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Excitation Experiments of a Cone Loudspeaker and Vibration-Acoustic Analysis Using FEM

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***Abstract*—**To focus on the vibration mode of a cone loudspeaker, which acts as an electroacoustic transducer, excitation experiments were performed using two types of loudspeaker units: one employing an impulse hammer and the other a sweep signal. The on-axis sound pressure frequency properties of the loudspeaker were evaluated, and the characteristic properties of the loudspeakers were successfully determined in both excitation experiments. Moreover, under conditions identical to the experiment conditions, a coupled analysis of the vibration-acoustics of the cone loudspeaker was performed using an acoustic analysis software program that considers the impact of damping caused by air viscosity. The result of sound pressure frequency properties with the numerical analysis are the most closely match that measured in the excitation experiments over a wide range of frequency bands.

***Keywords*—**Anechoic room, finite element method, impulse hammer, loudspeaker, reverberation room, sweep signal.

I. Introduction

CONE dynamic loudspeakers came into use in the 1930s and currently are the most widely used loudspeakers. The vibration analysis of conical loudspeakers was first reported in the 1940s by Brown [1] and Bordoin [2], who studied sound radiation using a loudspeaker cone as a rigid body. However, the rigid body model of a cone is only effective in the case of low-range piston vibration. In 1951, Nimura et al. [3] performed a theoretical analysis of the vibration of a loudspeaker cone. In this study, the eigenvalue of the vibration of a conical cone was calculated by a graphic solution. In 1975, Frankfort [4] obtained a solution to the membrane vibration of a conical cone, established an exact differential equation that considered flexural vibration, and performed detailed calculations of sound pressure frequency properties, vibration patterns, and driving-point admittance. However, Frankfort's analysis did not include calculations of the edge and center cap, which play important roles in conical loudspeakers. In the 1970s and 1980s, several vibration analyses of loudspeaker cones were performed using the finite element method (FEM) [5], [6]. The FEM has also emerged as an important technique for loudspeaker vibration analysis and design. In 2005, Kyouno et al. performed an acoustic radiation analysis of loudspeakers by considering electrical, mechanical, and acoustic coupling problems [7]. The study demonstrated the usefulness of addressing a mechanical system and an acoustic system as a coupled problem. However, excitation experiments of loudspeakers have been rarely conducted, and reports on analyses of vibration-acoustic coupling are also limited. This paper reports the measurement of the vibration mode of the vibration system components of a loudspeaker using excitation experiments performed with an impulse hammer. An excitation experiment using a sweep signal was also performed for comparison. Furthermore, the vibration-acoustic analysis of the cone loudspeaker was performed using an acoustic analysis software program; this program was developed considering the impact of damping caused by air viscosity. Consequently, the vibration and sound pressure frequency properties of the loudspeaker were evaluated.

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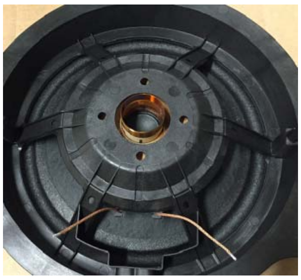

Fig. 1 Loudspeaker only the vibration system

Fig. 2 Loudspeaker

II. Excitation Experiments of Loudspeakers

The excitation experiments were performed using an impulse hammer to eliminate the electrical impact of the loudspeaker, which acts as an electroacoustic transducer, so as to measure only the vibration mode of the vibration system components of the loudspeaker. Fig. 1 shows the loudspeaker used for the experiments. A loudspeaker with a magnetic circuit was also used for comparison, as shown in Fig. 2. The experiments were conducted in a small reverberation room and a small anechoic room. In Fig. 3, the reverberation and anechoic rooms are shown on the left and right sides, respectively. The reverberation room was made anechoic by using glass wool blocks considering the impact of sound reverberation. Fig. 4 shows the dimensions of the reverberation and anechoic rooms. The unit is a millimeter.

