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Modeling and Performance Parameters Analysis of Closed-Box Loudspeaker

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Abstract: ***Our comprehensive research on closed-box loudspeaker systems, which act as second-order high-pass filters, is innovative in understanding their low-frequency response. Two main system parameters, resonance frequency and total damping, are explored in a novel way. The resonance frequency, the proportion of total damping contributed by electromagnetic coupling, and overall compliance all have quantitative relationships with the system's electroacoustic efficiency. Achieving a flat magnitude response, a key goal in this study, is approached from a fresh perspective. We utilise these parameters to optimise the loudspeaker's low-frequency performance using WinISD speaker design software for Windows, a significant finding that will significantly benefit the field of audio technology. Furthermore, the impact of varying the compliance ratio on system performance is analyzed using MATLAB R2015a software, adding a new dimension to our understanding of system performance.***

Keywords: ***Closed box loudspeaker, damping, resonance frequency, electroacoustic efficiency, Thiele parameters.***

I. INTRODUCTION

A loudspeaker is an electromechanical system that converts an electrical audio signal into airborne sound waves. It is also known as an electroacoustic transducer. The magnet, voice coil, and cone (or diaphragm) are its components. It generates sound by using an electrical current to vibrate a diaphragm or other sound-producing element, creating pressure waves that travel through the air and are perceived by the human ear as sound. Two fundamental system parameters govern its low-frequency response: resonance frequency and total damping. Contributing to total damping are electromagnetic coupling and total system compliance. To analyze the frequency response of a loudspeaker, it is necessary to comprehend controlling parameters such as resonance frequency, electromagnetic coupling, and total system compliance.

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A loudspeaker's acoustic model is the mathematical description of how the speaker's components interact to produce sound. The acoustic model incorporates variables such as the size and shape of the speaker driver(s), the materials used for the driver and enclosure, and the speaker's overall design. The acoustic model determines a loudspeaker's performance, including frequency response, sensitivity, and distortion characteristics. A well-designed acoustic model can produce a speaker that generates clear and accurate sound across a broad frequency range. Today's dynamic loudspeakers are the result of a tremendous amount of engineering effort. A light voice coil is positioned such that it can freely travel within a robust permanent magnet's magnetic field. The voice coil is attached to the speaker cone, which is then secured to the outer ring of the speaker base using a movable attachment. There is always a natural cone resonance frequency that is analogous to the frequency of a mass on a spring, since the speaker cone does have a 'home' or balance position, and the supporting frame is built of elastomeric material. The frequency can be altered by adjusting the mass and rigidity of the cone and voice coil, and the structure can attenuate and broaden it. Still, the natural mechanical vibration frequency is always there and accentuates the frequencies in the frequency band around resonance. One of the functions of a quality enclosure is to limit the impact of the resonance frequency. The frequency at which a speaker resonates is known as its resonant frequency. The movable components (cone, surround, spider, and voice coil) have a specific mass and compliance (opposite of rigidity). This combination is frequently reduced to a mass connected to a spring. The spring will expand when the mass is put into motion. A stretched spring stores energy and desires to revert to its initial state. At a certain point, the mass's motion energy is no longer sufficient to extend the spring. The stored energy in the extended spring is enough to exert an equal and opposite force on the mass. The moving mass surpasses the spring's equilibrium or rest state, causing the spring to compress. In addition, compression stores energy and ultimately causes the mass to move in the opposite direction. Fig. 1 depicts a schematic diagram of a dynamic loudspeaker. Fig.2 depicts the analogy between the spring and the speaker driver.

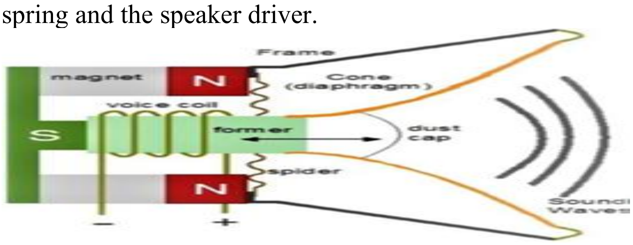

Fig.1. Schematic of Dynamic Loudspeaker Adapted from McGraw-Hill Dictionary of Scientific & Technical Terms

