can be seen that the sound pressure level in the high band is not affected by case vibration, but in the low band, it decreases by about 4 dB. This is because in the high band, the case vibration is partial vibration and the pressure of the sound radiating from the case is not large. On the other hand, in the low band, the case vibration is fundamental resonant vibration and the pressure of the sound radiating from the case is larger than that in the high band. Furthermore, in the low band, the pressure of the sound radiating from the speaker is smaller than that in the high band and the speaker sound wave is therefore easily affected by the sound wave from the case.

It can be considered that case vibration causes the sound pressure level to deteriorate because the sound wave radiating from the speaker and the sound wave radiating from the case have reverse phases and therefore cancel each other out.

Based on this, we evaluated the effectiveness of using a cushion in the mobile phone as a damping material. The cushion is attached at the point of maximum vibration of the case behind the LCD.

The results of our evaluation of the improvement of the sound pressure level are shown in Figure 14. By attaching the damping cushion, we could improve the sound pressure level in the low band.

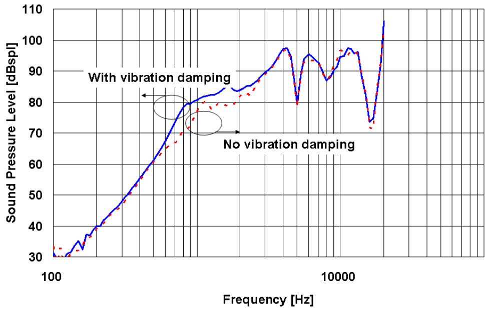
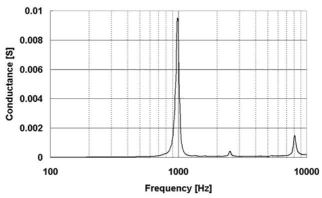


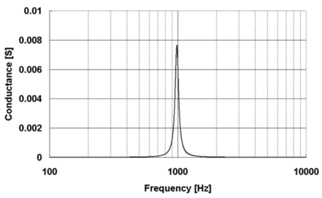
Figure 14. Improvement in sound pressure level caused by attaching a vibration damper.

3-3. Electrical design

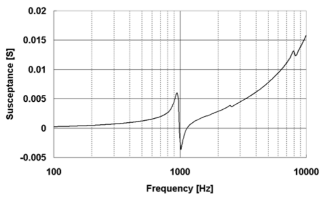
As shown in Figure 15, piezoelectric speakers have capacitive immittance. We used HP 4194A for the measurement. As shown in Figure 15 (b), the susceptance increases as the frequency increases.



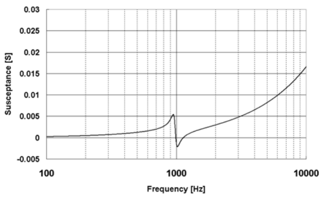
(a) Conductance (Measured data)



(c) Conductance (The approximation)



(b) Susceptance (Measured data)



(b) Susceptance (The approximation)

Figure 15. Admittance of piezoelectric speaker

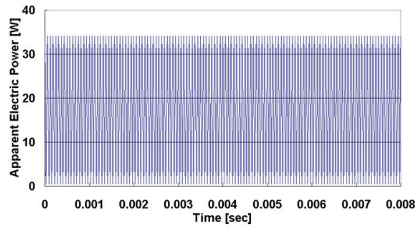
Therefore, because the electrical power consumption increases in the high band, the high frequency signal must be suppressed by an electrical pass filter. As a solution for this problem, we used the electrical pass design shown in Figure. 8. This design must achieve the following:

(A) If a signal with energy concentrated in the high band is input to this electrical pass filter, the electrical power consumption must be suppressed. A high band tone of 8 kHz was used in our experiment.

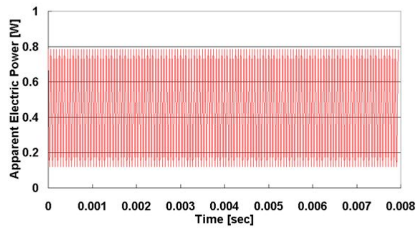
(B) If pink noise whose frequency distribution is close to actual sound (music) contents is input to this electrical pass filter, the input signal must go through the red box part in Figure 8. If white noise is input, this red box part should work to some extent.

We carried out simulation to examine the effectiveness of this electrical pass design. The process we used to carry out this simulation and the results are described below. In the simulation, we calculated the electrical power consumption as a product of the D/A conversion ratio , the convolution of the digital signal output from the red box part, and the admittance of piezoelectric speaker.