Fig. 3 Small reverberation room and small anechoic room

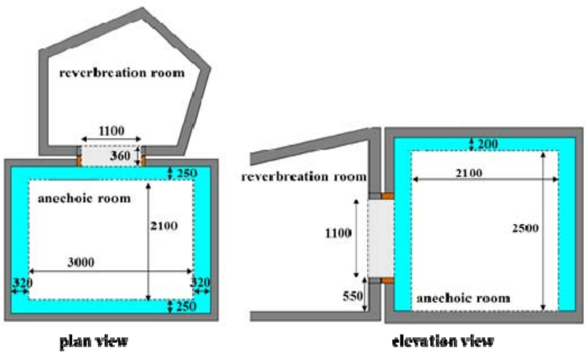

Fig. 4 Dimensions of the reverberation and anechoic rooms

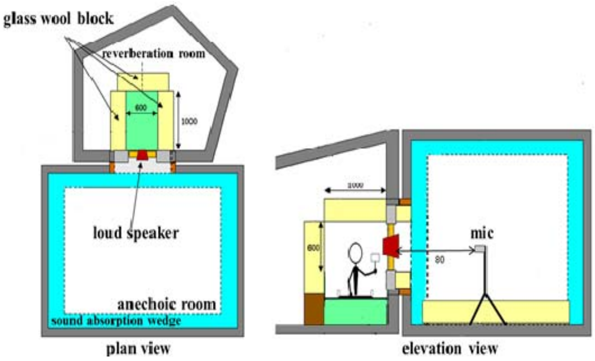

Fig. 5 Schematic of excitation measurement

Fig. 6 Reverberation room and anechoic room

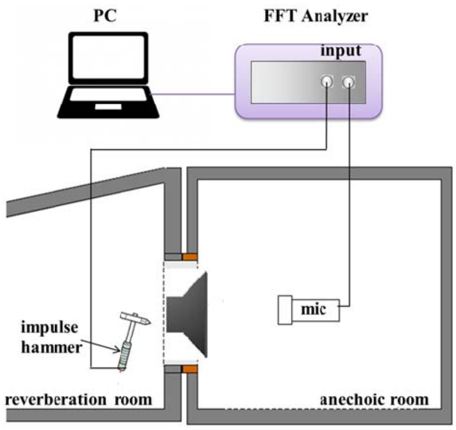

Fig. 7 Measurement system

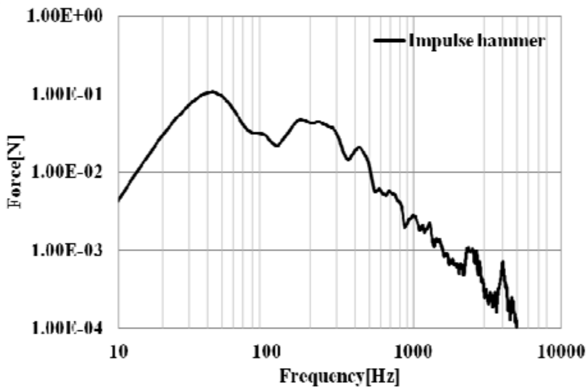

Fig. 8 Exciting force generated by the impulse hammer

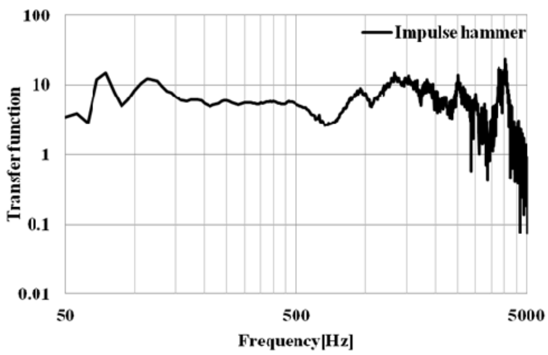

Fig. 9 Measurement result

A. Excitation Experiments Using the Impulse Hammer

To confirm the state of vibration of only the vibration system components of the loudspeaker, an impulse hammer was used in the excitation experiments. The advantages of this method include its ability to instantaneously generate vibrations over a wide frequency band and to prevent the occurrence of leakage errors in the exciting force [8]. The experiments were performed by considering the reverberation room as the excitation side and the anechoic room as the sound receiving side. Fig. 5 shows a schematic of the experiments and Fig. 6 shows the photographs of the actual reverberation and anechoic rooms.