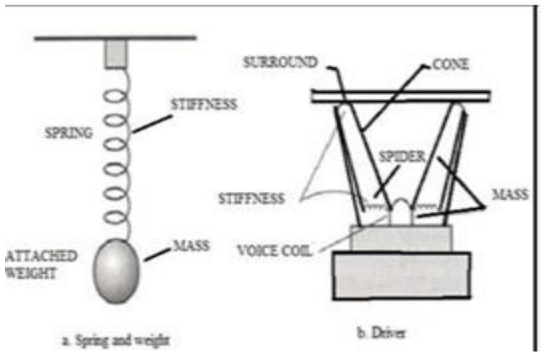

Fig.2. Analogy Between Spring and Speaker Driver

II. MODELLING AND PERFORMANCE PARAMETERS

A mechanical model is a mathematical representation of a physical system's behavior. The mechanical model of a loudspeaker describes how the mechanical components, such as the cone and suspension, interact with the electrical components, such as the voice coil and magnet. The mechanical model is crucial to a loudspeaker's performance because it impacts how the speaker produces sound. Specifically, the mechanical model determines the speaker's frequency response and the frequency range it can precisely reproduce.

The acoustic model is a crucial factor in the design and performance of loudspeakers. A well-designed model can produce a speaker that generates accurate, high-quality sound. A loudspeaker's acoustical model defines how it creates sound and can be broken down into several components.

Several parameters characterize the mechanical model, including the suspension's rigidity, the cone's mass, and the damping factor. These parameters can be altered to optimize the loudspeaker's performance for various applications. A high-rigidity suspension can enhance the speaker's ability to reproduce low-frequency sounds, whereas a low-mass cone can enhance the speaker's ability to reproduce high-frequency sounds. Increasing the damping factor can also minimize undesirable resonances in the speaker's response. Thiele-Small (T/S) Parameters are a group of measurements used to determine a loudspeaker's mechanical, electromechanical, and electrical properties. They specify the construction and performance of loudspeakers, specifically applying to individual drivers and enclosures (vented or ported). These parameters include the driver's electrical and mechanical properties, such as the electrical resistance, the mass of the moving parts, and the suspension compliance. Numerous Thiele-Small parameters should be considered, among which a few are more widespread (apply to more speakers). Thiele-Small parameters are a subset of speaker specifications obtained from the datasheets of individual drivers, as well as those with casings. In a closed-box loudspeaker system, the speaker is mounted within a sealed enclosure, creating a volume of air that compresses and expands as the speaker travels back and forth. This volume of air functions as a spring-mass system, a concept from physics where a mass (the speaker cone) is attached to a spring (the air in the enclosure), and the enclosure and speaker determine the resonant frequency of this system. A closed-box loudspeaker system comprises an enclosure or box that is entirely closed and airtight except for a single opening through which the driver is mounted. The acoustic compliance of the confined air in conventional closed-box systems is greater than that of the driver's suspension. Thus, driver compliance and moving mass determine the driver's resonance frequency in the enclosure [1]. The electrical equivalent circuit of the closed box loudspeaker system is depicted in Fig. 3.

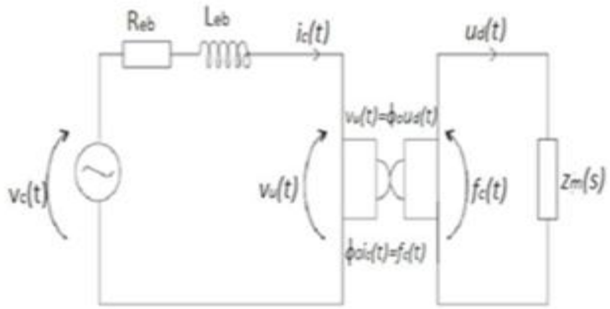

Fig.3. Electrical Equivalent Circuit of a Closed-Box Loudspeaker

Given that most amplifiers used for loudspeakers are constant-voltage, low-output-impedance, the voltage source Vc(t) represents the amplifier output.

The resistor Reb is a representation of the coil wire's resistance. The inductor Leb represents the electrical inductance caused by the voice coil's shape and the ferromagnetic material nearby. A gyrator, depicted in the centre of Figure 3, represents electro-mechanical transduction. The voltage drop induced by the gyrator is the product Φ0ud(t), where Φ0 is the constant of the gyrator. All these effects can be integrated into a single equation in the frequency (Laplace) domain.

$$v_c(s) = (R_{eb} + sL_{eb})i_c(s) + \Phi_0 u_d(s) \quad (1)$$

$$v_c(s) = Z_{eb}(s)i_c(s) + \Phi_0 u_d(s) \quad (2)$$

Φ_0 Transduction coefficient (same as '*B·l*-factor,' or 'force-factor.')

