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Parametric simulation study of miniature loudspeaker for performance evaluation and improvement

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ABSTRACT

Sound reproduction in a limited space with accumulation of functions for polyphonic sound is increasing demand of 4C products. Miniature loudspeaker has to generate smooth sound pressure level (SPL) over range of 100 Hz to 10 kHz as per requirements of 4C products. In this study we reports formulation and validation of equivalent circuit model for miniature loudspeaker. This is achieved by measuring electroacoustic (Thiele-Small) parameters and performing anechoic chamber measurements. The validated model is then simulated for investigating the effect of key parameters of miniature loudspeaker based on our past experience. Such parameters are transduction factor, electrical resistance of voice coil, electrical impedance of voice coil, mass of diaphragm, resistance of diaphragm, and compliance of diaphragm. These parameters are adjudged based on TS parameter and their effect on SPL. This study investigates the effect of parameters in two layer manner. In the first layer, diaphragm dependent mechanical parameters and voice coil dependent electrical parameters are isolated and simulation is carried out. We found very promising results. With these results, in second layer, an attempt is extended to combine them to get better information on the effect of these parameters on the SPL of miniature loudspeaker. Finally, an improvement in performance of miniature loudspeaker is obtained for reduction in fundamental resonance frequency, reduction in second resonance peak, increase in the bandwidth, increase in low frequency response and increase in SPL over complete range by careful tuning of these parameters.

INTRODUCTION

Growth of small, slim, multifunctional receivers/drivers/miniature-loudspeakers with high sound quality is important requirement for 4C (computer, communication, consumer electronics and car electronics) products. Quest for small sized speakers to integrate cache of functions into a small volume while capable of delivering polyphonic music is dream of manufacturer. Being an indispensable component of product like mobile phone, notebook computer, video recorder, digital camera, dictation device, personal digital assistant, iPod, MP4 player, etc., the performance of loudspeaker with in a small space is very important for the market success of concerned product. Out of various techniques for modeling and simulation of acoustic transducers, ECM is simple and easy to implement. In the current trend of miniaturization of product, space allocated for such components like miniature loudspeaker and other similar in main device is going to be reducing day by day with demands for improved performance.

In his work White [1] had explained the theory and frequency response curve of moving coil earphone. Tashiro et. al. [2] in their paper discussed ECM of loudspeaker for portable multimedia. Bai and coworkers [3-4] have carried out acoustic analysis and design of miniature mobile phone loudspeaker using electro-mechano-acoustical equivalent circuit and finite element method. Huang and coworkers [5] have carried out electroacoustic simulation and experimentation on miniature cellular phone loudspeaker. Huang and coworkers [6] investigated few key design parameters to improve the overall sound pressure level performance over the mid-frequency spectrum for loudspeaker. Klippel [7] in his application notes explained telecommunication driver measurement issues.

In this work, we have measured the frequency response of loudspeaker (DSH935 - 9 mm speaker, Merry Electronics Co., Taichung, Taiwan) for vent open and vent close conditions using B&K Electroacoustic equipment, with SoundCheck 7.02 software in an anechoic chamber. Thiele-Small parameters are measured using Klippel measurement system. ECM model has been formulated based on schematic of loudspeaker. This model is simulated to verify the performance of loudspeaker by comparison with performance obtained by anechoic chamber measurements. Validated ECM model is thus simulated further to investigate effect of various parameters of loudspeaker in two layer manners. In the first layer, diaphragm dependent mechanical parameters and voice coil dependent electrical parameters are isolated and simulation is carried out. In the second layer, the combination of diaphragm dependent mechanical parameters and voice coil dependent electrical parameters are grouped and simulation is carried out. With these results, in second layer, an attempt is extended to combine them again for improvement in the performance.

MATHEMATICAL MODELING

As mentioned earlier equivalent circuit method (ECM) is most simple, easy and fast method for simulation, hence adopted in this work. Miniature loudspeaker used in this study is schematically shown in Figure 1. Diaphragm is most important part of loudspeaker, which moves air in its vicinity and produces sound. It is generally made up of paper, polymer, metal, fabric, composites etc. Each material has very distinct dynamic properties responsible for producing unique response. Generally, a miniature loudspeaker produces sound not only from its front side but also from its back side at the same time. The phases of both sound sources are opposite and as a consequence, the interference between them will lead to the decline of the overall pressure level.

