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**AN AUDIO ENGINEERING SOCIETY PREPRINT**

# Development of a piezo-electric super-tweeter suitable for DVD-Audio

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**Abstract** - We have developed a piezo-electric super-tweeter that can reproduce the frequency range 10kHz-100kHz very flatly. It is suitable for the next generation of Hi-Fi audio products, such as DVD-Audio.

## 0. Introduction

A super-tweeter that can reproduce frequency range 20kHz-100kHz is demanded for next generation audio formats, such as DVD-Audio.

Some conventional dynamic type super-tweeters can reproduce 20kHz-100kHz. For example, those comprised of a dome shape diaphragm made from super-graphite material, or comprised of a leaf diaphragm made from chemical film material. But because such types require particular materials or constructions, they are unsuitable for mass production. In addition they are expensive. A super-tweeter that is not so expensive and easily mass produced is also required.

A piezo-electric loudspeaker can be constructed quite simply. And a piezo-electric element is relatively cheap. In addition, a piezo-electric transducer has been used for an ultrasonic vibrator conventionally, as it has resonance in the ultrasonic frequency range.

We have therefore considered that the piezo-electric loudspeaker has a strong potential for development as a super-tweeter, which would be easily mass produced and suitable for the next generation of Hi-Fi audio products such as DVD-Audio.

However, generally speaking, the conventional piezo-electric loudspeaker is not suitable for Hi-Fi audio products. Because it has much unevenness in frequency response due to its own sharp resonance.

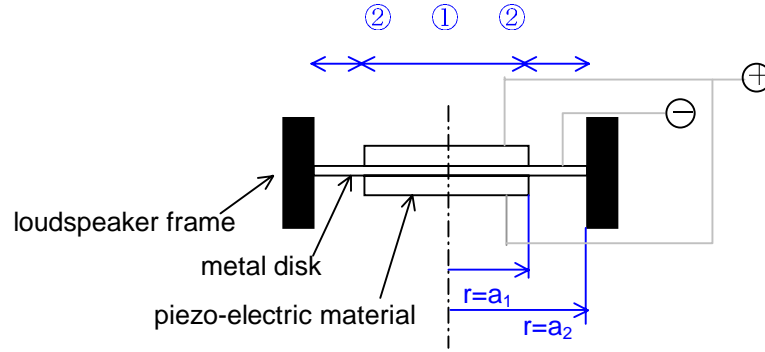
Now we have developed a piezo-electric super-tweeter that can reproduce the frequency range 10kHz-100kHz flatly, because we can control sharp resonance of the piezo-electric loudspeaker with resonance control elements. Resonance control elements are made of rubber.

We describe here the construction of the developed tweeter, theoretical analysis of the conventional piezo-electric loudspeaker with equations of motion, analysis of the developed super-tweeter action, the design of the resonance control element using Finite Element Method (FEM), and analysis of the effect of the cavity in front of diaphragm on sound pressure frequency response using Boundary Element Method (BEM).

## 1. Analysis of a conventional piezo-electric loudspeaker

A conventional piezo-electric loudspeaker has particular vibration modes, which depend on the shape and particular material of the piezo-electric element. Resonance of a piezo-electric element is very sharp because the internal loss of each material used to construct a piezo-electric element is very small. There is therefore much unevenness in the frequency response of the piezo-electric loudspeaker. It has been reported that it is not suitable for Hi-Fi audio products.

In [Fig.1], the cross section of a typical conventional piezo-electric loudspeaker is shown. The construction comprises a thin metal disk and two piezo-electric disks with radiuses smaller than the metal disk. They are attached to both sides of the metal disk. This construction is called a bimorph diaphragm. The diaphragm perimeter is fixed to the frame of the loudspeaker.



[Fig.1] Cross section of a typical conventional piezo-electric loudspeaker

In the theoretical analysis of a piezo-electric loudspeaker, equations of motion have been used in consideration of material parameters, piezo-electric constant  $d_{31}$ , and boundary conditions within the piezo-electric diaphragm (1). We discuss the conventional analysis and estimate differences between measured and calculated frequency responses.

Furthermore as shown in [Fig.1], symbol ① is the part which has piezo-electric elements adhered to it, ② is the only metal part between the piezo-electric element and the frame. And displacements of ① and ② are expressed as  $\xi_1(r)$ ,  $\xi_2(r)$  with the function of radius ( $r$ ) at the time of free vibration without driving force.

$$(\nabla^4 - k^4)\xi_1(r) = 0 \quad (1)$$

$$(\nabla^4 - k'^4)\xi_2(r) = 0 \quad (2)$$

Where,

$$\nabla = \frac{d^2}{dr^2} + \frac{1}{r} \frac{d}{dr} \quad (3)$$

$$k = \frac{\rho_1 h_1 + \rho_2 h_2}{D_1' + D_2'} \omega^2 \quad (4), \quad k' = \frac{\rho_2 h_2}{D_2} \omega^2 \quad (5)$$

$$D_1' = \frac{E_2 h_2^3}{3(1 - \mu_1^2)} Ce Ct \left( Ct^2 + \frac{3}{2} Ct Co + \frac{3}{4} Co^2 \right) \quad (6)$$

$$D_2' = \frac{E_2 h_2^3}{3(1 - \mu_1^2)} \left( Ct^2 - \frac{3}{2} Co + \frac{3}{4} Co^2 \right) \quad (7)$$

$$D_2 = \frac{E_2 h_2^3}{12(1 - \mu_1^2)} \quad (8)$$

$$Ce = \frac{E_1}{E_2} \quad (9), \quad Ct = \frac{h_1}{h_2} \quad (10), \quad Co = \frac{1 - Ce Ct^2}{1 + Ce Ct} \quad (11)$$