$u_d(s)$ Velocity of the diaphragm and coil assembly.

s the 'Laplace variable,' = – *i*ω, where $i=\sqrt{-1}$, and ω = 2π*f*, where *f* is the frequency in Hz.

A phenomenon known as eddy currents results in a substantially different reactive blocked electrical impedance than a simple inductor. Vanderkooy (1989) devised an excellent model of this phenomenon, wherein the effect was described as an inductance varying with the square root of frequency, i.e. $I_m\{Z_{eb}\} = \sqrt{f}$

Fig. 4 depicts an analogous mechanical system. The Mechanical representation of the dynamics of an electrodynamic loudspeaker has a single degree of freedom. Zrm represents acoustic loading.

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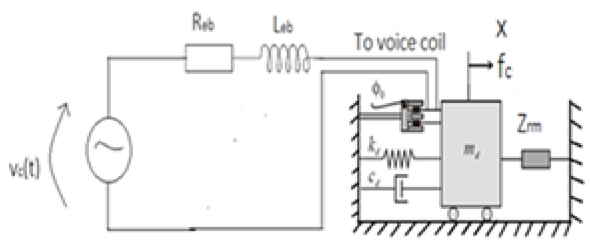

Fig.4. Mechanical Representation of Dynamics of an Electrodynamic Loudspeaker

A second-order linear inhomogeneous differential equation can represent the SDOF system:

$$m_d\ddot{x} + c_d\dot{x} + k_d x = f_c(t) \tag{3}$$

A generalized mechanical impedance Zmo can be represented by taking the Laplace transform of (3).

$$Z_{mo}(s) = \frac{f_c(s)}{u_d(s)}\bigg|_{\substack{i_c(s)=0\\ p_s(s)=0}} = sm_d + c_d + k_d/s \tag{4}$$

Zmo(s) is the open-circuit mechanical impedance in vacuum. It describes the force-to-velocity ratio of the diaphragm under two conditions: the voice coil is open-circuited (i_c(s) = 0). The loudspeaker is in a vacuum, thereby removing acoustic loading (Ps(s) = 0).

Mobility is a crucial transfer function of an SDOF system, as it directly characterises its resonance. The multiplicative inverse of impedance represents it.

$$Y_{mo}(s) = \frac{u_d(s)}{f_c(s)} = \frac{1}{Z_{mo}(s)} = \frac{1}{sm_d + c_d + k_d/s} = \frac{s}{s^2 m_d + sc_d + k_d} \tag{5}$$

$$Y_{mo}(s) = \frac{1}{m_d}\frac{s}{(s-\lambda_1)(s-\lambda_2)} \tag{6}$$

λ1 and λ2 are the roots of the denominator polynomial of (5). These indicate the location of the transfer function's poles in the s-plane, defining the eigenvalues of the mechanical system.

$$\lambda_1, \lambda_2 = -\omega_0\zeta \pm i\omega_0\sqrt{1-\zeta^2} \tag{7}$$

where ω0 represents the undamped inherent frequency, which is given by $\omega_0 = \sqrt{\frac{k_d}{m_d}}$ (8)

and the damping ratio ζ is given by:

$$\zeta = \frac{1}{2}\frac{c_d}{\sqrt{k_d m_d}} \tag{9}$$

The acoustic fluid affects the loudspeaker's mechanical behavior. If the linear acoustic equations adequately describe the acoustic pressures generated by the diaphragm, these effects can be modelled using linear components. The acoustic effects on the mechanical behaviour are referred to as acoustic radiation impedance. Therefore, Zm (s) defines the entire mechanical impedance.

$$Z_m(s) = \frac{f_c(s)}{u_d(s)} = Z_{mo}(s) + Z_{rm}(s) \tag{10}$$

Zrm (s) is the mechanically equivalent impedance of acoustic radiation. Sd is the effective radiating area of the loudspeaker's diaphragm, which relates to the traditional lumped-parameter acoustic impedance Zrad(s).

In most applications, the loudspeaker is mounted in a cabinet or baffle that inhibits acoustic interaction between the front and rear diaphragm sides. This allows the front and rear radiation impedances to be treated independently. From the 'point of view' of the loudspeaker, the front and rear loading summed together with the internal mechanical impedance can be determined as follows:

$$Z_m(s) = Z_{mo}(s) + Z_{rmf}(s) + Z_{rmr}(s) \tag{11}$$

where Zrmf(s) is the front-side acoustic impedance, and Zrmr(s) is that on the rear side.

