Acoust. Sci. & Tech. 33, 6 (2012)
©2012 The Acoustical Society of Japan

ACOUSTICAL LETTER

The driving system for piezoelectric speaker with low power consumption

Jun Kuroda[1,*], Yasuharu Onishi[1], Motoyoshi Komoda[1], Yasuhiro Oikawa[2] and Yoshio Yamasaki[2]

[1]*NEC CASIO Mobile Communications, Ltd., 1753 Shimonumabe, Nakahara-ku, Kawasaki, 211–8666 Japan*
[2]*Department of Intermedia Art and Science, Waseda University, 3–4–1 Ohkubo, Shinjuku-ku, Tokyo, 169–8555 Japan*

(*Received 26 January 2012, Accepted for publication 29 May 2012*)

Keywords: Piezoelectric speaker, Consumption power, Compressor
PACS number: 43.38.Fx, 43.38.Lc [doi:10.1250/ast.33.372]

1. Introduction

Piezoelectric speakers are useful to design slim mobile phones because they are no more than 1.0 mm thick. However, to use piezoelectric speakers, the power consumption in high frequency band must be suppressed carefully because they have the capacitive impedance. We propose using multiband compressor in high frequency band to suppress the consumption power for piezoelectric speaker. Multiband compressor is often used to maximize the loudness of the sound as one of mastering tools. However, they must be designed carefully when they are used as the suppressor of electrical power. This paper will show the design guidlines to use the multiband compressor as the suppressor of the electrical power for piezoelectric speakers.

2. Outline of the piezoelectric speaker

The electrical characteristics and the equivalent circuit for piezoelectric actuators have been studied in recent years [1–4]. The equivalent circuit of the piezoelectric speaker is shown as Fig. 1. In Fig. 1, from the top, the first branch shows the static impedance, which are consistent of the resistance R_d, and capacitance C_d. From the second path to n-th path shows the motion impedance for n-th mechanical resonance of the speaker, which consists of the mechanical friction loss R_{mn}, the stiffness C_{mn} and the mass L_{mn}. Almost all electrical power is consumed at the static capacitance C_d. The electrical admittance for the Fig. 1 is expressed as Eq. (1).

$$Y = \frac{\omega C_d}{\omega C_d R_d - j} + \sum_{k=1}^{n} \frac{\omega C_{mk}}{\omega C_{mk} R_{mk} - j(1 - \omega^2 C_{mk} L_{mk})} \qquad (1)$$

Figure 2 shows the approximated frequency response of admittance of piezoelectric speaker measured by the impedance analyzer. Figure 2(a) shows the conductance, and (b) shows the susceptance. These graphs show the approximation curve which has the fundamental resonance, i.e. in Eq. (1), $k = 1$. The higher resonances (in Eq. (1) $k \geq 2$) are omitted, because the influence on the power consumption is small. As shown in the Fig. 2(b), the susceptance increases in high frequency band. Table 1 shows the constants of the equivalent circuit of piezoelectric speaker. From Table 1, it can be said that the motion impedance is much higher than that of the static impedance except for resonance frequency. This is the reason why electrical power is mostly consumed at the static capacitance. These data are measured by using the impedance analyzer and the laser Doppler vibrometer, with 100 mV_{rms} of input voltage. Young's modulus and the permittivity change with the amplitude of velocity are not constant, if the magnitude of vibration velocity of piezoelectric ceramics is larger than 0.1 m/s [2–4]. The components of the equivalent circuit are simplified as the constant values, because the magnitude of the vibration velocity of piezoelectric speaker is not much larger than 0.1 m/s.

An electrical driving system consists of DSP, digital analog converter and D-class audio amplifier. Oscillation frequency of D-class audio amplifiers are from 100 kHz to 1 MHz. Therefore piezoelectric speaker needs a low pass filter at the input of it, to eliminate the oscillation frequency components from input signals. Though inductors are useful to realize the low power consumption system, inductors having the a few μH of inductance have to become large and it is difficult to be put on PCB board. The low pass filter has to be configured by RC filter even if the power consumption increases.