$\omega_i$ :	angular frequency	} $\begin{matrix} i=1: \text{part of piezo material} \\ i=2: \text{part of metal plate} \end{matrix}$
$\rho_i$ :	density	
$E_i$ :	Young's modulus	
$\sigma_i$ :	Poisson's ratio	
$h_i$ :	1/2 of material thickness	

General solution of equation (1), (2) can be expressed with Bessel function in considering that vibration amplitude has a limit at the center of a piezo-electric diaphragm.

$$\xi_1(r) = C_1 J_n(k_1 r) + C_2 I_n(k_1 r) \quad (12)$$

$$\xi_2(r) = C_3 J_n(k_2 r) + C_4 Y_n(K_2 r) + C_5 I_n(k_2 r) + C_6 K_n(k_2 r) \quad (13)$$

Where,

$C_1 \sim C_6$  : constants of integration  
 $J_n, I_n, K_n, Y_n$  : Bessel function of order  $n$

Next, boundary conditions are expressed in considering the bending moment by piezo-electric effect. This is induced when input voltage is supplied to a piezo-electric diaphragm.

It is continuously at  $r=a_1$ , the boundary where piezo-electric disks attached to the metal disk. It is fixedly at  $r=a_2$ , the perimeter of the diaphragm attached to the frame of the loudspeaker.

Equations (14)-(20) are acquired when boundary conditions, displacements, inclinations, bending moments, and shear forces are expressed as function of radius ( $r$ ).

$$(a) \ r=a_1 \quad \text{displacement} \quad \xi_1(a_1) = \xi_2(a_1) \quad (14)$$

$$\text{inclination} \quad \frac{\delta \xi_1(a_1)}{\delta r} = \frac{\delta \xi_2(a_1)}{\delta r} \quad (15)$$

$$\text{bending moment} \quad M_1(a_1) + M_v = M_2(a_1) \quad (16)$$

$$\text{shear force} \quad Q_1(a_1) = Q_2(a_1) \quad (17)$$

$$(b) \ r=a_2 \quad \text{Displacement} \quad \xi_2(a_2) = 0 \quad (18)$$

$$\text{Inclination} \quad \frac{\delta \xi_2(a_2)}{\delta r} = 0 \quad (19)$$

Where,

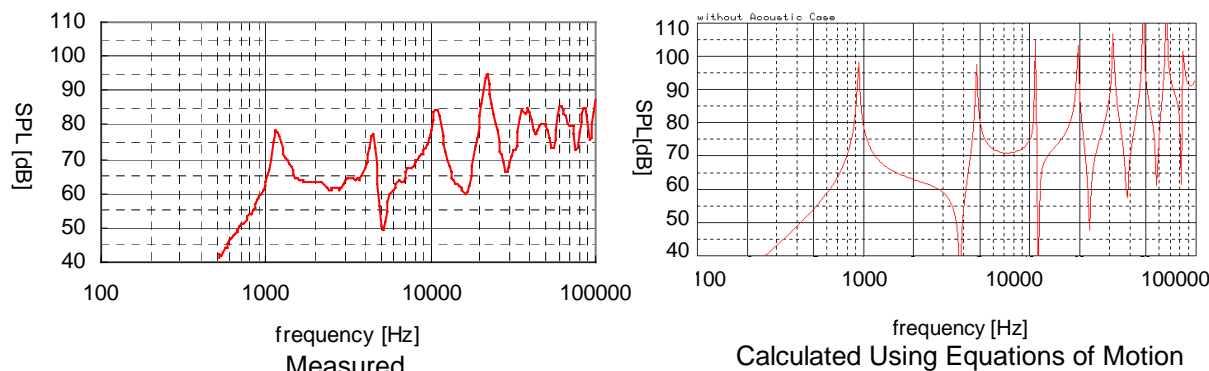
$$M_v = \frac{E_m t_m d_{31} E_v}{2(1 - \sigma_p)} \cdot \frac{C_e(1 + C_t)}{1 + C_e C_t} \quad (20)$$

$d_{31}$ : Piezo-electric constant

The displacement toward the vibration direction when input voltage is supplied to the piezo-electric loudspeaker can be calculated using equations (1)-(20). And the sound pressure frequency response is also calculated from the calculated displacements above. Sound pressure frequency response, which is measured and calculated as mentioned, is described comparatively in [Fig.2]. Specifications of the piezo-electric loudspeaker used for measuring and calculating are shown in [Table 1]. A good accordance is seen between measured and calculated response.

[Table.1] Specification example of a conventional piezo-electric loudspeaker

	piezo-electric material	metal disk
material name	PCM33A	Ni-Fe
diameter [mm]	$\phi 20.6 (=2a_1)$	$\phi 24 (=2a_2)$
thickness [mm]	0.05	0.05
Young's modulus [N/m <sup>2</sup> ]	$7.0 \times 10^{10}$	$1.47 \times 10^{11}$
Poison's ratio	0.23	0.29
density [kg/m <sup>3</sup> ]	7650	8200
piezo-electric constant $d_{31}$ [m/V]	$2.62 \times 10^{-10}$	
boundary condition	fixed at the perimeter of the diaphragm	



[Fig.2] Comparison of sound pressure frequency responses between measured and calculated using theoretical analysis