Fig. 7 shows the measurement system, which consists of a Fast Fourier Transform (FFT) analyzer (OR34J-4 4ch multi-JOB), a microphone (Aco Co., Ltd., type 4012, type 7012), and an impulse hammer (Ono Sokki Co., Ltd., GK3100).

An impulse response excited by the impulse hammer was measured repetitively for 10 times. An average of the response was used for frequency analysis.

Fig. 8 shows the exciting force exerted by the impulse hammer. The input force of the impulse hammer decreases in the high frequency range. This may occur because in the high frequency range, the SN ratio becomes low and therefore the exciting force exists instantaneously only once ; only noise is present for a subsequent period, and therefore, the excitation signal energy per frequency becomes extremely low [7]. The results of the transfer function of sound pressure obtained from measurements in the anechoic room are shown in Fig. 9.

B. Excitation Experiment Using the Sweep Signal

An excitation test using a sweep signal was performed with a loudspeaker containing a magnetic circuit for comparison. The measurement system comprised an audio analyzer (Etani Electronics Co., Ltd., ASA-10 Mark II) and a microphone (Aco Co., Ltd., type 4012, type 7012). The tests were performed in the frequency range of 20 Hz – 20 kHz, with an input voltage of 2 volt. The length of sweep signal is 4 seconds.

The experiments were performed in the small reverberation and anechoic rooms. Fig. 10 compares the measurement results of sound pressure frequency properties in the small anechoic room with that in a standard anechoic room, which is considered as a reference. The solid and dotted lines show the results of measurements in the small and standard anechoic rooms, respectively. In the case of the standard anechoic room, the properties of the sound pressure frequency at a point 1 m above the axis of the loudspeaker are shown. According to the results, the sound pressure levels in the small anechoic room are higher in the low frequency range. This may be because the small anechoic room is smaller than the standard anechoic room. The peak near 100 Hz is the lowest resonance frequency of the loudspeaker. Since almost the entire vibration system vibrates in the low to the middle frequency range, the sound pressure levels become almost flat. The dip in the middle range near 1 kHz is thought to be a result of resonance that causes vibrations with a phase opposite to that of vibrations of the diaphragm under the influence of the edge of the diaphragm; this leads to the cancellation of sound from the diaphragm and the edge. At and above 4 kHz, both the measurement results and analysis results show recurrent sharp peaks and dips. This frequency range is considered as the one in which cones usually undergo divided vibrations. The sound pressure levels of the loudspeaker could be confirmed in the small anechoic room similarly as in a standard anechoic room.

Fig. 11 compares the measurement results for the sweep signal and impulse excitation. Even in the impulse excitation case, the characteristics of sound pressure frequency properties were revealed.

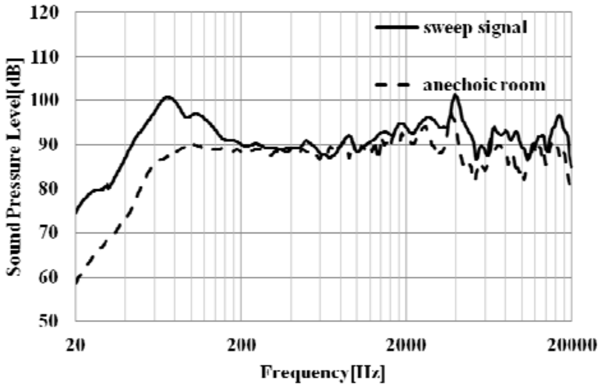

Fig. 10 Comparison of measurements in a small anechoic room and an anechoic room

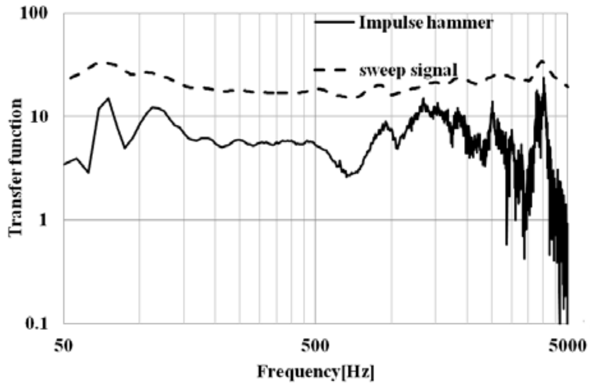

Fig. 11 A comparison of measurement results using the impulse hammer and sweep signal