3. Results and Discussion

3.1. Configuration of the system

As written above, the electrical admittance of the piezoelectric speakers increases as well as power consumption in high frequency band. Speakers of mobile phones have various kinds of audio signals. Therefore the driving system must be designed with consideration of signals whose energy concentrate in high frequency band. Although low pass filters can be used to suppress high frequency components, they work for standard signals which do not have concentrated energy in high frequency band. Low pass filters make worse the clearness and sound pressure level of standard signals. The sound processing system having multiband compressor is shown in Fig. 3 to solve this issue. (The compressor is used only for high frequency components.) A signal from the sound source is processed by the basic sound processing i.e. equalizer, surround, reverb etc. the processed sound signal are decomposited to high frequency and low frequency components. Low frequency components pass through without any processing and high frequency components are applied to the compressor. The compressor in high frequency

*e-mail: j-kuroda@bq.jp.nec.com

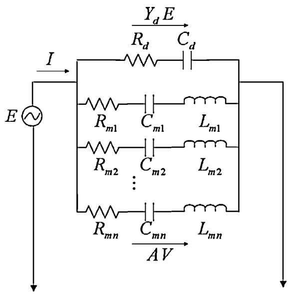

Fig. 1 The equivalent circuit of piezoelectric speaker.

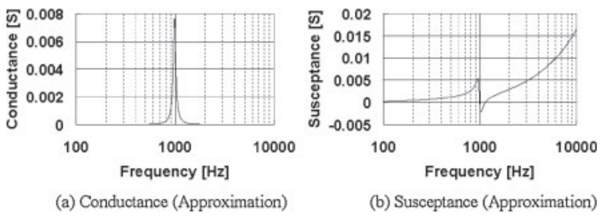

Fig. 2 Frequency response of the electrical admittance.

Table 1 Constants of the equivalent circuit.

Components	C_{d}	C_{m1}	L_{m1}	R_{m1}
Constants	252.00 µF	88.20 µF	0.30 H	134 Ω

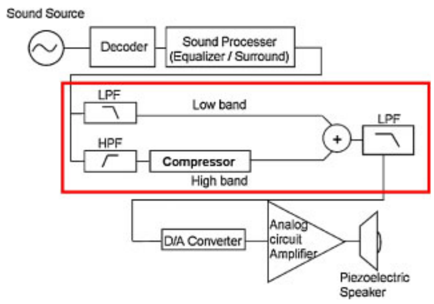

Fig. 3 Proposed sound processing.

band path adjusts the dynamic range of high frequency components. If energy of high frequency band is excess, the compressor suppresses the amplitude of them. After the low pass filter and the compressor in high frequency band, signals in two paths are added. Added signal are applied to the D/A converter, the amplifier and the piezoelectric speaker in order.

3.2. Examination of the performance

In this subsection, we examine the performance of the proposed system. The cutoff frequency of high pass and low pass filters and parameter of compressor have to be optimized to satisfy two requirements as below;

· Requirement 1: High frequency components of standard signal must go through without any suppression.

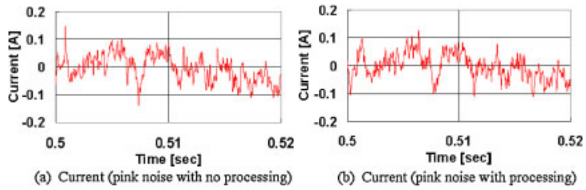

Fig. 4 Current supplied to speaker (pink noise).

· Requirement 2: If the energy of high frequency band is excess, they must be suppressed not to exceed the maximum rating of the driving system.