A closed-box enclosure is the simplest type of rear-acoustic loading commonly used for loudspeakers. Mounting in such an enclosure prevents front-to-back sound cancellation, resulting in monopole radiation.

If all cabinet dimensions are small compared to the largest wavelength considered, the pressure is constant throughout the cavity. In this case, the cavity's acoustic pressure p(t) is determined by the volume changes caused by the movement of the diaphragm [2]. Assuming adiabatic temperature variations, the cavity's acoustic pressure will be:

$$p(t) = \frac{V(t)}{V_0}\rho_0 c_0^2 \tag{12}$$

Here, V(t) equals the product of the effective area Sd and the average displacement -x(t), where a positive displacement is directed away from the cavity. Taking the time derivative of (12) and substituting $-S_d u_d(t)$ for V(t),

$$\frac{dp(t)}{dt} = -\frac{S_d u_d(t)}{V_0}\rho_0 c_0^2 \tag{13}$$

$$\frac{p_c(s)}{u_d(s)} = -\frac{S_d}{s}\frac{\rho_0 c_0^2}{V_c} \tag{14}$$

A positive reactive force resulting from a positive causal velocity denotes a negative impedance; consequently, the effective mechanical impedance produced by the cavity is equal to the negative of the right-hand side of (14).

$$Z_{rmr}(s) = \frac{S_d{}^2}{s}\frac{\rho_0 c_0^2}{V_c} \tag{15}$$

Most loudspeaker systems are driven by low-output impedance and constant output voltage amplifiers; the loudspeaker's response is defined by the frequency response function referenced to the voice-coil voltage, Vc(s). The classical electrodynamic interaction of line currents and static magnetic fields causes interaction between the electrical and mechanical components.

$$f_c(t) = \beta l i_c(t) \tag{16}$$

where Ic (t) is the voice-coil current and l is the effective length of the voice-coil wire in a magnetic field of flux density β.

$$i_c(s) = \frac{1}{\Phi_0}u_d(s)Z_m(s) \tag{17}$$

$$\frac{u_d(s)}{v_c(s)} = \frac{\Phi_0}{Z_{eb}(s)Z_m(s) + \Phi_0^2} \tag{18}$$

The simplest model for acoustic radiation is:

$$p_r(s) = s\rho_0 S_d u_d(s)\frac{e^{jkr}}{4\pi r} \tag{19}$$

$$\frac{p_{r_p}(s)}{v_c(s)} = s\rho_0 S_d \frac{\Phi_0}{Z_{eb}(s)Z_m(s) + \Phi_0^2}\frac{e^{ikr_p}}{4\pi r_p} \tag{20}$$

To formulate the voltage-to-pressure transfer function of (20), the general electrical, mechanical, and acoustic radiation impedances (Zeb, Zmo, and Zrm, respectively) must be parameterized as follows [3].

$$Z_{eb} = R_{eb} + sL_{eb} \tag{21}$$

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$$Z_{mo} = sm_d + c_d + k_d/s \qquad (22)$$

$$Z_{rm} = sm_a + \rho c^2 S_d^2/V_c s \qquad (23)$$

It is advantageous to define an exclusive expression for the total mechanical impedance, equal to the sum of the diaphragm and the mechanically equivalent acoustical impedance:

$$Z_m = Z_{mo} + Z_{rm} = sm_t + c_t + k_t/s \qquad (24)$$

$$k_t = k_d + S_d^2 \rho_0 c_0^2/V_c \qquad (25)$$

$$m_t = m_d + m_a \qquad (26)$$

It is required to presume that the effect of internal electrical inductance is negligible, i.e., Leb = 0, so that Zeb≅ Reb.

$$L_{eb}\frac{di_c}{dt} + \Phi_0 \mathrm{v} + R_{eb} i_c = V_c(t) \qquad (27)$$

$$L_{eb}\frac{di_c}{dt} + \Phi_0 \frac{dx}{dt} + R_{eb} i_c = V_c(t) \qquad (28)$$

$$I_c(S) = \left[\frac{V_c(S) - \Phi_0\, S\, X(S)}{R_{eb} + L_{eb} S}\right] \qquad (29)$$

$$F \propto i_c \qquad F = \Phi_0 i_c$$

$$F(S) = \Phi_0 \left[\frac{V_c(S) - \Phi_0\, S\, X(S)}{R_{eb} + L_{eb} S}\right] \qquad (30)$$

$$m_d s^2 X(S) + c_d S\, X(S) + k_d\, X(S) = \frac{\Phi_0 V_c(S)}{R_{eb} + L_{eb} S} - \frac{\Phi_0^{\,2} S\, X(S)}{R_{eb} + L_{eb} S} \qquad (31)$$