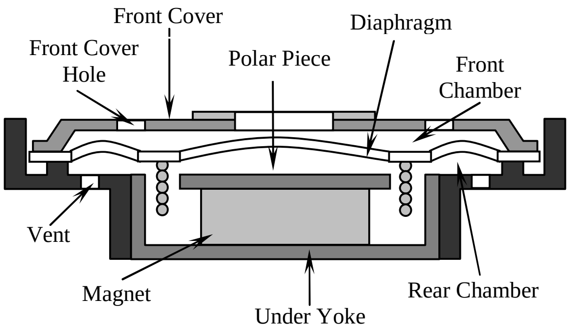

Figure 1. Schematic of miniature loudspeaker

Figure 2 shows the equivalent circuit diagram for miniature loudspeaker. Electrical domain and mechanical domains are related by the transduction/force factor (Bl). Acoustic domain is coupled with mechanical domain by front and rear chambers. Transformer is used to represent this coupling with coupling factor equal to cone/diaphragm area. Front chamber radiates sound through group of circumferential and single central hole in front cover. The leakage is provided to rear chamber by means of vent holes. This leakage does not maintain to direct proportionality between sound pressure and diaphragm excursion. Current flows through voice coil and generate force for excursion of diaphragm. This produces diaphragm velocity (*V*). These diaphragm vibrations promote the motion of air in the vicinity of the diaphragm. This in turn generates volume velocity (U_f) in front chamber and volume velocity (U_r) in rear chamber. The leakage in the rear chamber induces severe dropping-off of sound pressure in low frequency region. By preventing air leakage the dropping-off of sound pressure will be avoided. As shown in the Figure 2 (gray rectangle), for no leakage (vent close) condition, gray rectangle will vanish from the ECM model. In the followings the impedances are given.

The input electrical impedance (blocked impedance) of loudspeaker (neglecting the resistance of driving amplifier) is given as

$$Z_{eb} = R_e + j\omega L_e \quad [1]$$

Where, R_e is electrical resistance of voice coil, L_e is electrical inductance of voice coil, and ω is angular frequency. The mechanical impedance of the loudspeaker diaphragm is given as

$$Z_m = R_m + j\omega m_m + \frac{1}{j\omega C_m} \quad [2]$$

Where, R_m, m_m, C_m, are mechanical resistance, mass, and compliance of diaphragm respectively. The acoustic radiation impedance is adjudged as a parallel combination of acoustic radiation mass (m_{a-rad}) and acoustic radiation resistance (R_{a-rad}) as follows

$$Z_{a-rad} = \frac{j\omega m_{a-rad} \cdot R_{a-rad}}{j\omega m_{a-rad} + R_{a-rad}} \quad [3]$$

Where, $$m_{a-rad} = B_i \frac{\rho_0 a}{A}, \qquad R_{a-rad} = \frac{B_i^2}{B_r}\frac{\rho_0 c}{A} \quad [4]$$

Where, B_i and B_r are constants. For baffled piston condition $B_i = 0.85,\ B_r = 0.5$ and for unbaffled piston condition $B_i = 0.613,\ B_r = 0.25$, ρ_0 is density of air, *a* is radius of diaphragm, *A* is area of breathing sphere that is associated with acoustic radiation impedance, and *c* is speed of sound in air. Normally cavity in the acoustic domain acts as reservoir of compressible fluid with negligible inertia. Due to compressible nature of air in the cavity, it has compliance. Hence, the acoustic impedance of cavity is given by

$$Z_{af} = Z_{ar} = \frac{1}{j\omega C_a} \quad [5]$$

Where, C_a is compliance of cavity which is given as

$$C_a = \frac{V_c}{\rho_0 c^2} \quad [6]$$

Where, V_c is volume of cavity. The acoustic impedance of the small duct/port/tube along with cavity is modeled analogous to “Helmholtz Resonator” It is assumed as a series combination of acoustic mass and acoustic resistance which are given as

$$m_a = \frac{4}{3}\frac{\rho_0 l}{\pi a'^2}, \quad R_a = \frac{8\mu l}{\pi a'^4}, \quad \text{for } ka' < 1 \quad [7]$$

Where, l is length/thickness of the cover (It is analogous to the port length of Helmholtz Resonator), a' is radius of hole in cover (It is analogous to the port radius of Helmholtz Resonator) and k is wavenumber. Considering the loop analysis applied to Figure 2, one can formulate impedance matrix as follows

$$Z = \begin{bmatrix} Z_{T1} & -Z_{af} & -Z_{ar} \\ -Z_{af} & Z_{T2} & 0 \\ -Z_{ar} & 0 & Z_{T3} \end{bmatrix} \quad [8]$$

Where, $Z_{T1} = Z_{eb} + Z_m + Z_{af} + Z_{ar}$, $Z_{T2} = Z_{af} + Z_f$, and $Z_{T3} = Z_{ar} + Z_r + Z_{a-radr}$, Z_{af} is acoustic impedance of front chamber, Z_{ar} is acoustic impedance of rear chamber, Z_f is acoustic impedance of front chamber acoustic holes and acoustic radiation impedance thereafter, Z_r is acoustic impedance of rear chamber acoustic holes, $Z_{a\text{-}radr}$ is acoustic radiation impedance related to rear chamber. As explained earlier, for vent closed condition, the impedance matrix reduces to

$$Z = \begin{bmatrix} Z_{eb} + Z_m + Z_{af} + Z_{ar} & -Z_{af} \\ -Z_{af} & Z_{af} + Z_f \end{bmatrix} \quad [9]$$