III. Analysis

The verification of the vibration-acoustic coupled analysis of the loudspeaker was performed under conditions identical to the test conditions. This paper reports the numerical analysis performed using an acoustic analysis software program that was developed by [9].

The structure of the cone loudspeaker is briefly described below. The acoustic radiator of a cone loudspeaker is a diaphragm with a conical shape; therefore, the diaphragm is referred to a cone. This cone is supported by two parts: the cone edge that supports the periphery of the cone and the damper that supports its center. The cover of the center of the cone is called the center cap; in this model, it supports the upper register, known as the sub-cone. A voice coil is placed in the center of the cone to supply electric current. Next is placed a magnetic circuit unit that supplies a magnetic flux to the voice coil. In addition, magnetic circuit is compound of plate, magnet and yoke [10].

The model of the cone loudspeaker used for this analysis is an axially symmetrical loudspeaker with a 160 mm diameter, as shown in Fig. 12. This model is a 1/4 solid model symmetrical about the x-z plane and y-z plane.

When we made this loudspeaker and air models, we used HyperMesh v12.0 at Meshing. The model used 3D tetrahedral elements having four nodes.

Fig. 13 shows the mesh of the analysis model. The air around the voice coil was prepared in detail to make the motions due to air vibrations visible. The acoustic analysis model, shown in Fig. 14, was developed under the same conditions as the test model. The white mesh part represents the air mesh. The gray mesh outside the air mesh corresponds to the sound-absorbing material. The analysis model consists of 863,209 elements and 160,462 nodes. The driver point is denoted as an external force F (constant) along the z-axis around the center of the external periphery of the voice coil.

The boundary conditions were set as 3-degrees of freedom on the x, y, and z axes of the nodes on the bottom edge of the frame and outside the air. On the y-z and x-z planes, the displacement of nodes was fixed in the x-axis and y-axis directions, respectively. Furthermore, for the air in front of and behind the baffle plate of the loudspeaker, the displacement of the nodes was fixed in the z-axis direction.

Table I shows the parameters of the materials used to make the loudspeaker components. For the cone and edge, values were measured by the tensile test and the vibrating reed methods. The viscosity coefficient of air is 1.82E-05 pa/s.

The displacement and pressure distribution were analyzed in the frequency range from 50 Hz to 5 kHz at 10 Hz intervals. Fig. 15 shows the vibration mode of the loudspeaker. The red region represents parts with a large displacement, while the blue region represents parts with a small displacement. At low frequencies, the vibration system of the cone loudspeaker vibrated as a whole, and its movement was confirmed. The vibration mode of the air was determined and the movement caused by the vibration of air even in the gap around the voice coil was confirmed. In the z-axis direction of the anechoic room, the presence of a spherical wave form in free space was also confirmed.

TABLE I
MATERIAL AND GEOMETRIC PARAMETERS

Parts	Mass Density (kg/mm^3)	Young's Modulus (N/mm^2)	Poisson's Ratio
Cone	3.1E-07	1.164E+03	0.3
Edge	8E-07	1.390E+02	0.3
Spider	6.06E-07	8.900E+01	0.3
Whizzer Cone	5.74E-07	2.000E+03	0.3
Voice Coil	1.87E-06	3.900E+03	0.3
Magnet	4.8E-06	1.177E+05	0.3
Plate	7.69E-06	2.000E+05	0.3
Yoke	7.94E-06	2.000E+05	0.3
Frame	9.1E-07	1.660E+03	0.3
Air	1.21E-09	1.403E-01	—

