New Development of Combined Permanent-Magnet Type Microspeakers Used for Cellular Phones

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In mobile phones of multimedia era, microspeakers of high-quality sound are essential parts to generate human voice in speaker phone and MP3 song player. In this paper, two types of microspeakers, outer permanent magnet (PM) and combined PM type, are analyzed using electromagnetic, mechanical, acoustical and their coupling analysis. For performance comparison, voice coil diameter is chosen as a design parameter to change excitation position and magnet volume for both types. For combined PM type, sound pressure level (SPL) is improved due to increased PM volume compared to outer PM type. Also, with the decreased voice coil diameter for combined PM type, the 1st resonant mode of the diaphragm is more efficiently excited due to concentrative excitation, resulting in lower and broader frequency range. Therefore, it can be said that the combined PM type microspeakers are more advantageous for high performance microspeaker which are essential for multimedia era.

***Index Terms*—Broadband, finite-element method (FEM), magnetic circuit, microspeaker.**

I. INTRODUCTION

WITH the advent of 3G mobile phones, it can be realized to combine laptop PC and mobile phone that enables multimedia data communication such as web searching, MP3 song player etc. Therefore, microspeakers with high-quality sound, broader frequency range and reduced size are essential parts in multimedia era. With the rapid development of personal computers, finite-element method (FEM) has been used extensively in the field of engineering design [1]. For previous research, most work in electroacoustic devices is concerned with high-performance loudspeakers, which are typically driven beyond their linear output range [2], [3].

In this paper, two important performance characteristics, sound pressure level (SPL) and first resonant frequency, are analyzed for two typical types of microspeakers, outer permanent magnet (PM), and combined PM type, according to the structure of the magnetic circuit. For SPL and resonance analysis of microspeakers, magnetic force acting on the voice coil is determined by Lorentz law and electromagnetic FEM analysis. Harmonic analysis of diaphragm vibration and acoustical analysis are also followed using FEM to determine surface velocity of the diaphragm and sound pressure level. Noting that magnetic flux linkage is affected by vibrating voice coil, coupling between mechanical and magnetic analysis should be also considered. The simulated result of the proposed analysis is also compared with the experimental result for the prototype combined PM type microspeakers.

II. METHOD OF ANALYSIS

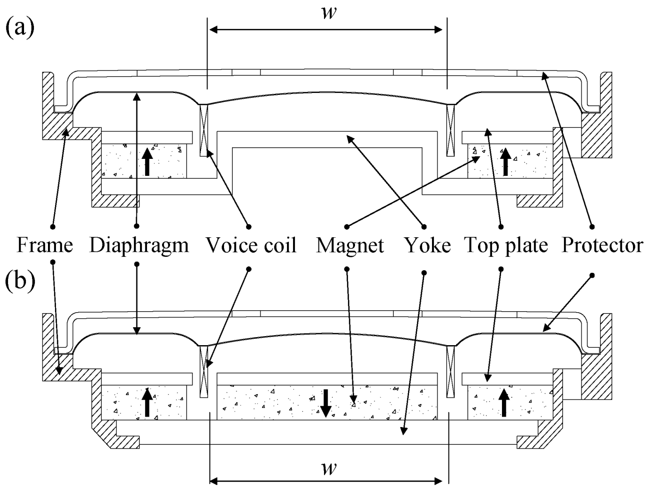

Fig. 1. Schematic of microspeakers (Diameter $= 15$ mm). (a) Outer PM type. (b) Combined PM type.

Fig. 1 shows the prototype outer PM and combined PM type microspeakers to be analyzed and the outer PM type is more popularly employed due to its structural similarity to the conventional loudspeakers. It should be noted that the magnetic circuit of the combined type is optimized in view point of magnet volume and magnetization direction for the given microspeakers. For performance comparison, w is chosen as a design parameter. It should be noted that w is related to the excitation position of voice coil on the diaphragm and the amount of PM volume. For the magnetic field analysis, a two-dimensional (2-D) FEM model can be implemented utilizing Maxwell's equations with axisymmetric boundary conditions. Voice coil current can be also determined by solving voltage equation of the equivalent circuit as in (1), where V, R, I, and L denote applied voltage, coil resistance, coil current, and inductance, respectively.