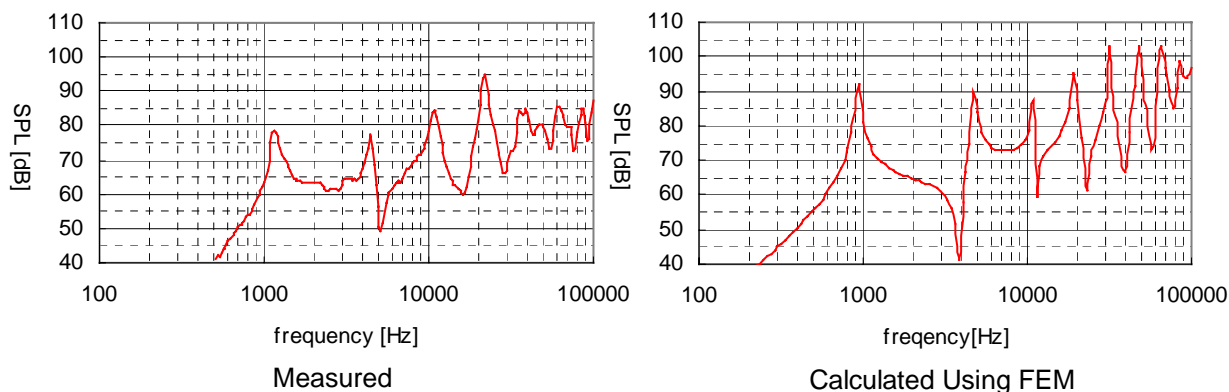
## 2. Analysis using Finite Element Method (FEM) and confirmation of the analysis accuracy

Boundary conditions will be complicated in the case of viscoelasticity material from rubber, for example, is applied to the piezo-electric vibrator in order to control its sharp resonance. We considered it to be difficult to analyze characteristics of the loudspeaker using the conventional analysis mentioned above.

Therefore we tried to analyze characteristics using the Finite-Element-Method (FEM). At first we checked the conformity between calculated response using FEM and measured or calculated response using conventional analysis of a conventional piezo-electric loudspeaker.

Driving force is induced toward a radial direction of the diaphragm by piezo-electric countereffect when input voltage is supplied to the loudspeaker. Then, to analyze frequency response using FEM, we applied driving force working toward a radial direction at the perimeter of the piezo-electric disks.

Sound pressure frequency responses of the piezo-electric loudspeaker, which has the same specifications shown in [Table.1], analyzed with FEM and measured are described comparatively in [Fig.3]. They have good accordance to that established by theoretical analysis. We refer to frequency response of the piezo-electric loudspeaker. Since resonance occurred in ultrasonic frequency around 100kHz [Fig.3], we consider that the piezo-electric loudspeaker has potential for construction of a super-tweeter for the next generation Hi-Fi audio products.



[Fig.3] Comparison of sound pressure frequency responses between measured and calculated using FEM

Returning to FEM analysis, in the method of supplying driving force using FEM analysis, sensitivity of the piezo-electric loudspeaker is not calculated accurately because the piezo-electric coefficient  $D_{31}$  is left out of consideration. But the efficiency acquired with FEM analysis can be modified to nearly actual efficiency, if three cases of sound pressure levels are compared, one measured via an actual loudspeaker, another calculated using the conventional analysis, a third is calculated using FEM analysis.

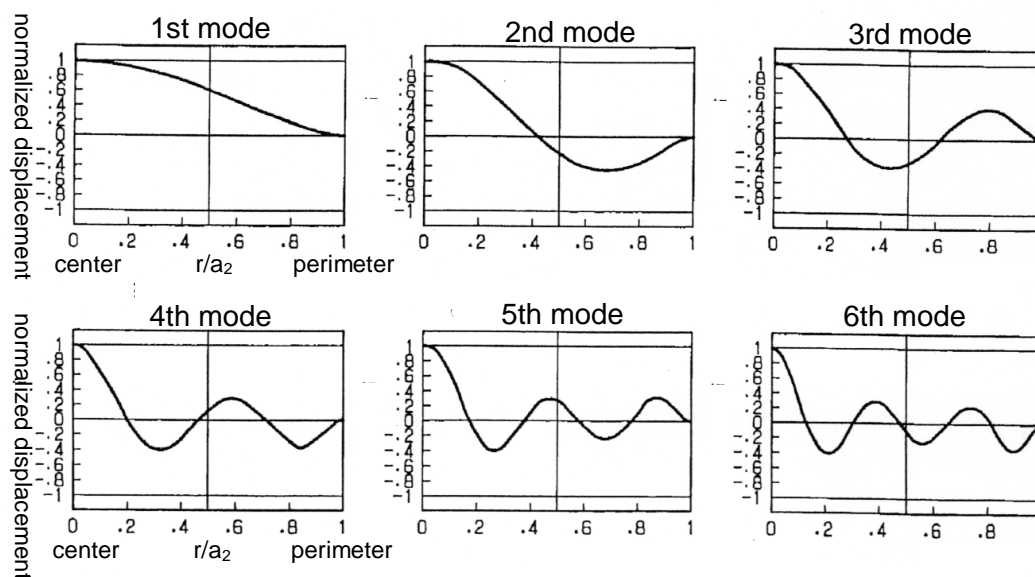
Driving force is generated by piezo-electric constant  $d_{31}$  within the whole of piezo-electric material when the piezo-electric loudspeaker is operated. But, in FEM analysis, driving force need not be applied to every element within piezo-electric disks. We have found that it can substitute simply for giving radial direction force to the perimeter of piezo-electric disks.