For a simple source with $ka < 1$, assuming flat circular piston, sound source results in on axis complex pressure at observation point at a distance r as follows

$$p(r) = \frac{p_s}{r} e^{(-jkr)} \quad [10]$$

Where, p_s is $j\frac{\rho kcU}{2\pi}$ is normally applicable for infinite baffle condition when piston emits volume velocity U ($U = V*A$). On axis SPL of loudspeaker can be obtained as

$$SPL = 20 * \log_{10}\left(\frac{p(r)}{p_{ref}}\right) \quad [11]$$

Where p_{ref} is a reference pressure, which is normally $2\text{x}10^{-5}$ Pa. This is a lowest possible SPL that human ear can recognize.

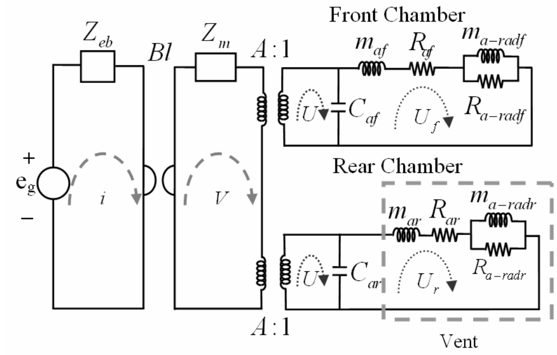

Figure 2. Equivalent circuit for loudspeaker

EXPERIMENTATION

Electroacoustic (TS) parameters for loudspeaker are being obtained by measurement using Klippel measurement system in air and vacuum. Measurements are also carried out in an anechoic chamber using B&K electroacoustic equipment, with SoundCheck 7.02 in accordance with the arrangement as shown in Figure 3. The standard test signal from 20 kHz to 20 Hz is used. The response thus obtained from the test measurement is further processed using SoundCheck. An anechoic chamber measurement result reported in this work is with vent open condition (Figure 2) and simulation investigations are limited to vent open condition only with measurement in air. However to illustrate the effect of vent on SPL response, it is plotted separately for comparison only.

RESULT AND DISCUSSION

Electroacoustic (TS) parameters obtained from Klippel measurement is shown in Table 1. The measurement data is shown for air and vacuum conditions. One can observe the variations in result due to absence of air load on the diaphragm. Comparison between measurement curve and ECM simulation curves (vacuum and air) for vent open condition is shown in Figure 4. Simulation curves exhibits insignificant but observable and permissible difference between them due to variations in the parameters used. Simulation curve follows measurement curve with in ± 3 dBSPL with in usable frequency range. Since, measurements have been performed in air; hence simulation curve in air matches better with measurement curve. Even measurement curve follows simulation curves up to 9 kHz within ± 3 dBSPL, some difference in the break up mode is observed. As expected we observed a big peak (second resonance or first break up mode) at 13 kHz in simulation curves corresponding to the peak at 9 kHz in measurement curve. This is due to limitations of ECM simulation at high frequency when device dimensions and wavelength are compromising. The ECM and measurement curves deviated by large amount at low frequency (20 - 80 Hz). This may be due to some untraced disturbance in the SPL that is beyond the limits of ECM. It is significant but normally acceptable due to its frequency and magnitude. However, within usable frequency range our ECM simulation curve matches with measurement curve, hence ECM model can be conclusively said to be valid for further studies. Figure 5 plots the simulation curve with air and vacuum measurement parameters with vent close condition. Comparison of Figures 4 and 5 clearly illustrate the effect of vent on the SPL response of loudspeaker.

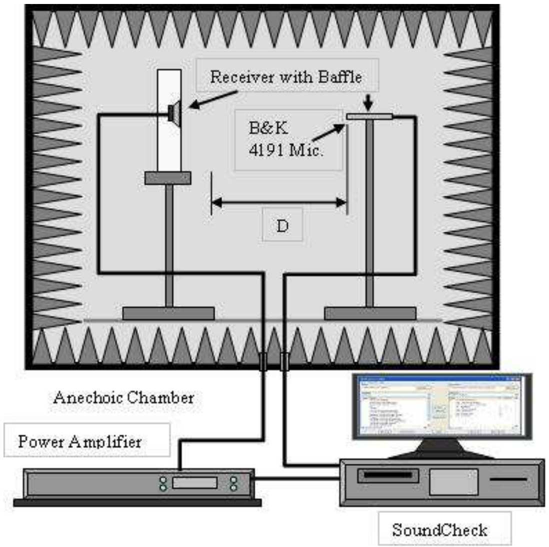

Figure 3. Acoustic measurement test rig/setup

Table 1. Electroacoustic (TS) parameter for loudspeaker

Parameter	Vacuum measurement	Air measurement
R_e (Ohm)	31.09	32.18
L_e (H)	7.50E-05	8.40E-05
m_m (kg)	8.00E-06	1.60E-05
C_m (m/N)	3.19E-03	2.04E-03
R_m (kg/s)	3.00E-03	8.00E-03
Q_t	9.40E+00	7.21E+00
Q_m	1.87E+01	1.11E+01
Bl (N/A)	2.87E-01	3.72E-01
F_s (Hz)	994.7	887.5