The voice coil motion generates the back-electromotive force, $Bl(z)\dot{z}$, where l, z and $\dot{z}$ are the voice coil length, the voice

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coil displacement and velocity. The magnetic exciting force resulting from the interaction between the magnetic field and the total electric currents can be expressed as in (2)

$$V = IR + L\frac{dI}{dt} + Bl(z)\dot{z} \tag{1}$$

$$F_{\text{coil}} = \oint Idl \times B. \tag{2}$$

The mechanical model of the vibrating diaphragm including voice coil can also be developed using FEM. Displacement and surface velocity of the diaphragm can be obtained by solving mechanical vibration equation as in (3), where $[M]$, $[C]$, $[K]$, and $\{F_{\text{coil}}(t)\}$ denote mass matrix, damping coefficient matrix, stiffness coefficient matrix, and magnetic exciting forces acting on voice coil, respectively

$$[M]\{\ddot{z}\} + [C]\{\dot{z}\} + [K]\{z\} = \{F_{\text{coil}}(t)\}. \tag{3}$$

For an acoustical analysis, the sound power radiated by a microspeaker vibrating in a mean root-mean-square surface with the spatial velocity of $\langle V_o^2(f)\rangle$, can be calculated as in (4)

$$W_{\text{rad}}(f) = \rho c S_{\text{rad}} \sigma_{\text{rad}}(f) < V_0^2(f) > \quad \text{(W)} \tag{4}$$

where f, ρ, c, S_{rad}, and σ_{rad} are the frequency of vibration, density of the air, the velocity of the propagation of sound in air, area of the diaphragm surface contributing to sound radiation, and the radiation efficiency, respectively. The sound radiation efficiency is calculated by a simplified equation, in which the diaphragm is considered as a monopole source, and is given as in (5) [4]

$$\sigma_{\text{rad}}(f) = \frac{k^2a^2}{1 + k^2a^2} \tag{5}$$

where $k = 2\pi f/c$ is the wave number and a is the diaphragm radius. The sound pressure level at distance d from the source can be expressed as in (6)

$$L_p(d) = L_w - 20\ \log_{10}\left(\frac{d}{d_0}\right) - 8 \quad \text{(dB)} \tag{6}$$

where L_w is the sound power level as in (7), and the normalized value for d_o is 1 m

$$L_w(d) = 10\ \log_{10}\left(\frac{W_{\text{rad}}}{10^{-12}}\right) \quad \text{(dB)}. \tag{7}$$

Fig. 2 shows the schematic of an experimental setup to measure SPL of the microspeaker.

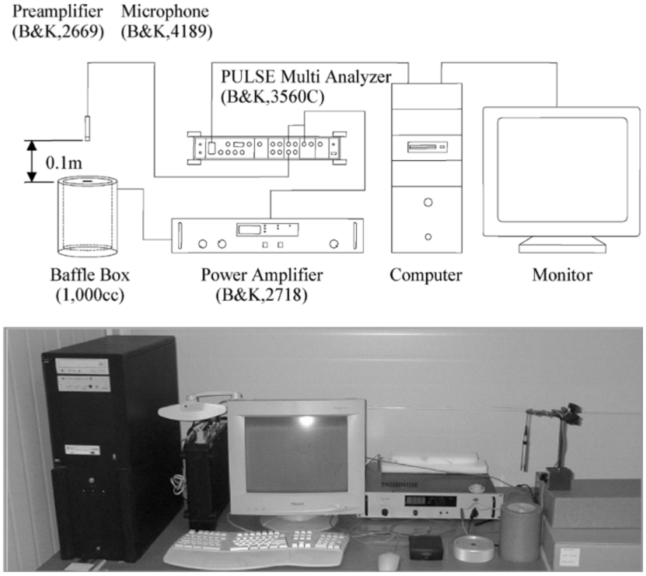

Fig. 2. Schematic of experimental setup.

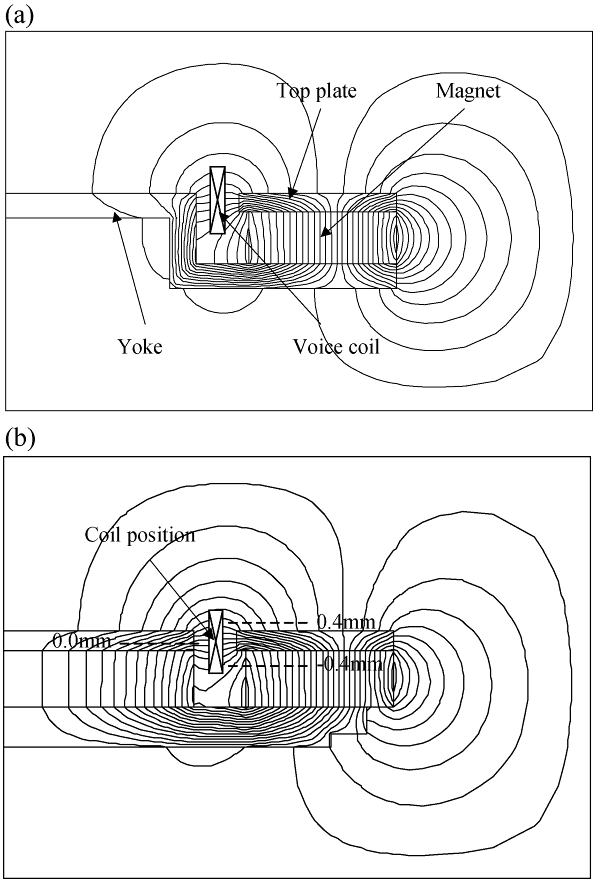

Fig. 3. 2-D FEM model flux line. (a) Outer PM type microspeaker. (b) Combined PM type microspeaker.