### 3. Resonance modes of a piezo-electric diaphragm and the method to suppress resonance

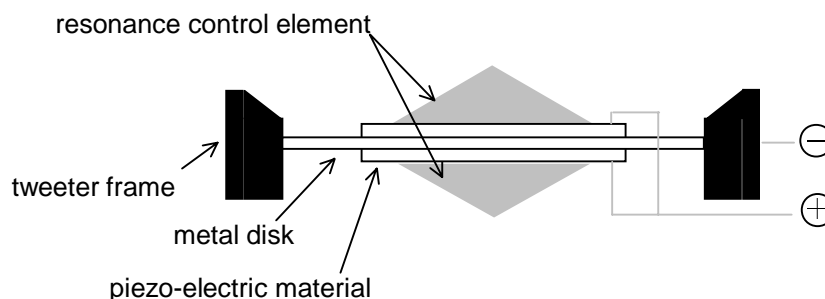
Next, we describe about the method of suppressing well sharp resonance of the piezo-electric type loudspeaker by applying rubber to the piezo-electric vibrator, and the optimal design of the piezo-electric super-tweeter using FEM analysis.

Vibrating amplitude of a piezo-electric diaphragm becomes largest at the center of a symmetrical vibrating mode. And the amplitude becomes smaller as it goes to the perimeter from the center of the diaphragm. The 1st to 6th vibrating modes of a piezo-electric diaphragm in the cross section are described in [Fig.4].

With consideration of vibrating modes, we have aimed at the effect of suppressing resonance at the center of the diaphragm to the largest extent, and less as it goes to the perimeter with resonance control elements. In [Fig.5], The structure of one example of piezo-electric super-tweeter with suppressed resonance due to resonance control elements is described. The resonance control element is made of rubber. Its base is circular in order to adjust to the shape of the diaphragm. A resonance control element has been attached to the center of each surface side of the diaphragm.



[Fig.4] The 1st to 6th vibrating mode of a piezo-electric diaphragm in the cross section



[Fig.5] Construction of the piezo-electric super-tweeter with 2 resonance control elements

#### 4. The optimal design of a resonance control element using FEM analysis

Using FEM analysis, we estimated the relation between sound pressure frequency response and the shape of a resonance control element, and tried to design an optimal shape in order to develop a piezo-electric super tweeter. Material parameters used in FEM analysis are described in [Table.2].

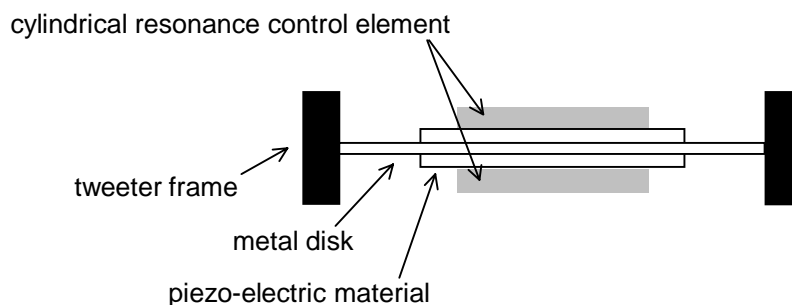
[Table.2] Material parameters of a piezo-electric diaphragm for the analysis using FEM

	piezo-electric material	metal disk	resonance control element
material name	PCM33A	Ni-Fe	rubber
Young's modulus [ $\text{N/m}^2$ ]	$7.0 \times 10^{10}$	$1.47 \times 10^{11}$	$2.0 \times 10^6$
Poison's ratio	0.23	0.29	0.48
density [ $\text{kg/m}^3$ ]	7650	8200	1608
$\tan \delta$	0.02	0.003	0.461

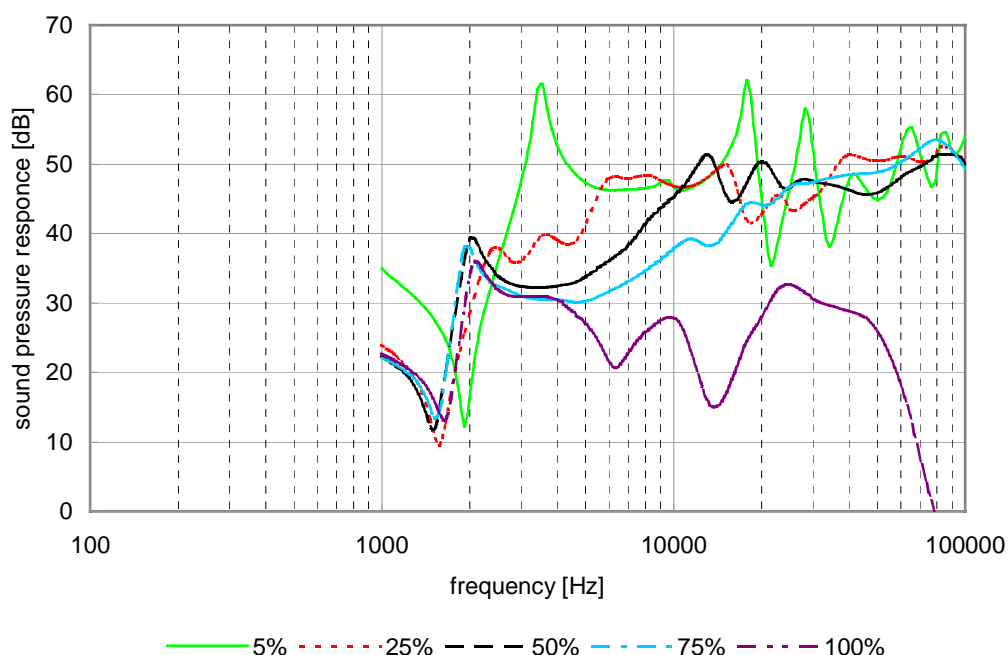
##### 4-1. Cylindrical resonance control element

At first, as shown in [Fig.6], the shape of the resonance control element was decided to be cylindrical temporarily. And the area of its base was changed. With the ratio of the base area of a cylindrical resonance control element to the surface area of a piezo-electric diaphragm has been changed to 5, 25, 50, 75, and 100%, each of the frequency response is shown in [Fig.7].

