25th International Congress on Sound and Vibration
8-12 July 2018 HIROSHIMA CALLING
ICSV25

EQUIVALENT-STRUCTURE ANALYSIS OF THE COMPRESSION DRIVER'S FRONT PART

Fang Houlin, Zhang Liangyong, Cheng Zhang, Liu Yang, Zhang Fang and Sun Deyu
Northwest Institute of Nuclear Technology, Xi'an, China
email: fanghoulin@nint.ac.cn

Equivalent circuit method is a common method of analyzing electro-acoustical transducers, which was used to investigate compression drivers. To get accurate results by Equivalent circuit method, some varied equivalent structures were proposed and structural differences were compared. Firstly, the equivalent circuits of equivalent structures were analyzed and key parameters were obtained. The formulas of acoustical parameters and conical horn's throat impedance were derived from the equivalent circuits. Moreover, programs were made to analyze sound pressure level frequency responses of different equivalent structures. Lastly, the verification experiments were carried out to testify the analysis results. The results show that the equivalent circuit method can be well applied within 1600 Hz and the results by the equivalent circuit method will be smaller beyond 1600 Hz. The difference between experimental and theoretical results increases with frequencies. Radiation characteristics of compression driver are not sensitive to microstructures in low frequency band, but the effects of microstructures are obvious in a specific or higher frequency band.
Keywords: compression driver, equivalent circuit, acoustic impedance, conical horn

1. Introduction

For the need of high performance loudspeaker, compression driver is developed, which is applied to high-intensity sound generator that plays an important role on acoustical denial and long range conversation.

The transition from loudspeaker to compression driver could be seen in the patents of 1970s and 1980s. Svetlomir Alexandrov[1] proposed a compression driver using V-shaped annular diaphragm which provides higher effective surface area and smaller mass. Eugene J. Czerwinski[2] researched the structure of diaphragm and its support portions to improve the performance of compression driver. Later, O'NEILL, Bernard M. Werner, etc.[3,4] all proposed different structures of compression driver. Hu[5] invented a new high frequency compression drvier with rectangle diaphragm for radiating appoximate linear sound wave. Alexander Voishvillo[6,7] invented compression driver with a plurality of entrances and exits, and dual diaphragms, which can prevents undesired attenuation of high-frequency acoustic signals and may result in delivering sound energy in phase from all parts of the diaphragm. Besides, there are many patents about compounded compression drivers and parts of compression driver. Finite element analysis of compression driver related to modeling of compounded structures, combination of multi methods, multi physical field coupling, etc[8-10]. In aspect of design of compression driver, Dodd Mark[11] presented new methodology for the acoustic design of compression driver phase plugs with concentric annular channels. Francesco Piazza[12] showed heuristic optimization of compression driver design. Moreover, many works were done about measurement and assessment, especially the study of harmonic and nonlinear problems. Early work describes equivalent circuit analysis of compression driver[13], further study about interaction radiation of array was done by Zhang[14].

In this paper we analyse radiation charactericstics of compression driver with different equivalent structures of front part, and derivate the expression of sound pressure level(SPL) and acoustic impedance of conical horn throat which are proved by experiment.

2. Equivalent-structure of compression driver's front part

Compression driver consists of magnetic system, diaphragm, voice coil, channels, phase plug and cacities, which is more complicated than traditional electroacoustic transducer, especially the structure in front of diaphragm increase and opposite diaphragm application, so it's necessary to simplify structure. Fig. 1 shows a simplified schematic of early work[13], in which front part is equivalent to a cavity neglecting too many detail features to get a good result at high frequency. So two new equivalent structures of front part are proposed in fig. 2. In fig. 2(a) front part is equivalent to one cavity and one conical horn, or one conical tube(change rule of cross section radius is contrary to conical hron) and one conical horn or two horns(closer to real structrue) in fig. 2(b).

Compression driver's lumped parameters: M_m is vibration mass of diaphragm. C_m is mechanical compliance of vibration system. R_m is mechanical damping of vibration. S is radiation area. V_1 is volume of cavity in front of diaphragm, C_{a1} is corresponding acoutic compliance. V_2 is volume of cavity behind of diaphragm, C_{a2} is corresponding acoutic compliance. V_3 is volume of cavity in front of channels, C_{a3} is corresponding acoutic compliance. M_{a1} is acoustic mass of channels, R_{a1} is acoustic resistance of channels, S_{a1} is effective area; Z_{a0} is acoustic impedance of front part(radiation acouctic impedance or acoustic impedance of horn throat or acoustic impedance of conical tube's port). U is volume velocity, equating to vS, where v is vibration velocity of diaphragm.

