

Design and construction of loudspeakers with low- Bl drivers for low-frequency active noise control applications

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ABSTRACT

The design and construction of small sound sources, as the elementary building components of a compound source for low-frequency noise control applications, is investigated. The need for small volume cabinet loudspeakers has led to a vented design with low force factor (Bl) drivers, exploiting their high compliance and low-frequency resonance. The combination of such small powerful sources can lead to dipole or multipole compound set-ups, in which the radiation directivity pattern in open spaces and modal coupling in closed spaces can be controlled via the parameters of the distinct driving signals. The construction constraints of the cabinet are accounted for, considering the loudspeaker's design optimization. A cabinet with two ports tuned close to the driver's resonance frequency is constructed to extend the loudspeaker's output at low frequencies. The impact of the position, dimension, and number of the tubes to the loudspeaker's frequency response are examined through measurements. The design analysis and experiments show the direction to the optimum construction. A pair of these sources combined in dipole configurations is measured in terms of polar radiation pattern. The implementation of such loudspeakers is advantageous in small rooms, where the available space is of great concern.

Keywords: Low- Bl Drivers, Low-Frequencies, Active Noise Control

1. INTRODUCTION

Low-frequency sound reproduction with small transducers is quite inefficient. There are applications in small enclosures where the available space is limited and the volume of control sources is of great importance, as the active noise control (ANC) of low-frequency sound which demands usual bulky secondary sources. ANC techniques have been proposed with secondary compound sources (1). The necessity that secondary sources should be efficient in the whole audible range is not a demand. In order for a driver to be efficient in the low-frequency range (< 100 Hz) or to a more restricted frequency area, it must be included in a large enclosure. So, the dilemma is for the designer to choose either high efficiency or a small enclosure.

Aarts (2) offered a partial solution to this by using the low- Bl concept in cases that small cabinets and high efficiency are important. The so-called low force factor driver has a high and maximum efficiency in a limited frequency region tuned at its low resonance frequency, f_s . The force factor Bl , which is the product of the flux density B [Wb] in the air gap and the effective length l [m] of the voice coil wire, has a very important role in the loudspeaker's design as it determines the efficiency, impedance, SPL response, weight, and cost. As this factor is a measure of the power of electromechanical conversion, low values typically show low damping of the loudspeaker's mechanical parts at f_s . In the same study, the optimum value of the factor to obtain the maximum sensitivity at the driver's f_s is given. This design offers higher power efficiency and voltage sensitivity than usual bass drivers. The loudspeaker may be of the moving-magnet type with a stationary coil because the magnet can be considerably smaller; therefore the cabinet's volume may be smaller. The efficient pass-band range of the driver decreases considerably. Such loudspeakers offer a potential optimization of the low-frequency reproduction because they behave as narrow bandwidth filters with high-quality factors and can be tuned at low resonance frequencies (3).

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In this work, two identical monopole sources of small volume are constructed and measured, after an optimum design. The concept of vented-box loudspeakers is utilized for the successful extension in the low-frequency range comparing to sealed-box ones. As in ordinary rooms the first axial modes extend up to about 80 Hz and below the Schroeder frequency, the aim is to construct monopole sources that have both small volume and high efficiency at a narrow range of about 20 Hz. The construction constraints are accounted via measurements. Two monopole sources are configured in several dipole set-ups and their polar patterns are measured in a fully anechoic chamber. The following sources present the potential of the adaptive directivity sources application to low-frequency ANC in small enclosures (4-8).