$$X(S)\left[m_d S^2 + c_d S + k_d + \frac{\Phi_0^{\,2} S}{R_{eb} + L_{eb} S}\right] = \frac{\Phi_0 V_c(S)}{R_{eb} + L_{eb} S} \qquad (32)$$

$$\frac{X(S)}{V_c(S)} = \frac{\left(\frac{\Phi_0}{R_{eb} + L_{eb} S}\right)}{\frac{R_{eb} m_d S^2 + m_d L_{eb} S^3 + c_d R_{eb} S + c_d L_{eb} S^2 + k_d R_{eb} + k_d L_{eb} S + \Phi_0^{\,2} S}{R_{eb} + L_{eb} S}} \qquad (33)$$

Considering Leb = 0 in (33), it becomes

$$\frac{X(s)}{Vc(s)} = \left(\frac{\frac{\Phi_0}{m_d R_{eb}}}{S^2 + \left(\frac{\Phi_0^{\,2}}{m_d R_{eb}} + \frac{c_d}{m_d}\right) S + \frac{k_d}{m_d}}\right) \qquad (34)$$

Examining the equivalent circuit of a closed box is the most comprehensive method for understanding its response. Fig. 5 depicts the equivalent circuit of a closed-box loudspeaker. The driver's mechanical circuit and the box's acoustic properties are related through the transformation ratio SD.

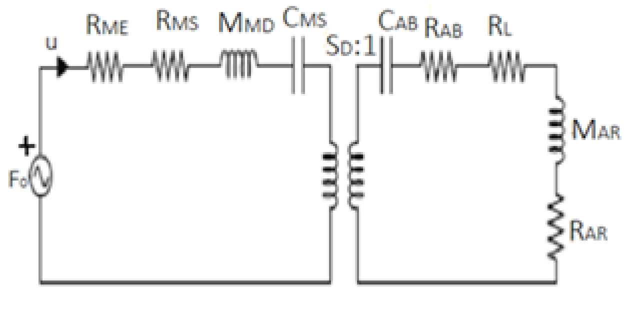

Fig.5. Equivalent Circuit of Closed-Box Loudspeaker

At low frequencies, the speaker's motion is primarily governed by the mass of the diaphragm and the compliance of the suspension system. The enclosure functions as a low-pass filter, dampening the high-frequency components of the signal.

As the frequency increases, the enclosure's acoustic compliance significantly influences the speaker's motion, and the system's response shifts towards a high-pass filter [4]. Two components are involved in closed-box designs: the woofer and the enclosure. The loudspeaker system's performance will be determined by the interaction of both and their factors. The key parameters are proclaimed in Tables 1 and 2.

Table 1. Enclosure and Driver Parameter Settings

Woofer Parameters	Enclosure Parameters
fs: resonance frequency	VB: physical box volume
Q_{ES} and Q_{TS}: quality factors	γ: increase of the acoustic volume
V_{AS}: equivalent air volume to C_{MS}	V_{AB}: apparent or acoustical volume
Ŋ0: efficiency	α: volume ratio V_{AS}/V_{AB}
Xmax: maximum linear displacement	QA: quality factor due to the damping material
peak PE: maximum input power	QL: quality factor due to leakage

Table 2. The Parameters that Define the Loudspeaker System's Responsiveness and Performance

Loudspeaker response	Loudspeaker performance
fc: system's resonance frequency	VB: physical box volume
Q_{TC}: system's quality factor	f6: lower cutoff frequency
	LF Peak (or LF boost)
	SPLmax: maximum achievable SPL

Two factors primarily determine the frequency response of a closed-box loudspeaker. 1)Resonance frequency 2) Total damping. The compliance ratio primarily determines the total suspension. As stated in the previous section, loudspeakers with a uniform frequency response are preferred. Numerous parameters, including driver diaphragm, system compliance, electromagnetic coupling, and enclosure dimensions, influence loudspeakers' frequency response. To achieve uniform frequency response, it is necessary to comprehend the relationship between all loudspeaker parameters.

The frequency response has the most influence on sound quality. Understanding the frequency response is essential for comprehending music or audio content. A speaker's performance and sound quality are not solely determined by its ability to reproduce a specific frequency range [5]. It is also essential to reproduce all frequencies at the same amplitude so they can be played back exactly as they were captured. The speaker must be capable of reproducing even the most complex sounds with several frequencies simultaneously and in harmony.