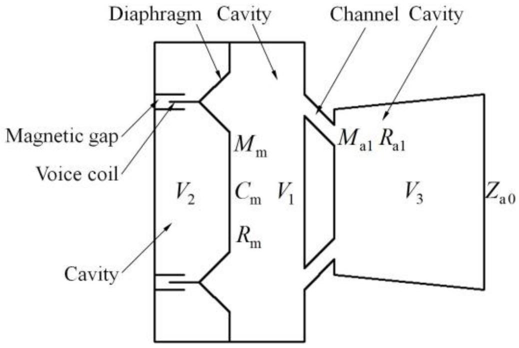
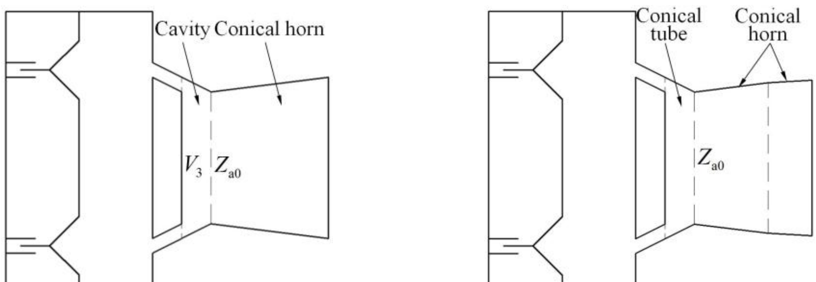


Figure 1: Simplified schematic of compression driver.



(a)Cavity and one conical horn (b)Conical tube and two conical horns

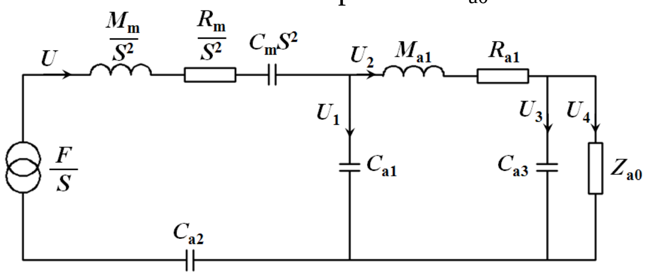
Figure 2: Different equivalent structures of front part.

3. Analysis of equivalent circuit

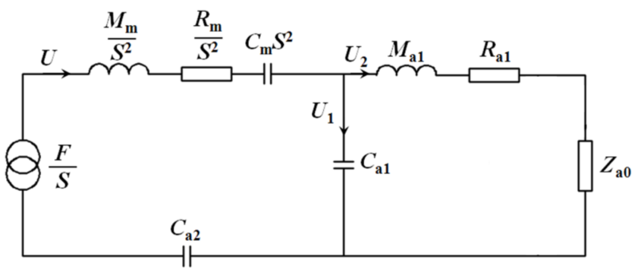
The electrical impedance of compression driver are obtained through equivalent circuit of simplified structure and transform among electrical, mechanical and acoustical circuit, radiation characteristics such as sound power, sound pressure and SPL are gained from further study.

3.1 Equivalent circuits of different equivalent structures

Based on early work[13], we get acoustical equivalent circuits of different structures shown in fig. 3. The difference between circuits shown in fig. 3(a) and fig. 3(b) is acoustic compliance C_{a3}, the difference leads to the difference of acoustic impedance Z_{a0}.



(a) Equivalent circuit of front part including cavity



(b) Equivalent circuit of front part without cavity

Figure 3: Acoustical equivalent circuits of different equivalent structures of front part.

Expressions of mechanical impedance of different equivalent circuits can be written as

$$Z_{\mathrm{m}} = \mathrm{j}\omega M_{\mathrm{m}} + R_{\mathrm{m}} + \frac{1}{\mathrm{j}\omega C_{\mathrm{m}}} + \frac{S^2}{\mathrm{j}\omega C_{\mathrm{a}2}} + \cfrac{1}{\cfrac{\mathrm{j}\omega C_{\mathrm{a}1}}{S^2} + \cfrac{1}{\mathrm{j}\omega M_{\mathrm{a}1} S^2 + R_{\mathrm{a}1} S^2 + \cfrac{1}{\cfrac{1}{Z_{\mathrm{a}0} S^2} + \cfrac{\mathrm{j}\omega C_{\mathrm{a}3}}{S^2}}}} . \tag{1}$$