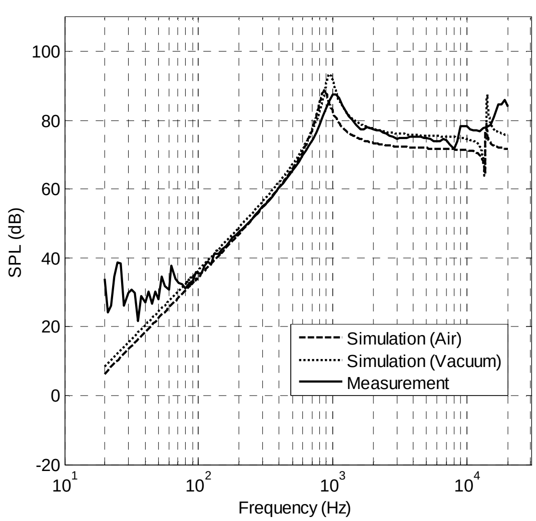

Figure 4. Frequency response with equivalent circuit simulation (vacuum and air) and anechoic chamber measurements for vent open condition of loudspeaker

In the following we are going to simulate our ECM model to understand the contribution of various parameters on the SPL response of miniature loudspeaker. It is accepted fact that simulation provides clear forecast about the performance of device well in advance before actual manufacturing. It was found that various parameters of loudspeaker can be divided into material parameters and design/geometric parameters. The material parameters can be adjudged based on the effect of parameter on the performances of device that are material dependent. Such parameters are magnetic flux density, electrical resistance and electrical impedance of voice coil, mass, resistance and compliance of diaphragm. The design/geometric parameters can be adjudged based on the effect of parameter on the performances of device that are design, dimension, shape and geometry dependent. Such parameters are length of voice coil, area of diaphragm, magnetic motor dependent parameters (height of magnet, thickness of polar piece, air gap, etc.). All other dimension dependent loudspeaker parameters (front chamber and rear chamber related) are grouped in this class. Due to limited scope of this work only material parameters are considered for further investigations.

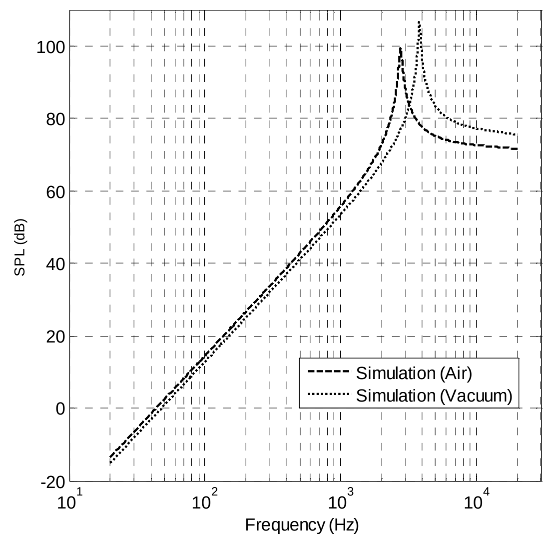

Figure 5. Frequency response with equivalent circuit simulation (vacuum and air) and anechoic chamber measurements for vent close condition of loudspeaker

Study of effect of individual parameters is an academic interest, which can be transferred to the practical device. It gives an astronomical vision about the effect of parameters on various parts of curve. In the following we are prompted to investigate the effect of some main parameters on SPL response of the miniature loudspeaker. These parameters are compliance, resistance and mass of diaphragm, transduction factor between electrical and mechanical domain, transduction factor between mechanical and acoustic domain, electrical resistance and electrical inductance of voice coil. We are not going to investigate transduction factor between mechanical and acoustic domain due to limited scope of this paper.

