A New Method for Measuring the Distortions of Electrodynamic Loudspeaker at Low Frequencies Part 1 : Closed-Box Loudspeaker

스피커 저주파대역 왜곡측정의 새로운 기법 제 1 부 : 밀폐형 스피커

Sejin Doo*, Koengmo Sung*
두 세 진*, 성 굉 모*

ABSTRACT

A method for measuring the loudspeaker distortions at low frequencies without an anechoic chamber is proposed. This method is based on the fact that the n-th harmonic distortion outside the enclosure is boosted by $40\log n$ dB compared to that inside the enclosure. The applicable frequency range is extended by cancelling the effect of stand ing wave inside the enclosure. Causes of measurement error are also analyzed.

요 약

저주파 대역에서의 스피커 왜곡을 무향실 없이 측정할 수 있는 방법을 제안한다. 이 방법은 제 n고조파의 경우 밀폐형 스피커 내부에 비해 외부에서 $40\log n$ dB 증폭된다는 사실에 기초를 두고 있다. 인클로저 내부의 정재파에 의한 영향을 상쇄함으로써 측정가능한 주파수 대역을 넓혔으며 측정오차의 원인을 분석하였다.
가 있다.

I. Introduction

For the objective assessment of a loudspeaker, it is customary to measure the frequency response and the distortions in an anechoic chamber. Anechoic chamber almost satisfies free field condition but it costs very much money to build it. In fact, the anechoic chamber has limitation in satisfying free field condition below the lower cutoff frequency. Even if the anechoic chamber is not available, frequency response of the loudspeaker can be measured using, for example, the impulse technique[1] or the cepstrum technique [2] if only high frequency range is of interest. In case of the distortion, however, there is no way of measurement but for an anechoic chamber.

R. H. Small[3] has devised a method to measure the frequency response of the loudspeaker by measuring the internal pressure of the enclosure. This method is useful for it is not necessary

* Applied Electronics Lab., Department of Electronics Eng., Seoul National University
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to measure in an anechoic chamber. However, the effect of standing wave inside the enclosure was not considered. To deal with this problem, there have been tries to find an optimum measuring position where the effect of standing wave is minimum, so that the frequency range applicable was as low as 200Hz. Moreover, for distortion analysis, there was little study except the measurement of total harmonic distortion using analog circuitry.

In this paper, a method is proposed by which the distortions of the loudspeaker can be measured without an anechoic chamber. The relation between the distortion level inside the enclosure and the distortion level outside the enclosure is first described. Although the standing wave inside the enlosure causes fluctuation in the frequency response and the distortions, the effect of standing wave could be cancelled and this procedure extended the applicable frequency range.

II. Relation of the distortions between inside and outside the enclosure

For adiabatic process, the volume and the pressure within an enclosure obey the relation[4]

$$(p_0+p_{in})(V_0+\Delta V)^{\gamma}=p_0V_0^{\gamma}, \quad (1)$$

where γ is the specific heat ratio of air, V_0 and p_0 are the undisturbed volume and static pressure respectively, and p_{in} and ΔV are the incremental pressure and volume inside the enclosure, respectively.

Applying the relation $\Delta V=Sx$, where S is the effective diaphragm area of a loudspeaker and x is the displacement of the diaphragm, and rewriting eq.(1) with respect to x, eq.(2) relating the pressure p_{in} inside the enclosure and the displacemant of the diaphragm x is obtained :

$$x=\frac{V_0}{S}\left[\left(1+\frac{p_{in}}{p_0}\right)^{-\frac{1}{\gamma}}-1\right]$$
$$\cong-\frac{V_0}{S\gamma p_0}\left(p_{in}-\frac{\gamma+1}{2\gamma p_0}p_{in}^2\right) \quad (2)$$

The 2nd term of the right side of eq.(2) is the distortion of the medium itself. This distortion may be easily calculated if we measure the SPL inside the enclosure. That is, the level of air distortion is (2 × SPL-195) dB relative to 20 μPa. For example, if SPL inside is 140dB, the level of air distortion is 85 dB. As long as this air distortion is much smaller than the distortion of a loudspeaker system, we can neglect the air distortion and consider the air as a linear medium[5]. Then x may be considered to be proportional to p_{in}, i.e.,

$$x\cong-\frac{V_0}{S\gamma p_0}\,p_{in}\,. \quad (3)$$

For a baffled piston vibrating with angular frequency ω and displacement x, far field sound pressure $p_{out}(r,\theta)$ as in [6]

$$p_{out}(r,\theta)=-\frac{\rho_0 S}{2\pi r}\,\omega^2 x\left[\frac{2J_1(ka\sin\theta)}{ka\sin\theta}\right]e^{j(\omega t-kr)}, \quad (4)$$

where r and θ are the distance and the angle to the measuring position respectively, k wave number, a the radius of the piston, and $J_1(\cdot)$ the Bessel function of the first kind of order 1. The bracketted term determines the directional characteristics of the baffled piston.