$$Z_{\mathrm{m}} = \mathrm{j}\omega M_{\mathrm{m}} + R_{\mathrm{m}} + \frac{1}{\mathrm{j}\omega C_{\mathrm{m}}} + \frac{S^2}{\mathrm{j}\omega C_{\mathrm{a}2}} + \cfrac{1}{\cfrac{\mathrm{j}\omega C_{\mathrm{a}1}}{S^2} + \cfrac{1}{\mathrm{j}\omega M_{\mathrm{a}1} S^2 + R_{\mathrm{a}1} S^2 + Z_{\mathrm{a}0} S^2}} . \tag{2}$$

where mechanical compliance $C_m=1/K_m$, and K_m is elastic coefficient of vibration system. Acoustic compliance $C_{a1}=V_1/(\rho_0 c_0^2)$, $C_{a2}=V_2/(\rho_0 c_0^2)$, $C_{a3}=V_3/(\rho_0 c_0^2)$, and ρ_0 is density of air, c_0 is sound velocity of air. Acoustic mass $M_{a1}=M_{m1}/(nS^2)$, M_{m1} is vibration air mass in one channel, n is the number of channel. Acoustic resistance $R_{\mathrm{a}1} = \rho_0 \sqrt{2\omega\mu} / \left[n \cdot \pi a^2 \left(L/a + 1 \right) \right]$ [15], μ is kinematic viscosity(under the condition of 20 degree of normal pressure), L is the length of channel, a is equivalent radius of channel. Z_{a0} is acoustic impedance, which is calculated by different methods for different structures. By the relation of circuit, the expression of volume velocity of branch including radiation impedance(acoustic impedance of throat) in equivalent circuits shown in fig. 3(a) and 3(b) can be written as

$$U_4 = U \cdot \frac{\frac{1}{\mathrm{j}\omega C_{\mathrm{a1}}} \cdot \frac{1}{1+\mathrm{j}\omega C_{\mathrm{a3}} Z_{\mathrm{a0}}}}{\frac{1}{\mathrm{j}\omega C_{\mathrm{a1}}} + \mathrm{j}\omega M_{\mathrm{a1}} + R_{\mathrm{a1}} + \frac{1}{\mathrm{j}\omega C_{\mathrm{a3}} + \frac{1}{Z_{\mathrm{a0}}}}}. \quad (3)$$

$$U_2 = U \cdot \frac{\frac{1}{\mathrm{j}\omega C_{\mathrm{a1}}}}{\frac{1}{\mathrm{j}\omega C_{\mathrm{a1}}} + \mathrm{j}\omega M_{\mathrm{a1}} + R_{\mathrm{a1}} + Z_{\mathrm{a0}}}. \quad (4)$$

where volume velocity of system U=F/(SZ_{a}), Z_{a} is acoustic impedance of system, F is harmonic force. On this basis, we can calculate consumed power of impedance Z_{a0}'s real part R_{a0}, which represents power of sound wave:

$$\begin{cases} P_{\mathrm{a}} = \left|U_4\right|^2 R_{\mathrm{a0}} \\ P_{\mathrm{a}} = \left|U_2\right|^2 R_{\mathrm{a0}} \end{cases}. \quad (5)$$

The SPL at 1 m can then be found as

$$p = \sqrt{\frac{P_{\mathrm{a}} \rho_0 c_0}{2\pi}}. \quad (6)$$

So we can obtain frequency response curve of SPL to analysis different structures.

3.2 Calculation of acoustic impedance Z_{a0}

Acoustic impedance Z_{a0} is different in different equivalent structures. Acoustic impedance of compression driver exit can be described as single side piston radiation. Acoustic impedance of conical horn's throat can be refer to exponential horn[16]. Fig. 4 shows diagrammatic sketch of conical horn, where a_0 is cross section radius of entrance. a_l is cross section radius of exit. L is the length of horn. Cross section radius is a when distance away from entrance is x.

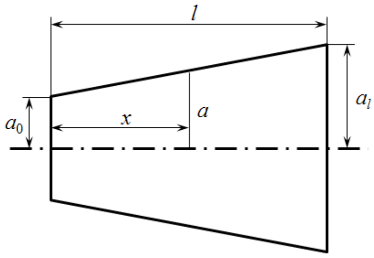


Figure 4: Sketch of conical horn.