III. Results and Discussion

Fig. 3 shows flux line for two types of microspeakers. It shows that the combined types have uniform magnetic field at air gap which is better for harmonic distortion. As voice coil vibrates, magnetic exciting force varies due to uneven magnetic field, which requires coupling analysis. Fig. 4 shows magnetic exciting forces of different w for two types. For $w = 5.1$ mm, $w = 6.3$ mm, and $w = 7.5$ mm, combined PM type shows similar magnetic exciting forces due to similar PM volume. For outer PM type, with the decreased voice coil diameter, magnetic force is increased 20%–40% due to increased PM volume. Noting that the SPL is linearly proportional to the magnetic exciting forces, the SPL can be effectively enhanced by increasing PM volume for the combined PM type.

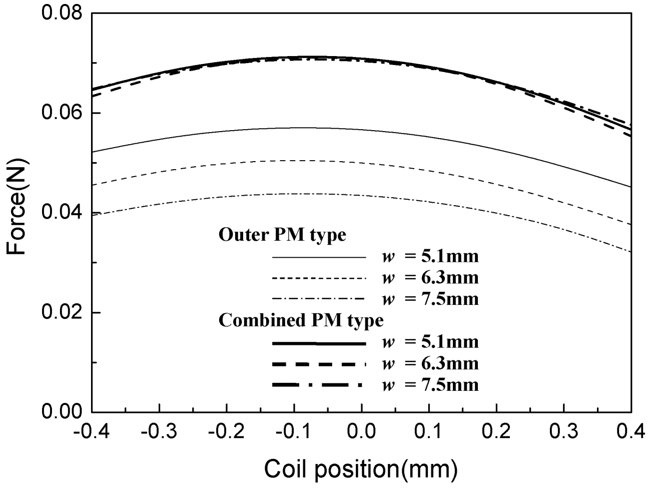

Fig. 4. Axial magnetic forces against w.

TABLE I
RESONANCE FREQUENCIES OF AXIAL MODES

Type	Model No.	First (Hz)	Second (Hz)
Outer PM type	w = 7.5mm	991.78	5826.1
	w = 6.3mm	819.45	8433.4
	w = 5.1mm	645.26	12367.0
Combined PM type	w = 7.5mm	991.78	5826.1
	w = 6.3mm	819.45	8433.4
	w = 5.1mm	645.26	12367.0

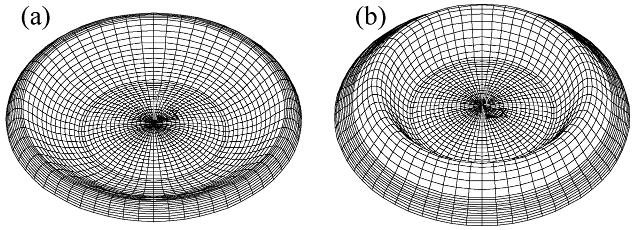

Fig. 5. Vibration axial mode of diaphragm. (a) First mode. (b) Second mode.

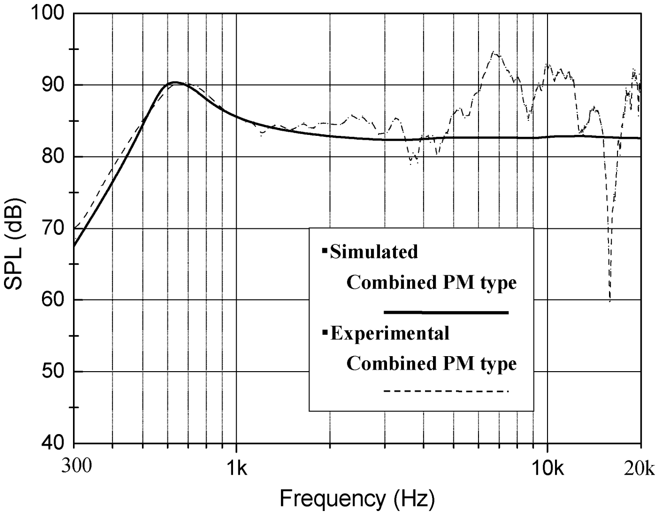

Fig. 6. Sound pressure level of the prototype.