If x is not pure sinusoidal but distorted to produce the harmonics, x can be denoted as

$$x=\sum_{n=1} x_n$$
$$=\sum_{n=1}\hat{x}_n\cos(n\omega t+\phi_n), \quad (5)$$

where n is harmonic number, ϕ_n the phase of the n-th harmonic component x_n, $\hat{x}_n$ amplitude of x_n, respectively. In this case, sound pressure outside the enclosure is found to be

$$p_{out}(r,\theta) = -\frac{\rho_0 S}{2\pi r}\sum_{n=1}(n\omega)^2 x_n \cdot \left[\frac{2J_1(nka\sin\theta)}{nka\sin\theta}\right] e^{j(n\omega t - nkr + \phi_n)}$$

$$= -\frac{\rho_0 S\omega^2}{2\pi r}\sum_{n=1} n^2 x_n \cdot \left[\frac{2J_1(nka\sin\theta)}{nka\sin\theta}\right] e^{j(n\omega t - nkr + \phi_n)} \qquad (6)$$

If the sound pressure is measured along the aris $\theta = 0$, eq.(6) is simplified as

$$p_{out}(r,0) = -\frac{\rho_0 S\omega^2}{2\pi r}\sum_{n=1} n^2 x_n e^{j(n\omega t - nkr + \phi_n)} \ . \qquad (7)$$

Substituting eq.(3) to eq.(7) the n-th harmonic component outside the enclosure, $p_{out,\,n}$, is related to the n-th harmonic component inside the enclosure $p_{in,\,n}$ as

$$|p_{out,\,n}| = \frac{\rho_0 V_0\omega^2}{2\pi\gamma p_0 r}\ n^2\ |p_{in,\,n}| \ . \qquad (8)$$

The sound pressure level outside is thus related to the sound pressure level inside the enclosure as follows :

$$SPL_{out,\,n} = SPL_{in,\,n} + 40\log\omega + 40\log n + C \ , \qquad (9)$$

where $C = 20\log(\rho_0 V_0 / 2\pi\gamma p_0 r)$. Eq.(9) reveals that the n-th distortion outside the enclosure is 'boosted' by $40\log n$ dB compared to that inside. For example, the 2nd distortion is boosted by 12 dB and the 3rd distortion is boosted by 19 dB outside the enclosure, respectively.

Eq.(4) is also used in predicting the intermodulation distortion outside the enclosure. That is, if ω_{IM} is the intermodulation angular frequency of interest, the on-axis pressure relation of the intermodulation distortions between inside and outside the enclosure is as follows :

$$p_{out,\,IM} = -\frac{\rho_0 S}{2\pi r}\ \omega_{IM}^2 x_{IM} e^{j(\omega_{IM} t - k_{IM} r)} \ , \qquad (10)$$

where x_{IM} is the intermodulated component of displacement vibrating with angular frequency ω_{IM}. Applying eq.(3) to eq.(10) and denoting the relation of the pressure of intermodulation distortions between inside and outside the enclosure, their relation is described as follows :

$$SPL_{out,\,IM} = SPL_{in,\,IM} + 40\log\omega_{IM} + C. \qquad (11)$$

Ⅲ. Standing wave inside the enclosure

If the vibrating frequency of the loudspeaker diaphragm is so high that the wavelength is comparable or shorter than the dimension of the enclosure, standing wave builds up inside the enclosure. The spatial pressure distribution is determined by

1) the inner dimension and shape of the enclosure,
2) the treatment of the damping material,
3) the vibrating frequency of the diaphragm, and
4) the velocity distribution.

For a specific loudspeaker enlosure, 1) and 2) are fixed and only 3) and 4) determines the spatial pressure distribution. Furthermore, if the diaphragm vibrates as a rigid body, i.e., if it does not break up, the velocity distribution is uniform over the diaphragm. In this case, the spatial pressure distribution inside the enclosure is solely determined by the vibrating frequency of the diaphragm.