With smaller base area, large unevenness occurs in the frequency response, as in a conventional piezo-electric speaker. Conversely, with a large base area covering almost the entire diaphragm, SPL decreases significantly due to excessive damping. Therefore, when the ratio of the base area to the surface area is about 50%, the resonance control element damping result in a piezo-electric super-tweeter is suitable for Hi-Fi audio products.



[Fig.6] Cross section of the piezo-electric super-tweeter with cylindrical resonance control elements

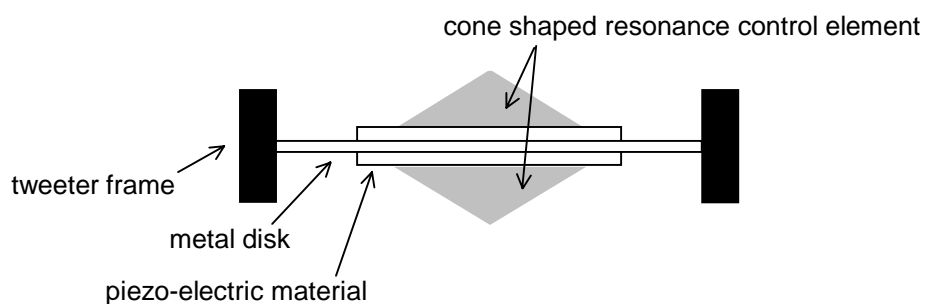


[Fig.7] Frequency response changes with ratio of base area of a cylindrical resonance control element to surface area of a piezo-electric diaphragm

## 4-2. Cone shaped resonance control element

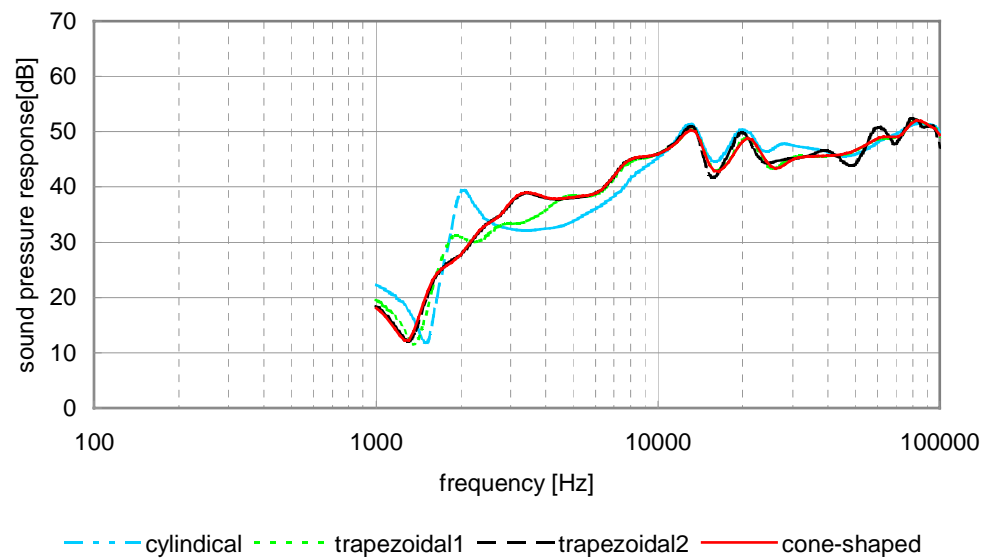
As the next step, since the resonance control element could provide damping vibration modes of the piezo-electric diaphragm, its shape was decided as a virtual cone. Construction of a super-tweeter with a cone-shaped resonance control object is shown in [Fig.8]. In order to provide better frequency response, we tried to optimize the shape of the resonance control element.

Frequency responses are shown in [Fig.9], as the shape of the resonance control element was gradually changed from a cylinder to a cone. Despite of differences in shape, these resonance control elements are all equal in weight. The nearer to a cone shape, the smoother the response observed at the low frequency in 1kHz-10kHz [Fig.9].



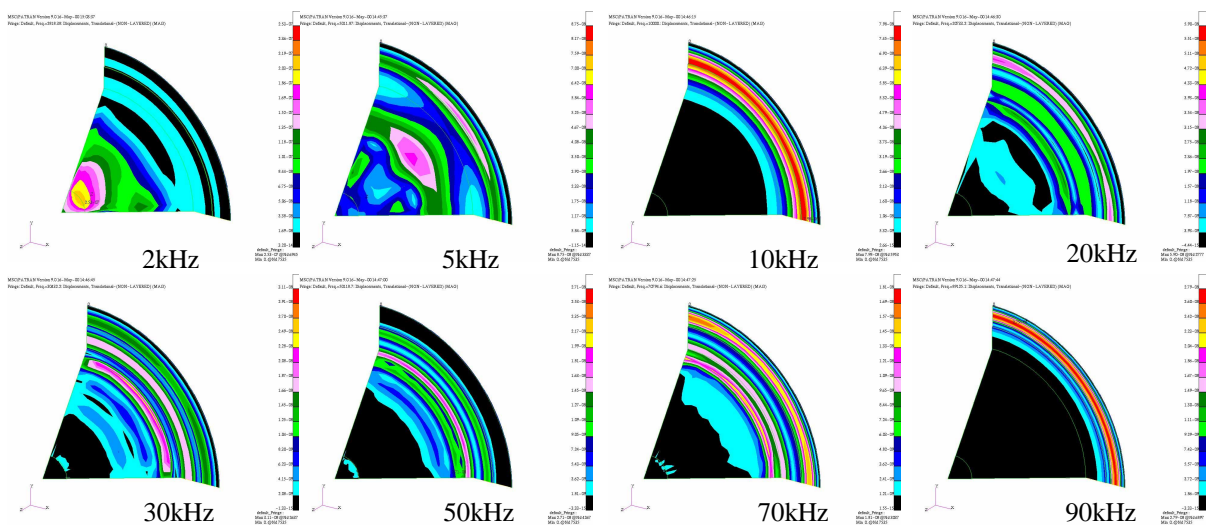
[Fig.8] Cross section of the piezo-electric super-tweeter with cone shaped resonance control elements