Resonance frequency: $fs = \frac{1}{2\pi\sqrt{Mms\ Cms}}$ (35)

Quality Factor: $Q_{TS} = \frac{1}{\frac{1}{Q_{ES}} + \frac{1}{Q_{MS}}}$ (36)

$$Q_{ES} = \frac{R_E}{Bl^2}\sqrt{\frac{M_{MS}}{C_{MS}}} \qquad (37)$$

$$Q_{MS} = \frac{1}{R_{MS}}\sqrt{\frac{M_{MS}}{C_{MS}}} \qquad (38)$$

$$Q_{EC} = Q_{ES}\sqrt{1+\alpha} \qquad (39)$$

$$Q_{MC} = Q_{MS}\sqrt{1+\alpha} \qquad (40)$$

Were, $\alpha = \frac{V_{AS}}{V_{AB}}$

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Here, VAB is the perceived volume, whereas VB is the actual volume of a box. It is proportional to the increase in apparent volume induced by filling with absorbent material. In addition to VB, three additional criteria define the performance of a loudspeaker: the lower cut-off frequency, the flatness of the frequency response, and the highest SPL that can be achieved.

$$f_6 = f_c\left(\frac{1}{6Q_{TC}^2}-\frac{1}{3}+\sqrt{\left(\frac{1}{6Q_{TC}^2}-\frac{1}{3}\right)^2+\frac{1}{3}}\right)^{\frac{1}{2}} \quad (41)$$

$$\mathrm{LF_{peak}} = 20log_{10}\left(\frac{Q_{TC}^2}{\sqrt{Q_{TC}^2-0.25}}\right) \quad [\mathrm{dB}] \quad (42)$$

$$SPL_{max} = 112.1 + 10log_{10}(\eta_0 P_{E_{max}}) \quad (43)$$

$$P_{E_{max}} = \left(\frac{X_{max}}{X_{peak@1W}}\right)^2 \quad (44)$$

$$X_{peak@1W} = \frac{C_{MS}Bl}{(1+\alpha)}\sqrt{\frac{2}{R_E}}\left[\frac{Q_{TC}^2}{\sqrt{Q_{TC}^2-0.25}}\right] \quad (45)$$

III. RESULTS AND DISCUSSION

Speaker drivers are the transducer elements that transform the audio signal (electrical energy) into sound (mechanical wave energy). Although numerous types of drivers exist, most employ a conductive component to move a diaphragm and generate sound. WinISD is a free, somewhat feature-rich bass response modeling application. It is popular due to its affordability, adaptability, and (after a little learning curve) usability. WinISD has a facility to select different drivers. This paper uses the Seas L26RFX-P driver to analyze loudspeaker parameters.

Driver parameters are tabulated in Table 3.

Table 3. Thiele Small Signal Parameters

Q_{ES}=0.400	Q_{MS}=2.300	Q_{TS}=0.341
VAS=166 l	fs=20 Hz	R_E=6.30 ohm
M_{MS}=58.9 gm	S_D=330 cm^2	C_{MS}=1.0746 mm/N
R_{MS}=3.21970 Ns/m	Bl=10.79971 N/A	LE=1.48 mH
Dd=205 mm	Xmax=14mm	PE=125 W
VD=0.46 l	ŋ=0.3229	R_{ME}=18.51328 Ns/m

Once driver parameters are selected, the loudspeaker's performance is observed by varying the compliance ratio(α). A loudspeaker's performance includes the overall quality factor, resonance frequency, low-frequency peak, cone displacement, and SPL max. The relationship between α and the overall quality factor is depicted in Fig. 6.

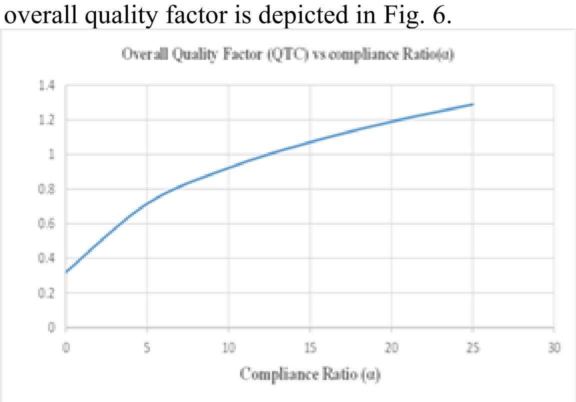


Fig.6. Graph of QTC with Change of α

Increased QTC values result in a low-frequency boost in closed boxes, which degrades the attenuation of the frequency response. A method for measuring flatness in enclosed spaces involves quantifying the amount by which the Low-frequency peak surpasses the passband sound pressure level.