To confirm Requirement 1, the pink noise is used because actual music and voice signals have the power spectra which decrease with the ratio of -3 dB or less per octave. About the Requirement 2, we choose the 8 kHz tone signal as an example. The simulation method to confirm the performance of the system is as follows. In Eqs. (2) and (3), all variables are discrete complex vectors in frequency domain. Let the input signal and the processed signal from the block surrounded by the square in Fig. 3 be $S[m]$ and $S_{\mathrm{prc}}[m]$, respectively. When input signal is not processed, the output signal is equal to the input signal $S[m]$ $(m \in \mathbf{N}, n = 0, 1, \cdots, N-1)$. Let the staic total analog sensitivity for digital full scale of the D/A converter and the amplifier be q[V/dBFs]. The electrical admittance $Y[m]$ is extracted from the measured data Fig. 1. The current supplied to the speaker for original signal and processed signal, $I[m]$ and $I_{\mathrm{prc}}[m]$ are expressed as the circular convolution of the input/output signal and the electrical admittance as shown below.

$$I[m] = qS[m] * Y[m] \tag{2}$$

$$I_{\mathrm{prc}}[m] = qS_{\mathrm{prc}}[m] * Y[m] \tag{3}$$

For accurate estimation, the response in time domain should be calculated as the solution of ordinary differential equations for the equivalent circuit. However, we used the stationary response, which is calculated by inverse Fourier transform of Eqs. (2) and (3), because the purpose of this calculation is to aquire a rough estimation of the current. Figures 4, 5 and 6 show these inverse Fourier transformed waveforms. The parameters of filters and compressor are decided as below. Details of the process to decide the parameters are described in the next subsection.

○ Low pass/High pass filters
· Cutoff frequency: 1 kHz
· Filter type: Fifth order Butterworth filter
○ Compressor in high frequency band
· Attack time/Release time: 0 s
· Threshold level: 4 V (peak detect)
· Ratio: ∞ : 1

Figures 4, 5 and 6 show the calculation results of the current supplied to the speaker for pink noise, white noise and 8 kHz tone signal. Input voltage is 8 $\mathrm{V_{rms}}$. In mobile phones, the maximum power of speaker system is about 1 W. The current supplied to speaker should be suppressed lower than 0.1 A.

As shown in Fig. 4, the current for pink noise is almost unchanged by the processing because this signal does not have

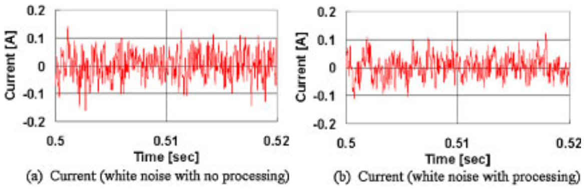

Fig. 5 Current supplied to speaker (white noise).

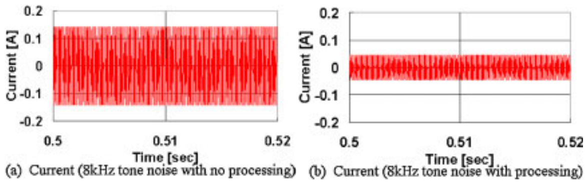

Fig. 6 Current supplied to speaker (8 kHz tone signal).

the excess energy in high frequency band. On the other hand, as shown in Figs. 5 and 6 the current for white noise and 8 kHz tone signal are suppressed by the processing. The current for 8 kHz tone is remarkably suppressed. The current for original signal is over 0.15 A and it is suppressed to lower than 0.05 A by processing. By this calculation, it is confirmed that our processing system can suppress the current supplied to speaker properly if signals have the excess energy in high frequency band.

3.3. Verification of the parameters

Although it is showed that proposed system can suppress the power consumption at the piezoelectric speaker, it must be confirmed that the parameters of high pass/low pass filters and compressor is appropriate for actual signals i.e. the processing system with these parameters does not change the sound quality. The actual voice and music wave forms are shown in Figs. 7(a), (b), (c) and (d) as examples. The voice is male talking voice in Japanese recorded in our laboratory. The music is pop music featuring the acoustic guitar with male vocals. The sampling rate of them is 32 kHz and the bit rate is 16 bit.