[Fig.9] Frequency response changes with variations of the shape of resonance control element

Calculated vibration modes of the piezo-electric super-tweeter with cone-shaped resonance control elements are shown in [Fig.10]. Around the perimeter of the diaphragm that was not attached resonance control elements vibrated largely above 10kHz. As for the surface of the resonance control element, vibrating amplitude became very small around the center and larger towards to the perimeter. Therefore, it can be thought to satisfy the objective of suppressing amplitude of vibration most at the center and less to the perimeter of a piezo-electric diaphragm, using the cone shaped resonance control elements.



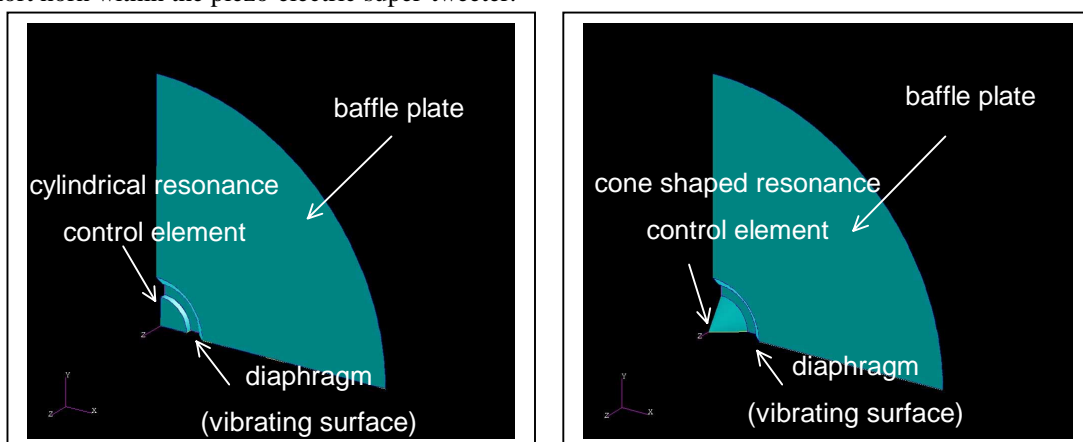
[Fig.10] Vibration modes of piezo-electric diaphragm stuck cone shaped resonance control elements

## 5. Analyzing the effect of the cavity in front of the diaphragm on frequency response using Boundary Element Method (BEM)

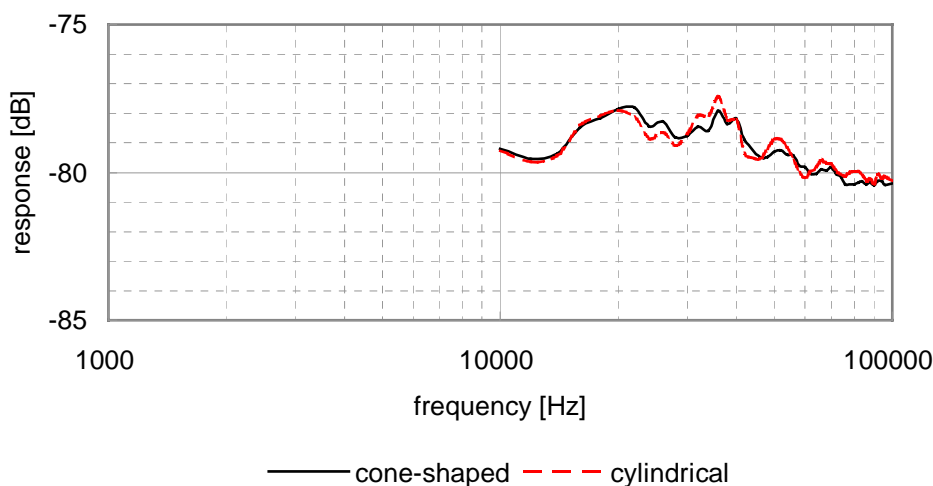
From analyzed results of frequency response shown in [Fig.9], the frequency response using cylindrical resonance control elements appears flattest in the frequency range 10kHz-100kHz. But to actually construct the tweeter with

resonance control elements, the effect of the cavity in front of the diaphragm on frequency response must be considered. The cavity exists between the frame of the tweeter and the surface of the resonance control element. It creates unevenness in the sound pressure frequency response.

We attempted to analyze the effect of the cavity using Boundary Element Method (BEM). In using both cylindrical or cone-shaped resonance control elements, the effects of the cavity were compared. Analyzed models are shown in [Fig.11]. These models are of a piezo-electric super-tweeter with resonance control elements on a baffle plate of 75mm diameter. The sound pressure frequency response was calculated 30cm from the center of the tweeter on the axis. Because the area between the resonance control element and the frame of the tweeter nearly reproduces sound pressure, velocity was supplied at the part corresponding to the area mentioned above in BEM analysis on the models shown in [Fig.10]. The calculated frequency responses are shown comparatively in [Fig.12]. Cone-shaped resonance control elements showed slightly unevenness than others in sound pressure frequency response. It is thought that the cone shaped resonance control element avoids the effect of the cavity because it forms a short horn within the piezo-electric super-tweeter.