Effect of compliance of diaphragm on SPL response is illustrated in Figure 6 for variation of compliance by 0.1, 0.2, 1, 5, 10 times. Here, we are attepting to plot base/original curve without any parameter modifications as black curve (solid line). This parameter modification would be follwed for all subsequent curves. It is evident from graph that diaphragm compliance affects frequency response before second resonance. After second resonance, response is independent of compliance. It is found that with increase in the compliance, fundamental resonance frequency reduces with improvement in low frequency response before fundamental resonance. It also improves bandwidth. However, the resonance peak diffuses. Specifically, for 5 times increase, the resonance is observed at 378 Hz, whereas for 10 times increase, it is at 275 Hz. However, on the other hand, decrease in compliance would reduce bandwidth, increase resonance peak frequency, height and sharpness. Excessively low compliance induces unwanted high excursion for diaphragm at fundamental resonance without affecting higher order resonances. One can find promising alternative as increase in compliance. From, above discussion, it is clear that compliance affect fundamental resonance and pre-fundamental resonance response only. Based on general trend of curves, compliance is adjudged as important parameter for SPL response towards further investigations for possible improvement in SPL response.

Effect of resistance of diaphragm (R_m) on SPL response is illustrated in Figure 7. Graph shows that diaphragm resistance affects fundamental resonance peak only. It influences peak height and peak sharpness without affecting resonance frequency. For increase in resistance, resonance peak reduces and becomes nearly flat, specifically for 10 times increase. On the other hand, peak height is found to increase and become sharp with reduction in resistance. One can easily conclude that resistance only control resonance peak.

Effect of mass of diaphragm (m_m) on SPL response is illustrated in Figure 8. Graph illustrates that diaphragm mass drastically affects complete usable frequency response except below 150 Hz. It affects resonance, post resonance and higher order resonance response. For increase in mass, resonance frequency reduces with improvement in bandwidth. The resonance peak becomes sharper, however a drop in SPL is found with reduction in height of second resonance peak. On the other hand, decrease in mass increases resonance frequency, decreases bandwidth, decreases sharpness of peak and increases height of second resonance peak, however SPL increases. Specifically, for 5 times increase, the resonance is observed at 376 Hz, whereas for 10 times increase, it is at 267 Hz. One can conclude that mass only controls high frequency and post resonance response and careful tuning is required to get best possible SPL curve for best possible resonance frequency, bandwidth and sound pressure.

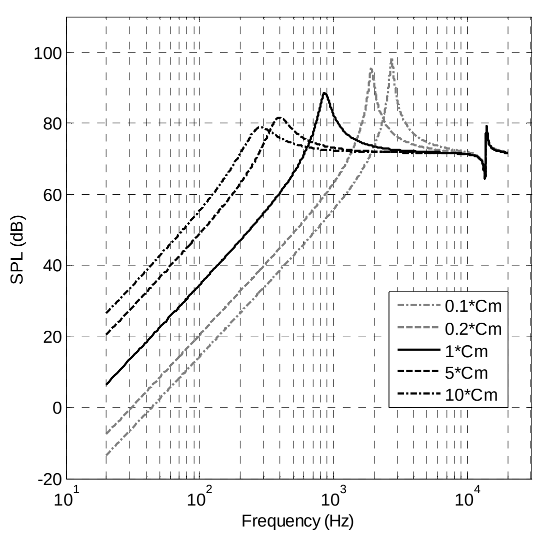

Figure 6. ECM frequency response of miniature loudspeaker for variation in compliance of diaphragm (C_m)

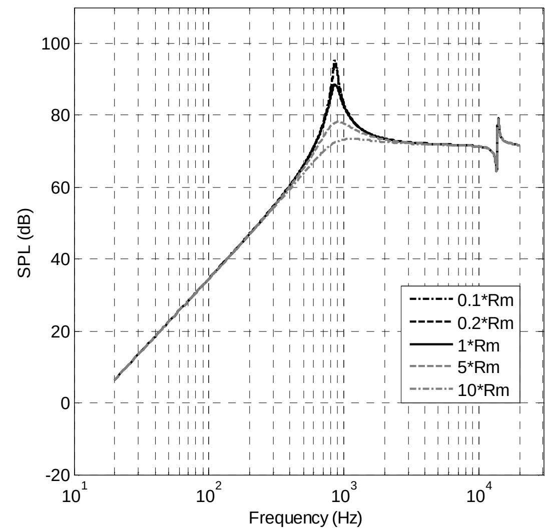

Figure 7. ECM frequency responses of miniature loudspeaker for variation in resistance of diaphragm (R_m)

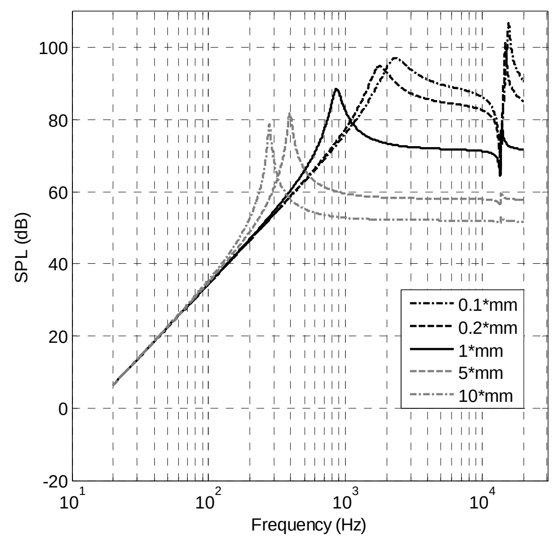

Figure 8. ECM frequency responses of miniature loudspeaker for variation in mass of diaphragm (m_m)