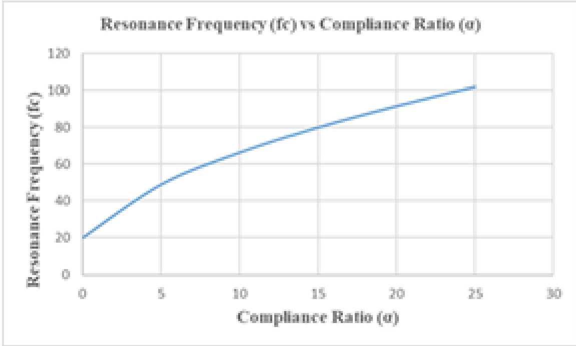


Fig.7. Resonance Frequency of Seas L26RFX-P driver in a Sealed Enclosure with Variable α.

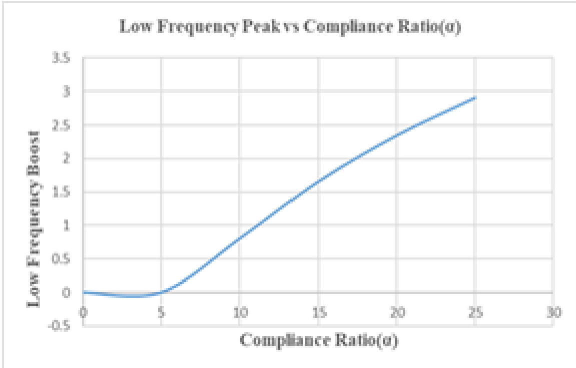


Fig.8. Low-Frequency Boost for Different Compliance Ratios

A significant performance parameter is the amount of SPL (1 m) a loudspeaker can generate while maintaining linearity. Assume linearity if cone movement is limited to less than Xmax (exceeding Xmax is a primary cause of distortion). For a given input power, the extra stiffness of the air inside the cabinet keeps the diaphragm closer to its state of rest, protecting the cone from displacement. Therefore, the cone's apex displacement depends on α and other characteristics. From the analysis of the analogous circuit, it is possible to determine the peak displacement. Figures 9 and 10 illustrate the cone displacement and SPLmax variation as a function of compliance ratios.

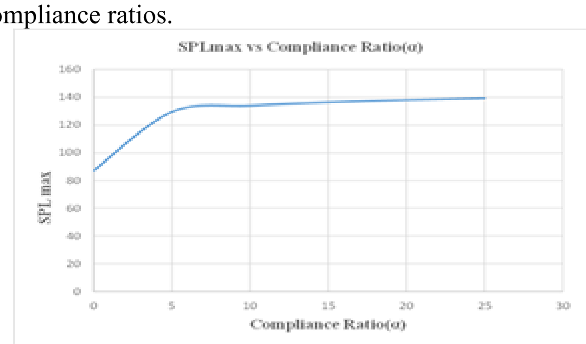


Fig.9. SPLmax for Different Compliance Ratios

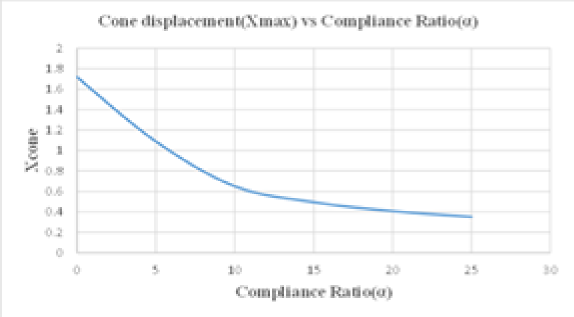
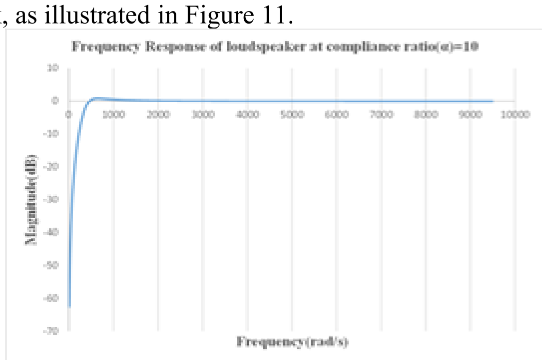
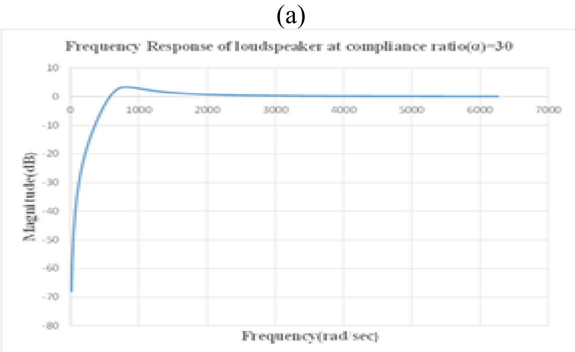