Figures 7(a), (b), (c) and (d) show the original voice, the original music, the high pass filtered voice and the high pass filtered music, respectively. Figures 7(a), (b), (c) and (d) are plotted with voltage as the vertical axis. The voltage is calculated as the product of digital level by the total analog sensitivity q. At first, the number of the quantized samples of high pass filtered signals, which exceed the threshold voltage in 1 second as Table 2 is examined. As shown in Table 2, when the threshold voltage is set to 4 V, the number of samples exceed the threshold is less than 30. It is expected that our system with $V_{th} = 4$[V] does not affect on the actual voice and music because almost all samples do not exceed the threshold voltage. When V_{th} becomes smaller, number of the samples exceed V_{th} increases. To confirm the appropriate threshold voltage V_{th}, we investigated the influence of the V_{th} on the waveforms in time and spectrum. Figures 7 and 8 show the waveforms and spectra of voice and Figs. 9 and 10 show

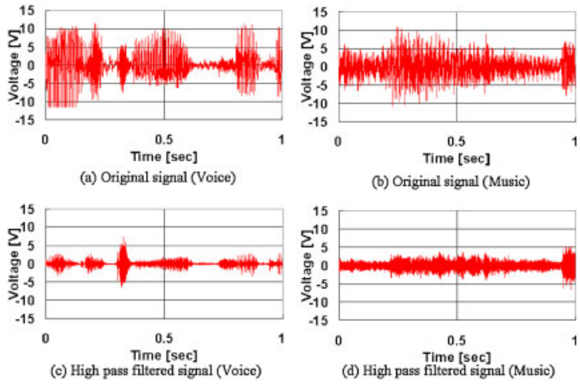

Fig. 7 Actual signals.

Table 2 Number of samples exceed the threshold.

Voice			
Threshold voltage (V_{th})	4 V	0.4 V	0.04 V
Number of samples	26	4,360	13,999
Time length (ms)	0.81	136.25	437.47
Music			
Threshold voltage (V_{th})	4 V	0.4 V	0.04 V
Number of samples	18	10,184	15,867
Time length (ms)	0.56	318.25	495.84

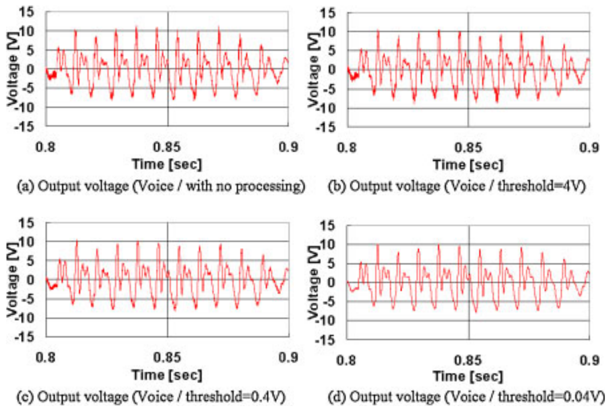

Fig. 8 Waveforms in time domain (Voice).

those of music. In Figs. 8, 9, 10 and 11, the analyzed time span is 0.1 second. In Figs. 9 and 11, spectra are calculated by fast Fourier transform of 1,024 points with Hanning window. Figures 8, 9, 10, 11 have four Figs. (a), (b), (c) and (d), respectively. Figure (a) corresponds to original signal with no processing. Figures (b), (c) and (d) correspond to processed signal with $V_{th} = 4, 0.4, 0.04$[V]. As shown in Figs. 8 and 10, high frequency components which appear as fine vibration are gradually suppressed due to decrease of the threshold voltage V_{th}. Especially this variation is clear in Fig. 10 because the high frequency components of the music signal is larger than

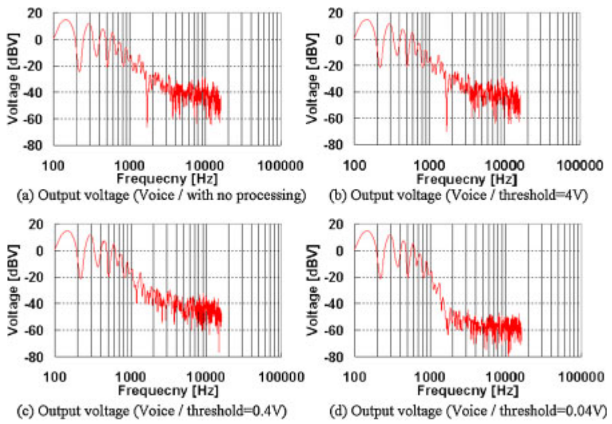

Fig. 9 Spectrum (Voice).