Effect of transduction factor (*Bl*) on SPL response is illustrated in Figure 9. It is evident from graph that transduction factor drastically affects complete frequency response except resonance frequency. Specifically, it influences resonance peak height and sharpness. It is found that with increase in transduction factor, SPL response increases. Specifically, at 5 times increase, response becomes more flat with elimination of resonance peak with slight gain in bandwidth. For 10 times increase, the pre-resonance slope becomes more flat with reduction in dBSPL per octave. On the other hand, decrease in *Bl* decreases SPL response. Fundamental resonance frequency does not get affected by variations in *Bl*, while bandwidth does not get affected for variations in *Bl*, except for minor variations for 5 times and major variations for 10 times increase in *Bl*. Also, higher order resonances remain unaffected by this variation. Hence this can also be adjuded as an impotant parameter.

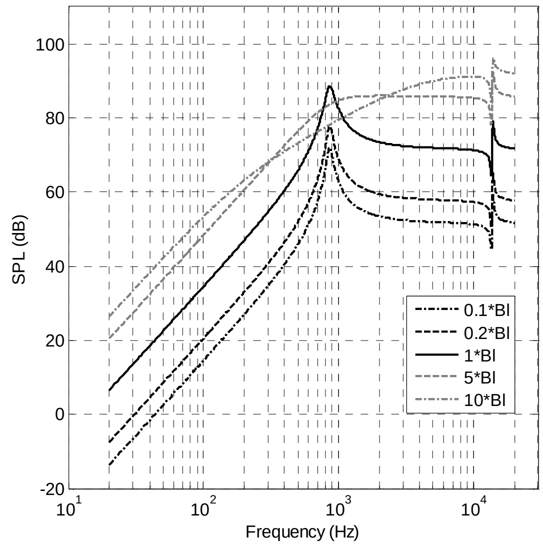

Figure 9. ECM frequency responses of miniature loudspeaker for variation in force factor (*Bl*)

Effect of electrical resistance (R_e) on SPL response is illustrated in Figure 10. It is evident from graph that electrical resistance affects complete frequency response of miniature loudspeaker except resonance frequency. Specifically, it influences SPL, resonance peak height and sharpness. It is found that with increase in R_e, SPL response decreases with increase in sharpness of resonance peak. On the other hand, with decrease in R_e, SPL response increases. Resonance frequency and bandwidth does not get affected by this variation. One can trace that R_e directly influences current through voice coil and hence Lorentz force.

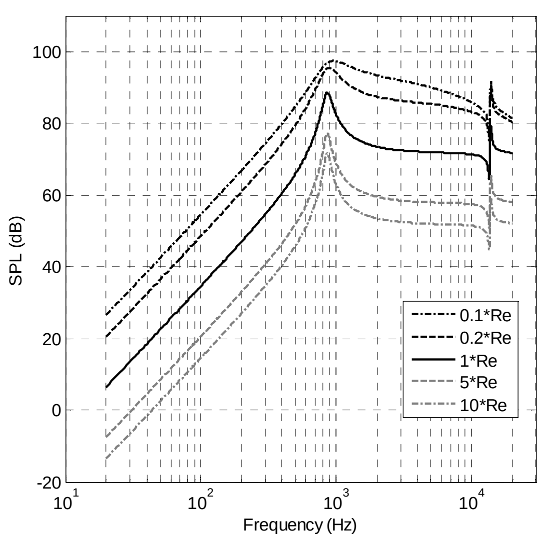

Figure 10. ECM frequency responses of miniature loudspeaker for variation in electrical resistance of voice coil (R_e)

Effect of electrical inductance (L_e) on SPL response is illustrated in Figure 11. It is evident from graph that electrical inductance marginally affects only high frequency response of miniature loudspeaker. Specifically, it influences second order resonance peak when diaphragm breaking may occur. One can observe dropping-off of SPL response for 5 times and 10 times increase in L_e after approximately 5 kHz and 3 kHz respectively.