The simulation results calculated based on the process described above are shown in Figures 16, 17 and 18. In these graphs, the vertical axis shows the apparent electrical power. The actual power is not shown because in slim mobile phones, the piezoelectric speakers have to be driven by an amplifier with nearly AB-class capacity, so the power consumed by the amplifier and piezoelectric speakers is the apparent power. Most slim mobile phones do not have enough space to include inductor chips on the output line of the amplifier. Therefore, if a D-class amplifier is used, the electrical efficiency is close to AB-class and the electrical power consumed is the apparent power. Test signals such as the 8 kHz tone, pink noise, and white noise are sampled as 32 kHz PCM raw data and their maximum peak level is -6dBFs (considering that the maximum frequency is about 16 kHz for the MPEG format used in mobile phones). We adjusted the scale of the time axis so that the waveform could be confirmed.

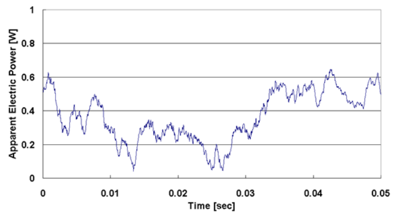


(a) Apparent electrical power for unprocessed signal

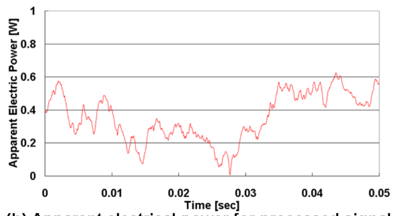


(b) Apparent electrical power for processed signal

Fig. 16 The apparent electrical power at the piezoelectric speaker for 8.0 kHz tone signal

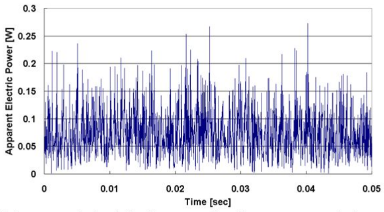


(a) Apparent electrical power for unprocessed signal

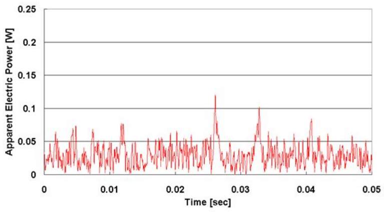


(b) Apparent electrical power for processed signal

Figure. 17 The apparent electrical power at the piezoelectric speaker for pink noise signal



(a) Apparent electrical power for No processed signal



(b) Apparent electrical power for processed signal

Figure 18. Apparent electrical power consumed by piezoelectric speaker for white noise signal

From Figure 16, the apparent power for the unprocessed signal in (a) exceeds 10 W. In an actual mobile phone, the maximum power output to the speaker is a few watts at most because of the driving capacity of the speaker amplifier and the battery. This result means that the speaker amplifier and the battery require electrical power larger than their capacities without this signal processing. On the other hand, from Figure 16 (b), the apparent electrical power is suppressed to lower than 0.8 W by this signal processing. We could therefore achieve the requirements of (A).

About (B):

From Figure 17, the apparent electrical power for processed and unprocessed signals is almost the same. This is because the high frequency component is small in pink noise. On the other hand, from Figure 18, the apparent electrical power is suppressed by this processing when white noise is input. These results show that the processing shown in the red box part of Figure 8 suppresses the high band if the energy in the high band is larger than that of standard music and voice contents.

We used this signal processing in our slim mobile phones to achieve high-quality sound and low-power operation.

4. Conclusion

In this paper, we studied design guidelines that could be used to realize high-quality sound in slim mobile phones that use our piezoelectric speakers.

Specifically, we studied how to suppress the high sound pressure level in the high band by optimizing the acoustic structure, how to use vibration damping to improve the sound pressure level, and how to use signal processing to limit the high band components for low-power operation.

Our study is summarized below.

To analyze the relationship between the sound pressure level and design factors such as the area of the sound hole and front cavity, we carried out simulation by using an acoustic equivalent circuit. We could thereby formulate guidelines for optimal design of the area of the sound hole and front cavity. We succeeded to suppress the high sound pressure level of the piezoelectric speaker in the high band.

To ascertain the effect of phone case vibration on the sound pressure level, we covered the surface of a mobile phone behind the LCD side with vibration damper and measured the sound pressure level. We also evaluated the effectiveness of a cushion as an actual vibration damper attached to the point of maximum vibration on the case and confirmed the cushion is effective enough as a damper.

Based on these experiments, we formulated guidelines for damping phone case vibration.

To realize a system that enables the piezoelectric speaker to operate on low power and produce high-quality sound, we studied level limitations in the high band. By implementing effective sound processing, we could suppress the electrical power consumption of signals whose energy is concentrated in the high band such as high-frequency tones and white noise.

Base on the guidelines that we formulated, we developed a series of slim mobile phones that use our piezoelectric speakers and succeeded in realizing high-quality sound. These phones were then commercialized and launched on the market.

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