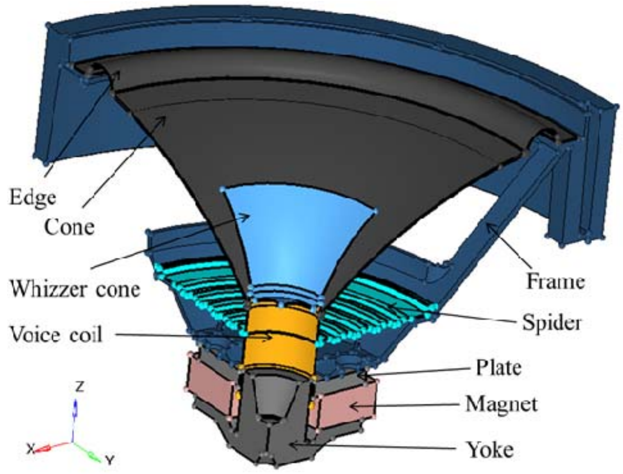

Fig. 12 1/4 solid model of a loudspeaker

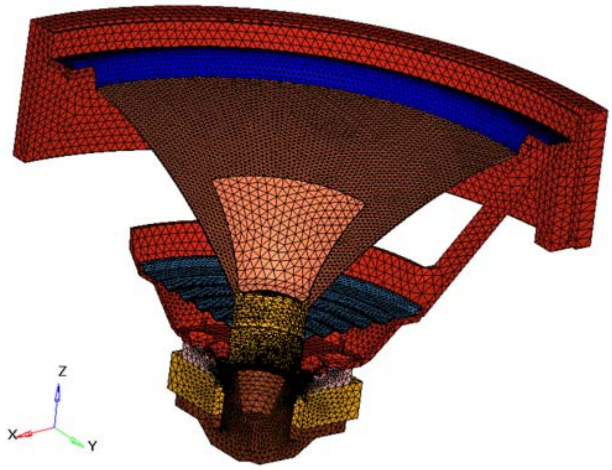

Fig. 13 Loudspeaker mesh

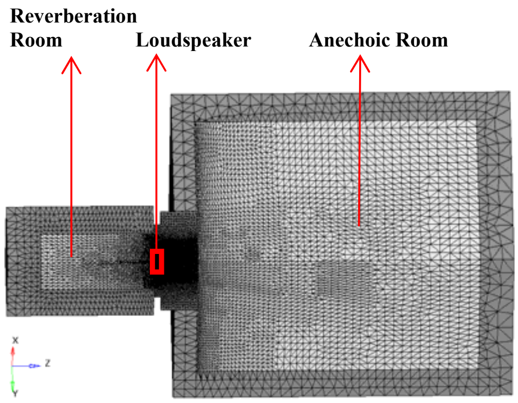

Fig. 14 Analytical model

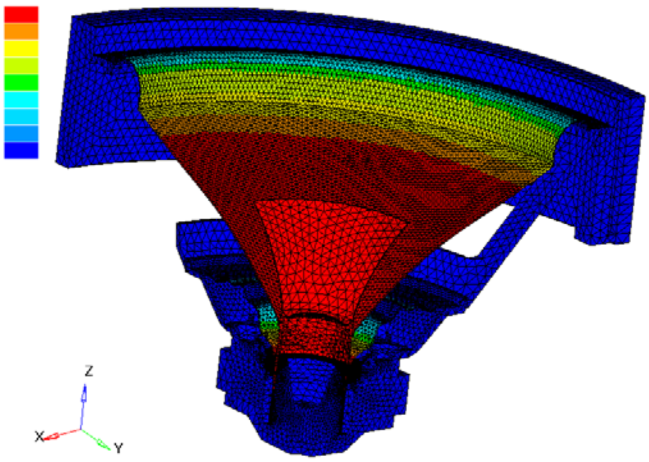

Fig. 15 Point displacement distribution of a loudspeaker panel

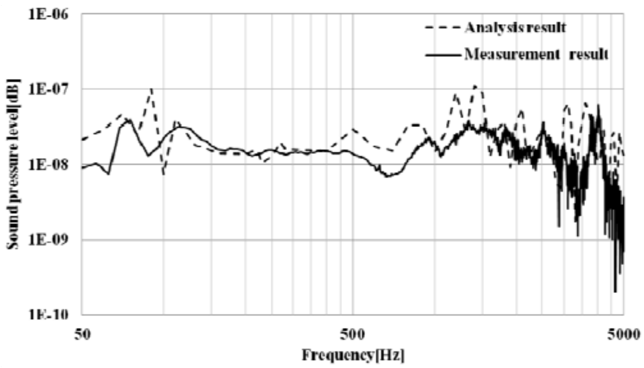

Fig. 16 Measurement result based on impulse hammer and analysis result

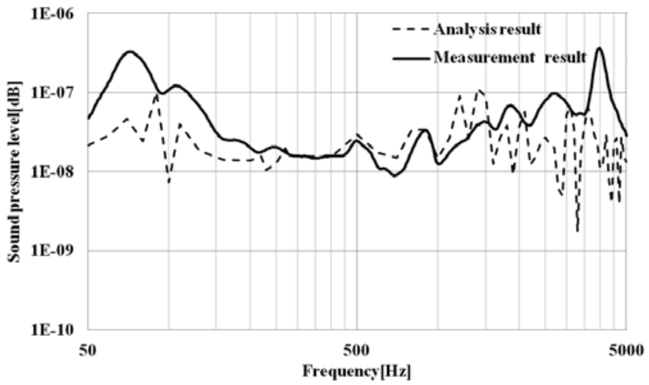

Fig. 17 Measurement result based on sweep signal and analysis result

IV. Comparison of Measurement Results and Numerical Calculations

The experiment measurement results were compared with the analysis results based on the FEM. Fig. 16 shows a comparison of the results of the impulse hammer excitation and the analysis results for the sound pressure frequency properties in the axial direction of the loudspeaker. Fig. 17 compares the results of the sweep signal excitation with the analysis results. The solid and dotted represent the measurement and analysis results, respectively. In Figs. 16 and 17, the results are based on the sound pressure levels at 500Hz. The comparison of the on-axis sound pressure frequency revealed that for frequencies above 100 Hz, the sound pressure frequency properties tended to conform closely. In particular, from 100 Hz to 1 kHz, the frequencies of troughs or peaks of the properties are consistent. The dip in the middle frequency region near 1 kHz can be affected by edge around the diaphragm. From 4 kHz onwards, recurrent troughs and peaks with sharp features were observed in both measurement and analysis results. This frequency range is considered to be the one in which the cone undergoes divided vibration. Further, this discrepancy may occur because the loudspeaker that was computed is a 