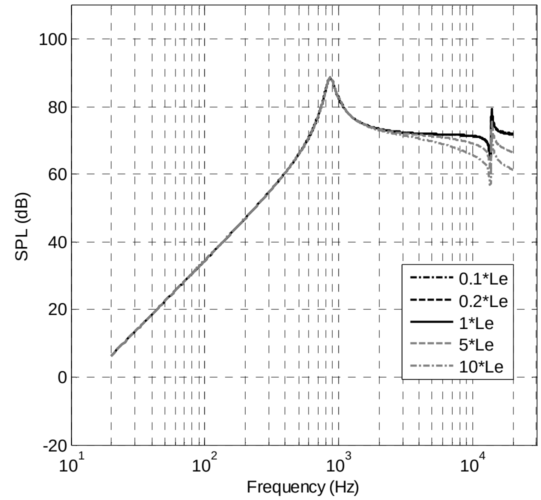

Figure 11. ECM frequency responses of miniature loudspeaker for variation in electrical inductance of voice coil (L_e)

Based on above investigations, we have tried to classify effect of individual parameters on SPL curve. For simplicity we have designated SPL curve into following characteristic regions. These are fundamental resonance peak height, fundamental resonance frequency, second resonance peak, bandwidth pre-resonance slope, post resonance SPL and preresonance SPL. In Table 2 these key characteristics of SPL curve and parameters that affect them are given along with certain remarks. At the same time pertinent finding is given alongside. Study of effect of individual parameters is an academic interest, which can aid to transfer to practical device for improvement in performance. Such simulations, however gives an astronomical vision about effect of various parameters on various parts of curve. To make a sense, we are prompted to investigate effect of integration of various parameters on SPL curve. We have grouped them in logical manner for further study.

Table 2. Effect of parameters on the SPL

Characteristics of SPL curve	Parameter	Remark
Fundamental resonance peak height	C_m, R_m, m_m, Bl, R_e	
Fundamental resonance frequency	C_m, m_m, Bl	*Bl* affects during increase only
Second resonance peak	m_m, Bl, Le	*Bl* affects negligibly
Bandwidth	C_m, m_m, Bl, L_e	*Bl* affects during increase only
Pre resonance slope	Bl	*Bl* affects during increase only
Post resonance SPL	m_m, Bl, R_e, L_e	
Pre resonance SPL	C_m, Bl, R_e	

With above explanation, the second layer investigations are planned for parametric combination. It is found that diaphragm is a key component that controls response. Hence, it is a logical choice to initiate further investigations. In the following we are going to investigate the effect of these combinations in details. The effect of C_m, m_m, and R_m is investigated first. Henceforth this parametric combination is identified as *C1*. Careful tuning of these parameters is required to get desired response. The objective for this simulation is to enhance low frequency response, increase band width of loudspeaker and obtain gain in SPL. It was found that increase in m_m would lower fundamental resonance frequency, lower SPL, improve bandwidth and reduce high frequency higher order resonance peaks. On the other hand, increase in C_m would not affect the SPL but improves bandwidth and low frequency response. The increase in the R_m would only add damping to freeze the rise of SPL at resonance. Hence, all these parameters are increased from 1 to 5 with increment of one. Response thus obtained is shown in Figure 12. The base curve is shown with black color (solid line) for comparison and clear distinction. As per expectation, bandwidth improves at the cost of SPL. Increase of all parameters by two would reduce fundamental resonance to 423 Hz by reduction of approximately 7 dBSPL as compared to base curve. Similarly by increase of all parameters by three, four and five times would reduce fundamental resonance to 287 Hz, 220 Hz and 178 Hz respectively with corresponding reduction of approximately 9 dBSPL, 12 dBSPL and 14 dBSPL as compared to base curve.

In the following we are going to focus our attention on electrical parameters. It is found from earlier graphs, that *Bl* affect complete SPL response, R_e do affect complete response as well, and L_e affect only high frequency response and second resonance peak. Here we would like to focus our attention on material parameters of voice coil. The variation in geometry of coil would affect *Bl*, R_e, and L_e, that may be another research issue, hence it is skipped here. So specifically, we are assuming to change *B* of magnetic material and resistance of voice coil. Henceforth this parametric combination has been identified as *C2*. We have tried some combination of *Bl* and R_e for investigation. For increase or decrease in *Bl* and R_e in combination would not affect the response as per our expectations for improvement. Finally, increase in *Bl* (1 to 5 at an increment of 1) and decrease in R_e by same amount yields the result as shown in Figure 13. Variations in *C2* combination by two and three times yield promising result with appreciable increase in SPL response. Fundamental resonance peak also exhibits acceptable variations. Here, it is important to note that an increase in *Bl* would not affect voice coil inductance.

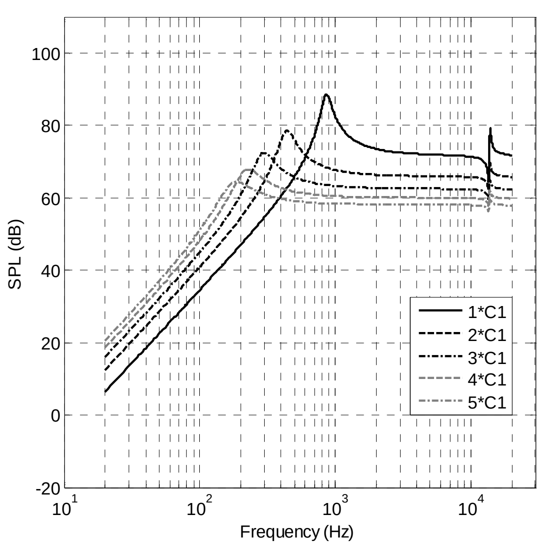

Figure 12. ECM frequency responses of loudspeaker for variation in mass, resistance, and compliance of diaphragm by a factor of 1 to 5 successively.