If the displacement of the diaphragm is distorted, the vibrating frequency contains the higher harmonics as well as the fundamental and each of them can be considered as independent source. The fundamental component with frequency f and the n-th harmonic component whose fundamental frequency is f/n will give rise to an identical spatial pressure distribution since they are of the same frequency f. In this case, we can use the curve of standing wave of the fundamental to cancel out the effect of standing wave of the distortions. The procedure is as follows :

1) First, we measure the frequency response $H(f)$ inside the enclosure. $H(f)$ contains the effect of standing waves.
2) The theoretical frequency response $H_{th}(f)$ inside the enclosure is calculated. $H_{th}(f)$ can be simply calculated by measuring the resonance frequency f_0 and the Q-factor of the loudspeaker[5].
3) The difference between $H(f)$ and $H_{th}(f)$ is due to standing wave. Let this be $R(f)$. That is, $R(f)=H(f)-H_{th}(f)$ in dB scale.
4) We measure the n-th harmonic distortion $D_n(f)$. As in the case of $H(f)$, $D_n(f)$ contains the effect of standing wave $R(f)$.
5) Since it is necessary to exclude the effect of standing wave to measure the distortions, $R(f)$ should be excluded from $D_n(f)$. Therefore, $D_n(f)-R(f)$ results in the correct measurement of the n-th harmonic distortion(In practice, the graph of the distortion is plotted along the fundamental frequency scale, e.g., $D_n(f)$ is plotted as $D_n(f/n)$. Therefore, $R(f)$ should also be rescaled as $R(f/n)$ and $D_n(f/n)-R(f/n)$ is the prediction of the distortion.).

This process makes it possible to measure the distortions of the loudspeaker without an anechoic chamber.

However, if the diaphragm does not move in-phase, that is, the diaphragm breaks up, or if the amplitude of vibration is not the same everywhere at the diaphragm, which occure near the first break-up frequency, the relations of eqs.(9) and (11) do not hold and the measurement will be incorrect. The proposed method is thus valid only at low frequency range below the first break-up frequency where the diaphragm is assumed to move as a rigid piston.

Ⅳ. Experimental result

Sound pressure inside the enclosure is measured with the experimental set-up shown in Fig.1. The outer dimension of the loudspeaker is 16.9×21.1×35.7cm and the diaphragm diameter is 10 cm. The thickness of the enclosure panel is 9mm. A condenser microphone B&K 4133 is placed inside the closed-box loudspeaker enclosure. A $4V_{rms}$ sweep signal is applied to the loudspeaker from 20 Hz to 1kHz, which is much lower than the first break-up resonance frequency. The calculated first break-up frequency is closed to about 12kHz for the loudspeaker under test[7].

Fig.2 shows the sound pressure levels of fundamental, 2nd harmonic, and 3rd hamonic components

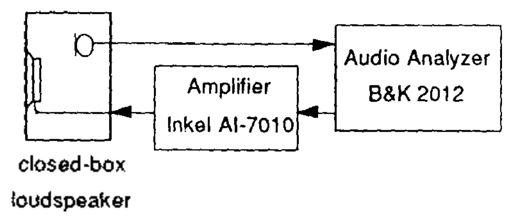

Fig.1. Experimental set-up for measuring the sound pressure level inside the loudspeaker enclosure.

measured inside the enclosure, and the air distortion level, respectively. At the low frequency range below about 300Hz, the fundamental component in Fig.2 can be considered to represent the curve of the displacement of the diaphragm since eq.(3) holds and the fundamental is dominant in total pressure. There exist fluctuations over 300Hz of the fundamental. If there would be no standing wave inside the enclosure, the slope of the fundamental above the loudspeaker resonance frequency would be −40 dB/decade[8]. One thing to note is that the fluctuations also appear in the 2nd and 3rd harmonics and they have similarity with each other. The difference $R(f)$ between the fundamental in Fig.2 and the theoretically calculated one is shown in Fig.3, which results from the standing wave inside the enclosure.

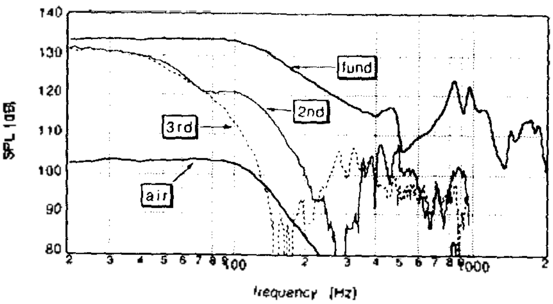

Fig.2. Sound pressure levels of the fundamental, 2nd harmonic components, 3rd harmonic, and air distortion measured inside the loudspeaker. The 2nd, 3rd harmonic and air distortion level are raised up by 30dB for graphical presentation.