The change rule of conical horn's cross section area can be described as

$$S(x) = S_0 (1+\alpha x)^2. \quad (7)$$

where change coefficient of cross section radius α=(a_l-a_0)/($a_0 l$). Cross section radius $a(x)$=a_0(1+αx), which is substituted into expression of sound pressure general solution's coefficient to get

$$\begin{cases} A(x) = \dfrac{1}{r_0 (1+\alpha x)} \\ \gamma = \pm k \end{cases}. \quad (8)$$

So the general expression of conical horn's can be written as

$$p = p(x) \mathrm{e}^{\mathrm{j}\omega t} = \mathrm{e}^{\mathrm{j}\omega t} \frac{1}{1+\alpha x} \left(A\mathrm{e}^{-\mathrm{j}kx} + B\mathrm{e}^{\mathrm{j}kx} \right). \quad (9)$$

where A and B are constant. The first part represents forward wave along the positive direction of x axis, and the second part represents back wave along the negative direction of x axis. We can write the particle velocity as

$$v=-\frac{1}{\rho_0}\int\frac{\partial p}{\partial x}\mathrm{d}t=-\frac{A\mathrm{e}^{\mathrm{j}\omega t}}{\rho_0 c_0 k(1+\alpha x)}\left[\frac{\mathrm{j}\alpha}{1+\alpha x}\left(\frac{B}{A}\mathrm{e}^{\mathrm{j}kx}+\mathrm{e}^{\text{-j}kx}\right)+k\left(\frac{B}{A}\mathrm{e}^{\mathrm{j}kx}-\mathrm{e}^{\text{-j}kx}\right)\right]. \tag{10}$$

Acoustic impedance in the horn can be written as

$$Z_\mathrm{a}(x)=\frac{p}{vS}=-\frac{\rho_0 c_0 k}{S}\left[\frac{\frac{B}{A}\mathrm{e}^{\mathrm{j}kx}+\mathrm{e}^{\text{-j}kx}}{\frac{\mathrm{j}\alpha}{1+\alpha x}\left(\frac{B}{A}\mathrm{e}^{\mathrm{j}kx}+\mathrm{e}^{\text{-j}kx}\right)+k\left(\frac{B}{A}\mathrm{e}^{\mathrm{j}kx}-\mathrm{e}^{\text{-j}kx}\right)}\right]. \tag{11}$$

x equates to l at the exit of horn, where cross section area is S_l. By assuming acoustic impedance at exit as $Z_{\mathrm{a}l}$, we can have

$$\frac{B}{A}=e^{-\mathrm{j}2kl}\frac{\frac{Z_{\mathrm{a}l}S_l}{\rho_0 c_0}-\left[1+\mathrm{j}\frac{Z_{\mathrm{a}l}S_l\alpha}{\rho_0 c_0 k(1+\alpha l)}\right]}{\frac{Z_{\mathrm{a}l}S_l}{\rho_0 c_0}+\left[1+\mathrm{j}\frac{Z_{\mathrm{a}l}S_l\alpha}{\rho_0 c_0 k(1+\alpha l)}\right]}. \tag{12}$$

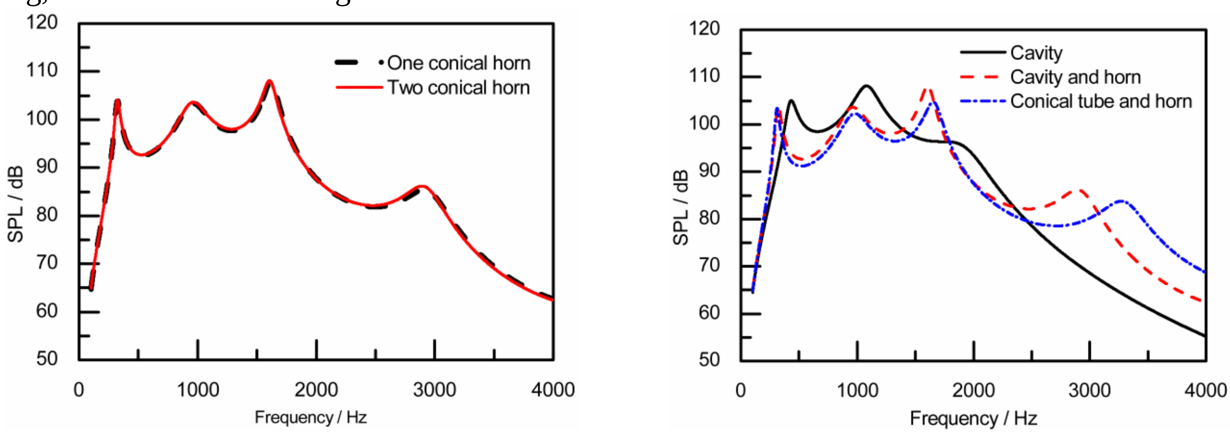
By equating x=0, the acoustic impedance of horn throat can be get as