From Figures 12 and 13, we can modify our loudspeaker for possible improvement in SPL, increase in bandwidth and reduction in resonance frequency by proper tuning of *C1* and *C2* parametric combinations. Results are as shown in Figure 14. A better response is seen for *2-C2+C3* and *3-C2+C3* combinations. These shows reduction in fundamental resonance frequency and second resonance peak; increase in the bandwidth, low frequency response and SPL over complete range. Specifically for *2-C2+C3* combination we can observe fundamental resonance at 457 Hz, more flatness of curve, better gain in SPL and better low frequency response.

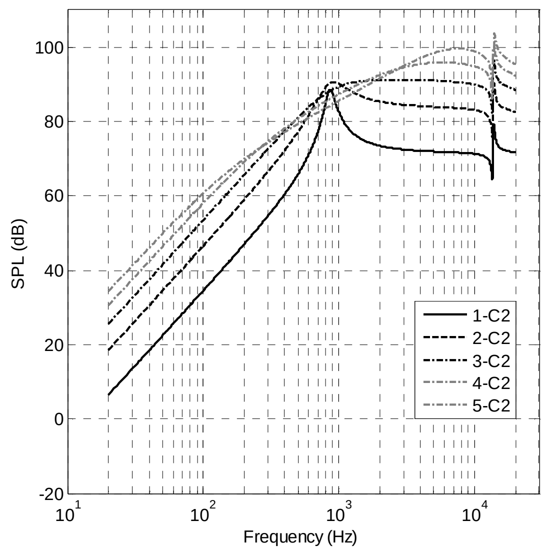

Figure 13. ECM frequency responses of loudspeaker for variation in force factor (increase) and electrical resistance (decrease) of voice coil

CONCLUSION

Equivalent circuit model for loudspeaker has been validated by comparison between simulation curve and an anechoic chamber measurement curve. It is then investigated to find effect of various material dependent parameters of loudspeaker (compliance, mass and resistance of diaphragm; and magnetic flux density of magnet and resistance of voice coil) on SPL. SPL curve has been divided into various sections for clear investigations. The C_m affects fundamental resonance peak height and frequency, hence bandwidth. The R_m affects fundamental resonance peak height only. The m_m affects fundamental resonance peak height and frequency, second resonance peak, bandwidth and post resonance SPL. The *Bl* affects complete curve SPL, fundamental resonance peak height and frequency, second resonance peak, bandwidth and pre resonance slope. The R_e affects complete curve SPL and fundamental resonance peak height. The L_e affects second resonance peak only. Specifically, an increase of C_m, m_m, and R_m by two times would reduce fundamental resonance to 423 Hz with reduction of approximately 7 dBSPL. On the other hand, an increase of all these parameters by three, four, and five times would decrease the fundamental resonance to 287 Hz, 220 Hz, and 178 Hz respectively. Variations in *Bl* and R_e affects complete curve except fundamental resonance frequency and higher order resonance frequency. Specifically, variations in *C2* combination by two and three times yield promising result with appreciable increase in SPL response. Finally, for *2-C2+C3* combination we can observe fundamental resonance at 457 Hz, more flatness of curve, better gain in SPL and better low frequency response. Hence we can expect better response in the vicity of *2-C2+C3* curve.

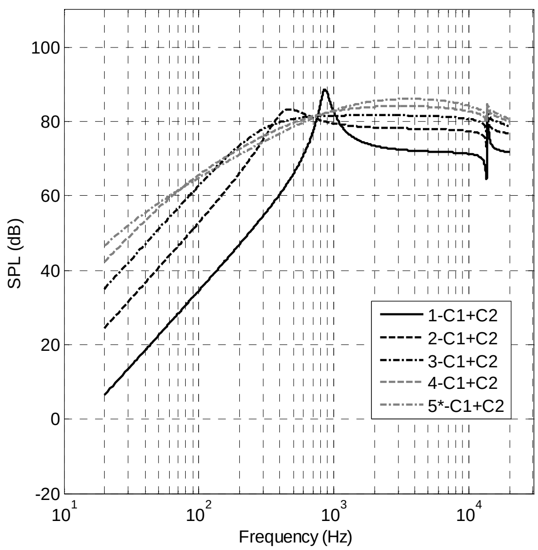

Figure 14. ECM frequency responses of loudspeaker for variation in mass, resistance, and compliance of diaphragm along with force factor and electrical resistance of voice coil

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