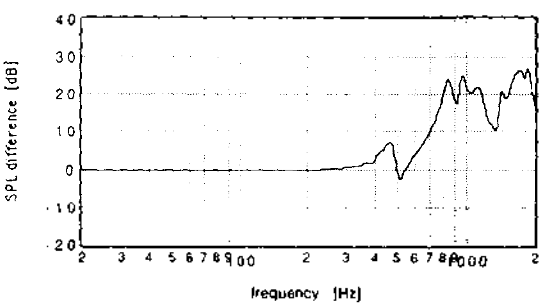

Fig.3. Difference R(f) between the measured component and the calculated sound pressure of the fundamental frequency component.

The relation given in eq.(9) allows us to estimate the sound pressure level outside the loudspeaker enclosure from the measured data of Fig. 2. In order to obtain the correct prediction of the distortions, the effect of standing wave should be cancelled out. To do this, the frequency axis of R(f) is rescaled as R(f/2) for the 2nd distortion and as R(f/3) for the 3rd distortion and then they are subtracted from the 2nd and 3rd harmonic distortions shown in Fig.4 respectively.

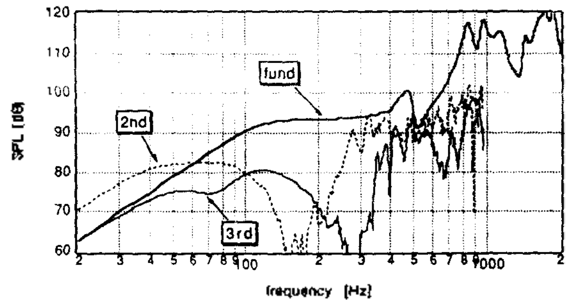

Fig.4. Fundamental, 2nd, and 3rd harmonic distortions containing the effect of standing wave (2nd and 3rd harmonic raised up by 20dB).

This process corresponds to the cancellation of the effect of standing wave.

In Fig.5, the 2nd harmonic distortion estimated by the proposed method is compared with the 2nd harmonic distortion measured in the anechoic chamber. We can see fairly good agreement between them. Except several frequency ranges, for example, between 250Hz and 400Hz, the deviation is within ±2dB.

In Fig.6, the estimation result of the 3rd harmonic distortion is shown. The curves obtained by the proposed method and by the anechoic chamber method do not well agree as in the case of the 2nd harmonic distortion. While, below 100 Hz, the proposed method shows very good agreement with the anechoic chamber method, the de-

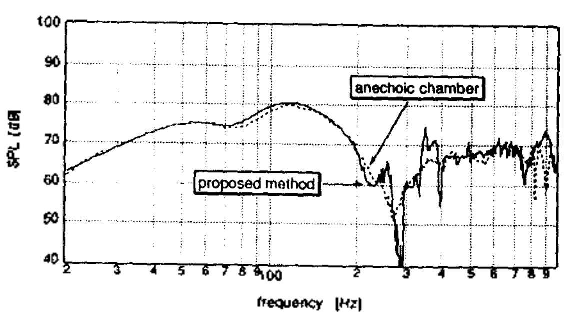

Fig.5. Comparison of the proposed method and the anechoic chamber method for the 2nd harmonic distortion.

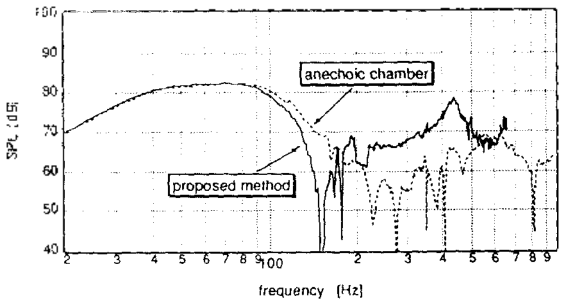

Fig.6. Comparison of the proposed method and the anechoic chamber method for the 3rd harmonic distortion.

viation between the two methods is as high as ± 10dB at some frequencies above 100Hz.

The causes of discrepancy arise mainly from the air distortion[5] and the enclosure vibration [9]. The amount of air distortion depends on the pressure level. If the level of the air distortion exceeds the level of the diaphragm distortion, the diaphragm distortion may not be measured correctly. The level of air distortion is (2×SPL−195) dB and if this exceeds the levels of the 2nd and 3rd harmonic distortions shown in Fig.2, a correct prediction is not expected. In the case of the 2nd harmonic component, the diaphragm distortion level is below the air distortion level in 270Hz to 300Hz and in the case of the 3rd harmonic component, 130Hz to 190Hz. Therefore, in these frequency ranges respectively, the two methods show large discrepancy.