[Fig.11] Analysis models for BEM



[Fig.12] Effect of the cavity in front of the diaphragm on frequency response analyzed using BEM

## 6. Comparison of measurement results by experiment

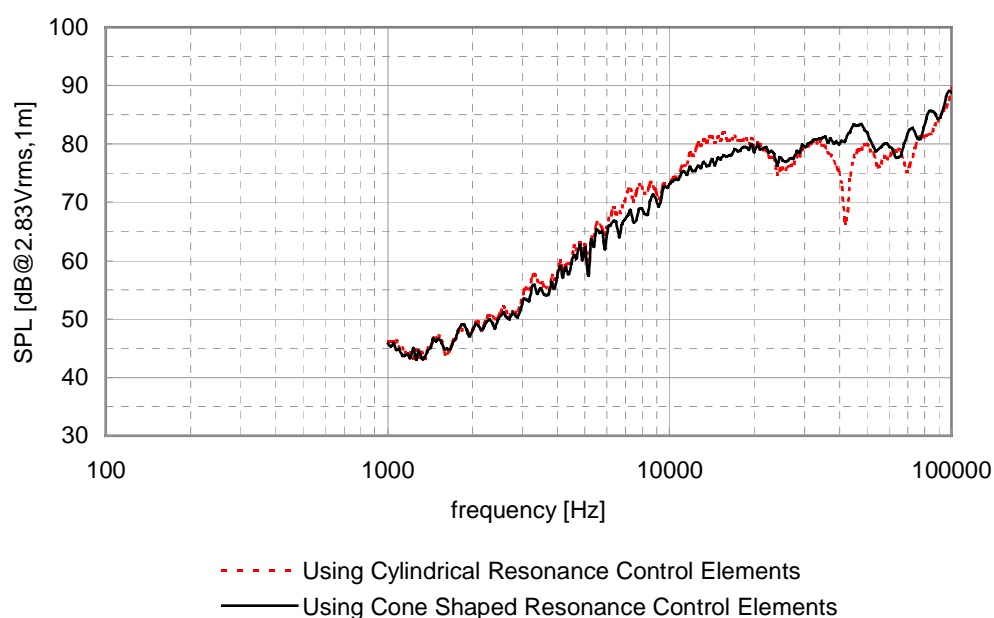
We made cylindrical or cone-shaped resonance control elements for trial testing, and measured sound pressure frequency response of the piezo-electric super-tweeter using each of them. Measured responses are shown in [Fig.13]. Similar tendencies are observed between measured and calculated response.

But regarding difference of response between cone-shaped and cylindrical units, the difference was larger in trial experiment than in calculations.

As fully described above, we have been able to develop a superlative piezo-electric super-tweeter reproducing wide frequency range with very flat response.

We believe that why it has wide and flat frequency response using a cone-shaped resonance control element due to the following reasons:

- ① The vibration amplitude of the piezo-electric diaphragm becomes smaller towards the perimeter from the center of the diaphragm. The cone-shaped resonance control element can suppress vibration complying with the vibration amplitude above.
- ② It can prevent the mechanical impedance from changing suddenly by differences of material and shape around the boundary between the perimeter of the resonance control element and the piezo-electric diaphragm.
- ③ A short acoustical horn is formed in the space between the frame of the tweeter and the resonance control element due to its cone-shaped surface. This short horn can mitigate the effect of the cavity in front of the diaphragm on frequency response.



[Fig.13] Measured sound pressure frequency responses of the piezo-electric super-tweeter using cylindrical, or cone-shaped resonance control elements

## 7. Many characteristics of the developed piezo-electric super-tweeter

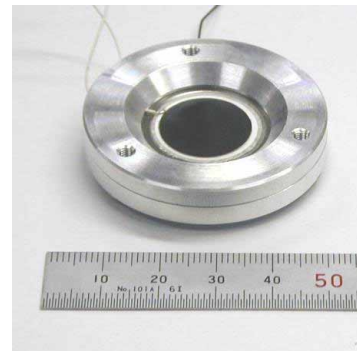
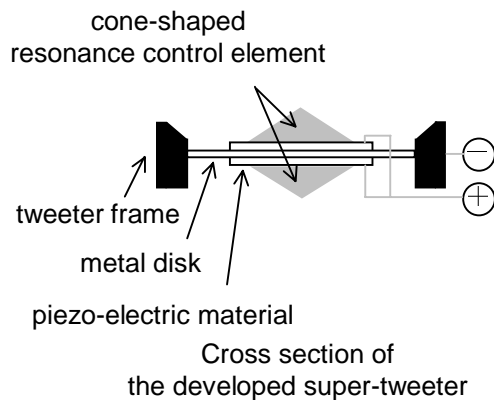
We have shown specifications of the developed piezo-electric type super-tweeter in [Table.3]. Its structure is shown in [Fig.14]. It is comprised of a bimorph piezo-electric diaphragm, cone-shaped resonance control elements attached to each side of a diaphragm, and a frame fixing the perimeter of the diaphragm.

The sound pressure frequency response and the impedance curve are described in [Fig.15]. It can reproduce 10k-100kHz with flatness. Impedance frequency response becomes  $-6\text{dB/oct}$  curve and follows  $Z=1/j\omega C$  because the piezo-electric material has electric capacitance.