$$Z_{\mathrm{a}0}=-\frac{\rho_0 c_0 k}{S_0}\frac{\frac{B}{A}+1}{k\left(\frac{B}{A}-1\right)+\mathrm{j}\alpha\left(\frac{B}{A}+1\right)}. \tag{13}$$

We shall calculate acoustical impedance from exit to throat one by one for two or more conical horns. Conical tube is contrary to conical horn in structure, but same in substance, so the above formula can also be used to calculate.

3.3 Characteristic analysis of different equivalent structures

Having derived the expression of SPL and determined parameters in the expression, we may now draw the frequency response of SPL curves of different equivalent structures by software programming, which are shown in fig. 5.



(a) Comparison of different horns (b)SPL frequency response of different equivalent structrues

Figure 5: Frequency response of SPL of different equivalent structures.

The frequency response of one conical horn and two conical horns are shown in fig. 5(a). SPL of two conical horns is a little higher within 3000 Hz, after which is a little smaller. But there is no significant difference between one conical horn and two conical horns, So we do later analysis using only one conical horn model for convenience.

Frequency response of three structures including “Cavity”, “Cavity and horn”, “Conical tube and horn” are compared in fig. 5(b). “Cavity and horn” and “Conical tube and horn” structures make the increase of peaks from three to four, and peaks have a trend of left moving. “Conical tube and horn” structure comparing to “Cavity and horn” structure has a almost same trend, but the last three peaks move right, in which the fourth changes evidently. SPL of “Cavity” structure has an advantage in 370~1400 Hz band and 1800~2350 Hz band. “Cavity and horn” and “Conical tube and horn” structure evidently have a higher SPL in 100~370 Hz , 1400~1800 Hz and beyond 2400 Hz band. “Conical tube and horn” structure comparing to “Cavity and horn” structure has a little higher only beyond 3100 Hz, that is because conical tube is contrary to conical horn in structure, so that sound wave can be weaken in conical tube comparing to conical horn.

4. Experiments

To research and verify results of equivalent circuit analysis, we may begin to test compression driver in semi-anechoic room shown in fig. 6. Sound signal is produced by signal generator, which is loaded to compression driver to radiate sound wave after being amplified by power amplifier. Sound signal on the central axis is collected by microphone, so frequency response of SPL can be obtain by changing input signal.

Figure 6: The test of frequency response of SPL of compression driver.

Fig. 7 shows the results of equivalent circuit analysis of different equivalent structures and experiment, which show that the equivalent circuit method can be well applied within 1600 Hz and the results by the equivalent circuit method will be smaller beyond 1600 Hz. The difference between experimental and theoretical results increases with frequencies. SPL of “Cavity” structure is a little higher than “Cavity and horn” and “Conical tube and horn” structure, which is closer to experimental results, so radiation characteristics of compression driver are not sensitive to microstructures in low frequency band. But SPL of “Cavity and horn” and “Conical tube and horn” structure are a little higher in a specific or higher frequency band, which is closer to experimental results relatively, namely the effects of microstructures are obvious.

We analyze reasons of difference between theoretical results and experimental results : (1) The diaphragm vibrates as distribution at high frequency range, so equivalent circuit method is no longer applicable. (2) The real structure doesn’t satisfy the three assumed conditions when simplifying the compression driver structure for equivalent circuit analysis. (3) Approximate formulas are used for partial parameters calculation.