In order to analyze the effect of enclosure vibration, the accelerations at the front panel where the driver is attached and at the side panel are measured respectively. The fundamental component of the acceleration is shown in Fig.7. As expected, it is seen that the vibration of the enclosure corrupts the frequency response. The effect of the panel vibration is shown to be made on the distortions as well. In Fig.8, the 2nd harmonic distortion of panel acceleration is overlaid on the 2nd harmonic distortion of the loudspeaker measured with the proposed method. We note that the corruption of the 2nd harmonic distortion is more severe than that of the fundamental. And it is found that the 2nd harmonic distortion of the panel is higher between 250Hz and 400Hz, which may indicate that the discrepancy in that range of Fig.5 is mainly due to panel vibration.

The 3rd harmonic distortion of the panel is far more severe than the fundamental or the 2nd harmonic distortion, as shown in Fig.9. It is worth noting the relation between the high level of the 3rd distortion of panel acceleration between 100 Hz and 500Hz and the large discrepancy in Fig.6 in that range. From this, it may be deduced that the discrepancy is due to the panel vibration. For more precise agreement with the anechoic chamber method, it is necessary to fix the loudspeaker driver to a more rigid enclosure.

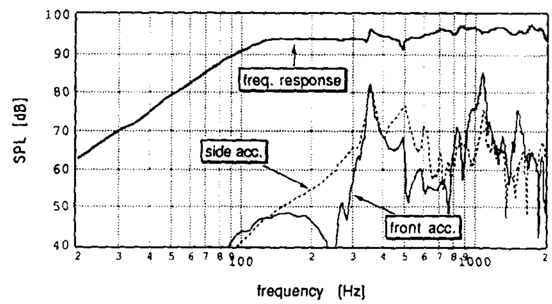

Fig.7. Frequency response affected by the vibration of the enclosure. Accelerations are in arbitrary reference.

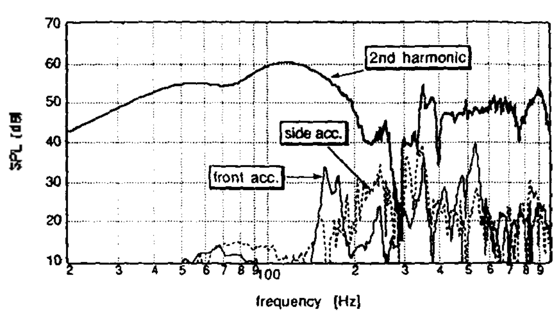

Fig.8. 2nd harmonic distortion affected by the vibration of the enclosure.

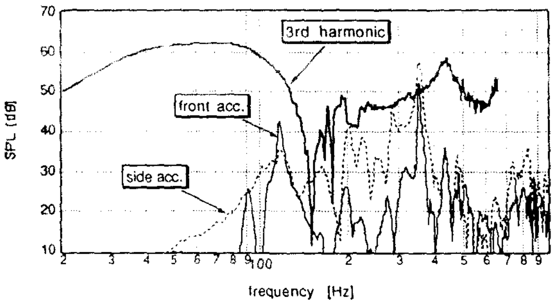

Fig.9. 3rd harmonic distortion affected by the vibration of the enclosure.

V. Conclusion

A method to measure the distortions of the closed-box loudspeaker without an anechoic chamber is proposed. This method is based on the fact that the n-th harmonic distortion is boosted by $40\log n$ dB outside the enclosure compared to that of inside the enclosure. Using the fact that the frequency dependence of the standing wave is the same in both the fundamental and the harmonic components, the effect of standing wave is successfully cancelled out. This enables the correct measurement of harmonic distortions without anyaid of the expensive facility of the anechoic chamber.

Experimental results show fairly good agreement between the proposed method and the anechoic chamber method. It may be concluded that the enclosure should be rigid enough not to cause great errors in measurement.

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▲Sejin Doo

Sejin Doo was born in Gunsan, Korea on Aug.17, 1960. He received the B.S., M.S., and Ph.D. degrees in electronics engineering from Seoul National University in 1983, 1987, and 1994 respectively. He was a research engineer of Samsung electronics company from 1983 to 1984. He is currently a senior engineer in Korea Automotive technology Institute. His research interests include electro-acoustics and musical acoustics.

▲Koengmo Sung

Koengmo Sung was born in Inchon on Feb.1, 1947. He received the Dipl.-Ing. degree in communication engineering in 1977 and the Dr.-Ing. degree in acoustics in 1982 from Technische Hochschule Aachen, Germany. He was a research engineer at the Institute of Applied Acoustics in RWTH Aachen, from 1977 to 1983. Since 1983 he has been with the Department of Electronics Engineering at Seoul National University, where he is currently a professor. He is also the vice-president of the Acoustical Society of Korea. His research interests are electroacoustics, musical acoustics, and ultrasonics.