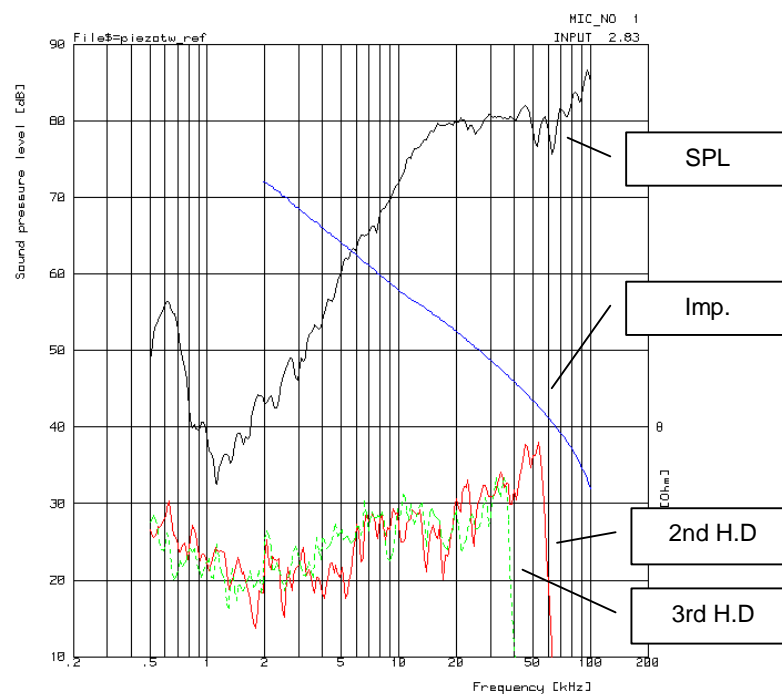
The directional characteristic has been examined by FEM analysis and measuring, and is described in [Fig.16]. We have obtained good accordance between calculation using FEM analysis and measurement, concerning response from on axis to 30 degrees. As for the response at around 45 degrees, decrease in measured sound pressure level is larger than that calculated. Then the directional characteristic of the actual super-tweeter is sharper than in calculations. Also from vibration figures in [Fig.10], the area around the perimeter of the diaphragm, where the resonance control element is not attached, contributes to sound reproduction. Then we think that the directional characteristic is similar to a ring-shaped diaphragm.

[Table.3] Specifications of the developed piezo-electric super-tweeter

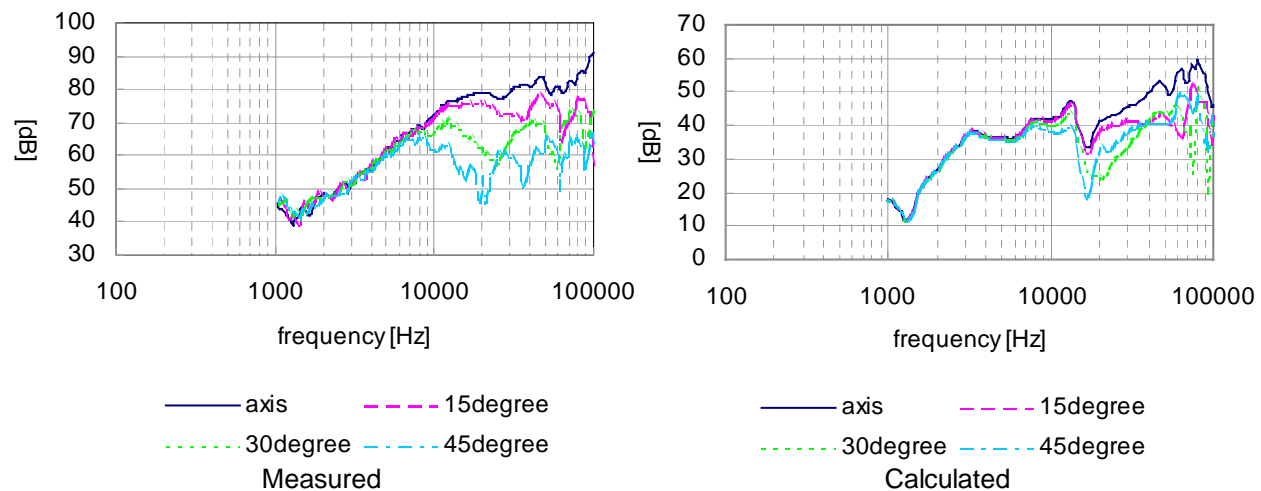
frequency range	10~100 [kHz] (-10dB)
SPL	82 [dB@2.83Vrms,1m]
distortion ratio	1[% @40kHz] (-40dB)
electrical impedance	70 [ $\Omega$ @10kHz] (-6dB/oct)



[Fig.14] Cross section and appearance view of developed piezo-electric super-tweeter



[Fig.15] Frequency characteristics of the developed piezo-electric super-tweeter



[Fig.16] Directional characteristics of the developed super-tweeter measured and calculated with FEM

## 8. Conclusion

It has been reported that piezo-electric loudspeakers are not suitable for Hi-Fi audio products because of the effect of sharp resonance on sound pressure frequency response. But we have investigated the use of a piezo-electric element as an ultrasonic vibrator, given its high potential for mass production. Additionally we have worked on controlling its resonance.

The sharp resonance of a piezo-electric element can be optimally suppressed with a cone-shaped resonance control element. The effect on sound pressure frequency response due to the cavity in front of diaphragm can be decreased also with cone-shaped resonance control elements. As a result, we have been developed a piezo-electric super-tweeter suitable for DVD-Audio, due to its ability to reproduce the wide frequency range of 10kHz-100kHz very flatly.

## References

- (1) For example: Yutaka ICHINOSE, "Telephone Sounder and Receiver Using Piezoelectric Ceramics", Technical Report of IEICE, EA80-25.