1/4 solid model, whereas an actual loudspeaker is not necessarily axially symmetrical. This shows that the results of the vibration-acoustic analysis of a loudspeaker cone using the FEM agreed well with the measurement results. This confirms the applicability of the FEM to vibration-acoustic analysis of loudspeakers.

In the future, it will be possible to study properties by analyzing models of loudspeakers, which are difficult to realize in practice. This will save measured time and reduce costs.

V. Summary

To focus on the vibration mode of a conical loudspeaker, which acts as an electromechanical acoustic transducer, excitation tests were performed using two types of loudspeaker units: one using an impact hammer and the other a sweep signal. The on-axis sound pressure frequency properties of the loudspeaker were evaluated, and both excitation experiments successfully measured the characteristic properties of the loudspeaker.

An acoustic analysis software program developed by the authors was used to perform the vibration-acoustic coupling analysis of the model with consider the vibration components of the loudspeakers: the cone, edges, voice coil, damper, and sub-cone.

The results of the excitation experiments of the loudspeakers were compared with the analysis results, and they were found to be consistent. This confirms the applicability of the analysis method based on the FEM to the design and development of loudspeakers.

In the future, we wish to improve the precision of analysis in comparison with the vibration-acoustic mode of an actual cone loudspeaker. Further, we will also vary the shape of the cone and the physical properties of its materials to achieve an optimized design that realizes the flat sound pressure properties.

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