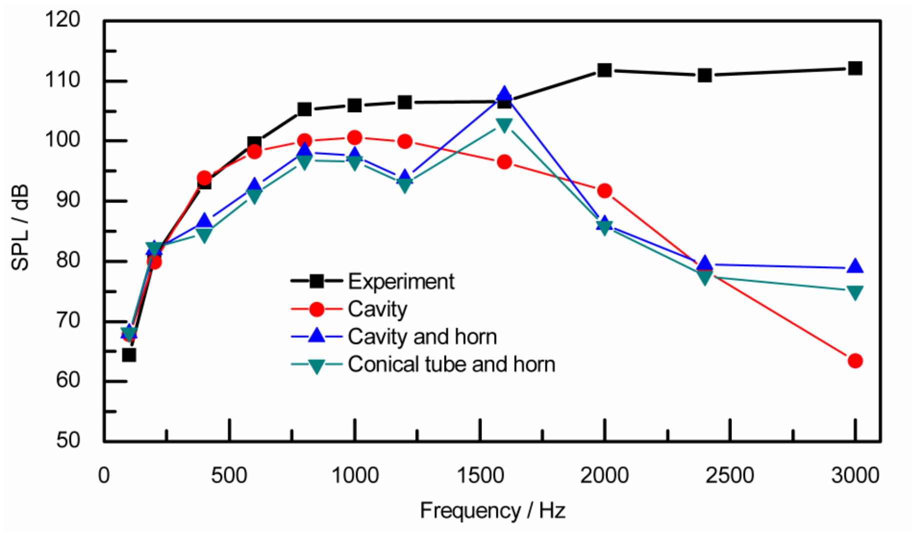


Figure 7: Comparison between academic results of different structures and experimental results.

5. Conclusion

This paper proposed some varied equivalent structures for the front part of compression driver, SPL expressions of different equivalent structures were derived by equivalent circuit method after comparing the structural differences, which were compared with experimental results. The results show that the equivalent circuit method can be well applied within 1600 Hz and the results by the equivalent circuit method will be smaller beyond 1600 Hz. The difference between experimental and theoretical results increases with frequencies, so equivalent circuit method can be used by frequency. Radiation characteristics of compression driver are not sensitive to micro-structures in low frequency band, but the effects of microstructures are obvious in a specific or higher frequency band. Results of this paper can provide some references for study of similar structure to compression driver.

REFERENCES

1 Alexandrov S. Compression driver. U.S. Patent 005878148A, (1999).

2 Czerwinski E J, Alexander V. High frequency compression driver. U.S. Patent 20020057819A1, (2002).

3 O'NEILL R M. Compression drivers and horn structure. WO. Patent 2008112175A1, (2008).

4 Werner B M. Horn-loaded compression driver system. U.S. Patent 20030215107A1, (2003).

5 Hu B Q, Wang Y Z, He G L. New linear middel-high frequency compression driver. CN. Patent 201010002558.5, (2010).

6 Alexander V. Dual compression drivers and phasing plugs for compression drivers. U.S. Patent 20110085692A1, (2011).

7 Alex Voishvillo. Dual diaphragm compression drivers, *Proceedings of 131th Audio Engineering Society Convention*, New York, USA, 20-23 October, (2011).

8 David J. Murphy, Rick Morgans. Modelling compression drivers using T matrices and finite element analysis. *Proceedings of 119th Audio Engineering Society Convention*, New York, USA, 7-10 October, (2005).

9 Alex Voishvillo. Simulation of horn driver response by combination of matrix analysis and FEA, *Proceedings of 129th Audio Engineering Society Convention*, Sam Francisco, CA(US), 04-07 November, (2010).

10 Rene Christensen, Ulrik Skov. Simulation of a 4'' compression driver using a fully coupled vibroacoustic finite element analysis including viscous & thermal losses, *Proceedings of 132th Audio Engineering Society convention*, Budapest, Hungary, 26-29 April, (2012).

11 Dodd M, Oclee-Brown J. A new methodology for the acoustic design of compression driver phase-plugs with concentric annular channels, *Journal of the Audio Engineering Society*, **57**(10), 771-787, (2009).

12 Francesco Piazza, Emiliano Capucci, Romolo Toppi, et al. Multiphysic modeling and heuristic optimization of compression driver design, *Proceedings of 136th Audio Engineering Society Convention*, Berlin, Germany, 26-29 April, (2014).

13 Fang H L, Xu X Z, Dong M R, et al. The equivalent circuit analysis of the compression driver, *Technical Acoustics*, **32**(8), 53-56, (2013).

14 Zhang L Y, Xu X Z, Fang H L, et al. Equivalent circuit model analysis for mutual interaction on high-power loudspeakers, *Journal of Nanjing University (Natural Sciences)*, **51**(Supplement), 134-138, (2015).

15 Boesch H E, Jr. , Reiff C G, Benwell B T. Technical Report ARL-TR-2349, A High Intensity Infrasonic Acoustic Test System, (2001).

16 Du G H, Zhu Z M, Gong X F. *Acoustical fundament*. Nanjing University Press, Nanjing, (2001).