Fig.10. Cone Displacement for Different Compliance Ratios

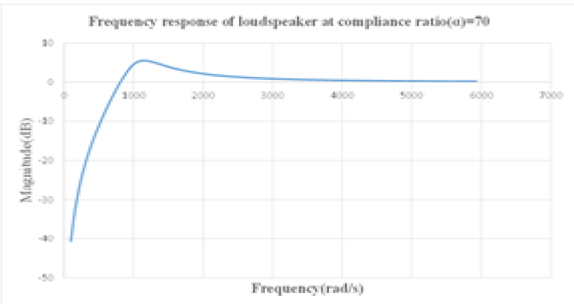
The response function of the closed-box system is a second-order high-pass filter function; it describes the system's amplitude, phase, latency, and transient response characteristics. Since the system is in the minimum phase, these features are interdependent; adjusting one affects the others. In audio systems, the flatness and extent of the steady-state amplitude-versus-frequency response, or simply the frequency response, are typically regarded as of the utmost significance. Fig. 11 illustrates the frequency response curves of the closed-box system for various values of α. Variation in the compliance ratio leads to a peak in the frequency response. The compliance ratio increases to its peak, as illustrated in Figure 11.



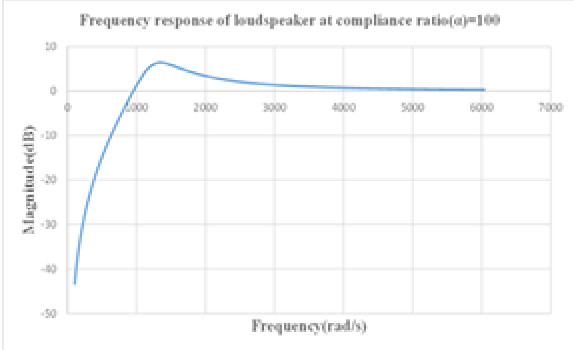
(a)



(b)



(c)



(d)

Fig.11. Frequency Response of Sealed Loudspeaker for a) α=10, b) α=30, c) α=70, d) α=100

IV. CONCLUSION

It is possible to model and analyze closed-box loudspeakers. All performance parameters of closed-box loudspeakers are examined based on fluctuations in compliance ratios. The frequency response of loudspeakers with varying compliance ratios is investigated.

When designing a speaker system from scratch, the effect of filler material on compliance is unquestionably advantageous. It indicates that the enclosure size can be reduced, efficiency can be increased, or responsiveness can be improved. Any mass increase resulting from the compliance increase is accounted for when building the driver, ensuring that the overall moving mass is precisely the intended amount.

When designing a loudspeaker system around a specific driver, the material's increased compliance is still advantageous because it allows the enclosure to be smaller for a particular (achievable) response. It may or may not be beneficial for increased mass to diminish driver reference efficiency by the square of the mass increase. The additional mass will also result in a better value of Q_{EC} for a given value of F_C. This will be offset by the effect of QMC's material losses.

The loudspeaker's resonant frequency depends on linear characteristics such as compliance and mechanical resistance. In addition to losses in the absorbent material and losses owing to leakage, losses in the absorbent material will also affect the total quality factor (QTC). The losses caused by QA and QL lower the total quality factor (QTC). Still, the closed box significantly increases QTC, making it much higher than the driver's total quality factor (QTS). In closed boxes, increased QTC values induce a low-frequency bump, which affects the flatness of the frequency response. A method for measuring flatness in enclosed spaces involves quantifying the amount by which the LF peak exceeds the passband sound pressure level.

A significant performance parameter is the amount of SPL (1 m) a loudspeaker can generate while maintaining linearity. If the cone displacement is restricted below Xmax, linearity is assumed (otherwise, exceeding Xmax is a significant cause of distortion). For a given input power, the additional rigidity of the air within the cabinet maintains the diaphragm closer to its resting position, protecting the cone from displacement. Therefore, the peak cone displacement is dependent on other parameters.

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