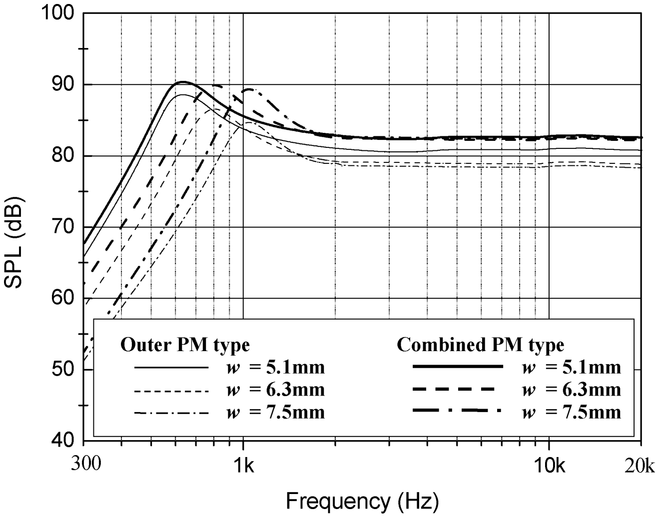

Fig. 7. Sound pressure level of outer PM and combined PM type.

From the modal analysis of diaphragm with the attached voice coil, as in (3) without exciting forces, resonant frequencies and the corresponding mode shapes can be obtained. If the symmetry of the microspeakers is maintained, only the axial modes are to be excited with the proper excitation. However, if there exist any dissymmetry either in diaphragm or in voice coil excitation, the circumferential modes are also excited, degrading the sound quality due to harmonic distortion.

Table I shows resonant frequencies of axial modes for different types and voice coil diameter, w. Fig. 5 shows the first two axial modes for the given microspeaker. The first mode corresponds to the vibration of the side dome and the second mode, the center dome. For $w = 7.5$ mm, it shows higher first resonant frequency and lower second resonant frequency. This can be explained with the excitation position of the voice coil to the diaphragm. With the increased w, the side dome is more difficult to excite resulting in higher first resonant frequency, and the center dome is easier to excite resulting in lower second resonant frequency. The same observation can be also applied for the $w = 5.1$ mm. With the decreased w, the side dome is easier to excite due to concentrative excitation resulting in lower resonant frequency, and the center dome is more difficult to excite due to increased constraints resulting in higher resonant frequency.

Fig. 6 shows the SPL comparison between simulated and experimental results. It can be seen that the analyzed result matches well with the experimental result especially at first resonance frequency. Some discrepancy at higher frequency region results from the complicated acoustic impedance characteristics of surface hole of the microspeaker. Noting that the frequency range of 500 Hz–4 kHz in SPL characteristics is the most important range in mobile phones, the proposed analysis is good enough to predict the performance of the microspeakers. Fig. 7 shows the SPL of both types with respect to the design parameter w. It can be seen that combined PM types show increased SPL due to increased magnet volume. Also, with the decreased w, the first resonant frequency is lowered due to concentration excitation, which gives wider frequency range of sound generation. Figs. 8 and 9 show photographs for both types.

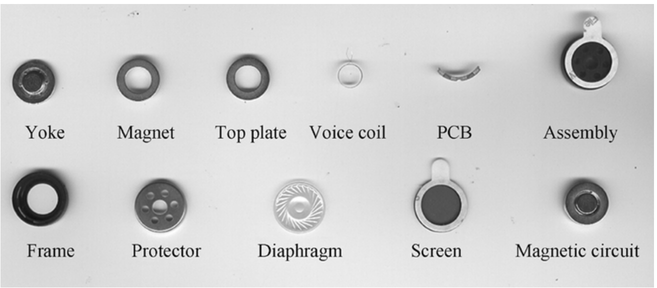

Fig. 8. Photograph of outer PM type microspeaker.

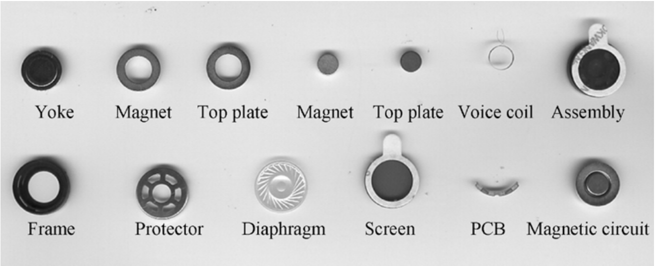

Fig. 9. Photograph of combined PM type microspeaker.

IV. CONCLUSION

To meet the customer demand in multimedia era, microspeakers in mobile phones need to be smaller with better performance, such as higher SPL and broader frequency range. This paper analyzes two types of microspeakers, outer PM and combined PM types, by considering electromagnetic, mechanical, acoustical, and their coupling effects. With the decreased w, voice coil diameter, the combined type shows the increased SPL due to increased PM volume, and the lower first resonant frequency due to concentrative excitation of the voice coil to the diaphragm. Therefore, it can be said that the combined PM type is more advantageous in microspeakers with higher performance and broader frequency range, for multimedia function.

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