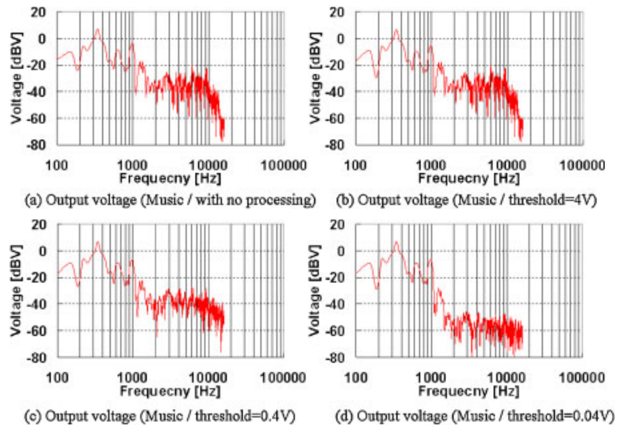

Fig. 11 Spectrum (Music).

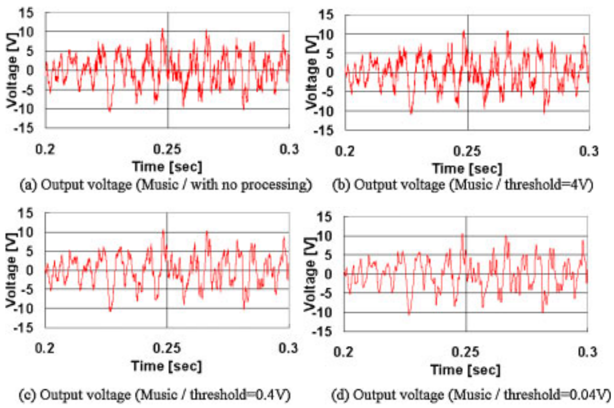

Fig. 10 Waveforms in time domain (Music).

the voice signal. Between no processed signal and processed signal with $V_{th} = 4$[V], there are small variation. The fine vibration is gradually suppressed between no processed signal and processed signal with $V_{th} = 0.4$[V], and finally disappear at $V_{th} = 0.04$[V]. This tendency is same for the spectrum. Furthermore, we carried out actual listening test about these signals which are generated as the output signal of block surrounded by square in Fig. 3. There was no change of the sound quality between no processed signal and processed signal with $V_{th} = 4$[V]. As the matter of course, we could find that the sound quality of processed signal with $V_{th} = 0.04$[V] is muffled extremely.

From these results, the optimum voltage threshold is $V_{th} = 4$[V].

4. Conclusion

The sound processing system composed of multiband compressor is proposed, which can drive speakers with low power consumption and showed the guideline to design the parameters of multiband compressor as suppressor of electrical power. We have already applied this system to our mobile phones having piezoelectric speakers since 2005. Technologies for low power consumption are important for mobile phones and handy electrical devices. Small speakers besides piezoelectric type in handy electrical devices has poor efficiency in middle range. Therefore they need lots of electrical power to achieve good sound quality and enough loudness. To realize the good sound quality and enough loudness under such physical limitations, technological innovation is needed, which differs from the field of High-end audio. Research for the low power consumption and high quality sound is very interesting and will give useful outcomes and great benefits to general consumers.

References

[1] T. Ikeda, *Fundamentals of Piezoelectricity* (Oxford Science Publications, Oxford, New York, Tokyo, 1996).

[2] S. Takahashi and S. Hirose, "Vibration-level characteristics of lead zirconate titanate ceramics," *Jpn. J. Appl. Phys.*, **31**, 3055–3057 (1992).

[3] S. Takahashi, S. Hirose and K. Uchino, "Stability of PZT piezoelectric ceramics under vibration level change," *J. Am. Ceram. Soc.*, **77**, 2429–2432 (1993).

[4] S. Takahashi, S. Hirose, K. Uchino and K. Y. Oh, "Electromechanical characteristics of lead zirconate titanate ceramics under vibration-level change," *Proc. 9th IEEE Int. Symp. Appl. Ferroelectrics*, pp. 377–382 (1994).