2. LOUDSPEAKER DESIGN

2.1 Theory

The Thiele/Small parameters specify the low-frequency performance of a loudspeaker driver and contain the information to calculate the speaker response in any box (9, 10). The resonance frequency of the moving system of a driver is f_s given by Eq. (1), in which the input impedance is maximum. The quality factors Q_{ES} and Q_{MS} of a driver at f_s considering electrical and non-electrical resistances only respectively, lead to Q_{TS} , the total Q of the driver at f_s . Also, V_{AS} is the volume of air in liters having the same acoustic compliance as the driver suspension and is given by Eq. (2).

$$f_s = \frac{1}{2\pi\sqrt{C_{MS}M_{MS}}} \text{ Hz} \quad (1) \quad V_{AS} = \rho c^2 S_D^2 C_{MS}^{-1} \quad (2)$$

where M_{MS} [g] is the mass assembly including air load, S_D [m²] the effective projected surface area of the driver's diaphragm, C_{MS} the suspension compliance, ρ the air density [kg/m³] and c the speed of sound [m/s].

The closed box significantly improves the loudspeaker response at low frequencies and introduces the parameter of the enclosure's air V_{AB} , i.e. the addition of a second compliance C_{AB} , as given in Eq. 3 along with that of the speaker's suspension. The ratio of the two volumes or compliances denoted by α in Eq. 4, determines the degree of coupling of the box with the loudspeaker (11).

$$C_{AB} = \frac{V_{AB}}{S_D^2 \rho c^2} \text{ m/N} \quad (3) \quad \alpha = \frac{V_{AS}}{V_{AB}} = \frac{C_{AS}}{C_{AB}} \quad (4)$$

When inserting the diaphragm into a sealed enclosure, the resonant frequency f_c and the quality factor Q_{TC} are changed accordingly to α . Because of the small volume of the speaker under development ($\alpha > 3$), it is an "air suspension" model, in which the compliance of the enclosed air is smaller than that of the suspension and the damping power of the diaphragm comes mainly from the air of the box. While $f_c > f_s$ in this case, if it is necessary to extend the efficient operating frequency range lower than or even as same as f_s , another action must be taken. In case that the C_{MS} is increased, the f_s is reduced and so does the f_c . Hence, for a fixed enclosure size the ratio α and, therefore the f_c , is increased. One technique for extending the loudspeaker's function to lower frequencies is to add extra mass to the diaphragm, as it is observed by Eq. 1.

With a bass-reflex box (also vented box or reflex-port system) the loudspeaker's efficiency is increased from the sound of the diaphragm's rear side comparing to a closed box at low frequencies. An extra degree of freedom is inserted through the port in the speaker's transfer function as it is a duct of variable dimensions and operates as a Helmholtz resonator since the mass of air inside reacts with the air in the box. There are two resonant frequencies; f_s and that of the port-box resonance, f_B . The ratio $h = f_B/f_s$ is the coupling measure of the loudspeaker with the vented box. The contribution of the port is significant for one to two octaves above the f_B . The output of the port can be combined properly with that of the loudspeaker in a reciprocal way by enhancing the system's response in the lower frequencies. An example of the effect of the parameters h and α on the speaker's response is depicted in Figure 3.

Based on the Small's analysis (11), it is shown that in the acoustical analogous circuit of a vented box loudspeaker system, an induction M_{AP} expressing the acoustic mass of port is added in parallel to the box compliance of air, C_{AB} . Therefore, the LC-loop created by the box-port system has a tuning frequency $f_B = 1/\sqrt{C_{AB}M_{AP}}$ and a factor $Q_L = \omega_B C_{AB} R_{AL}$ that represents the Q of the resonant

circuit at ω_B , with R_{AL} to be the acoustic resistance of enclosure losses caused by leakage, along with the other T - S parameters given by Eq. (4)-(9) from the same work. One more resonance is inserted to the system in addition to that of the closed box. The loop circuit offers an inverse resonance to the input impedance with its minimum at f_B and combined with the f_S results in the impedance response shown in Figure 1. The vent dimensions in accordance with the f_B are calculated by:

$$L_V = \frac{1.463 \cdot 10^7 R^2}{f_B^2 V_b} - 1.463R \quad (5)$$

with the length L_V [in], the box volume V_b [cu in] and the radius R of vent [in]. The minimum diameter to avoid a power loss is $d_V = 39.37 \sqrt{f_B V_D}$ with $V_D = S_D x_{max}$ the cone displacement volume [cu m] (12).

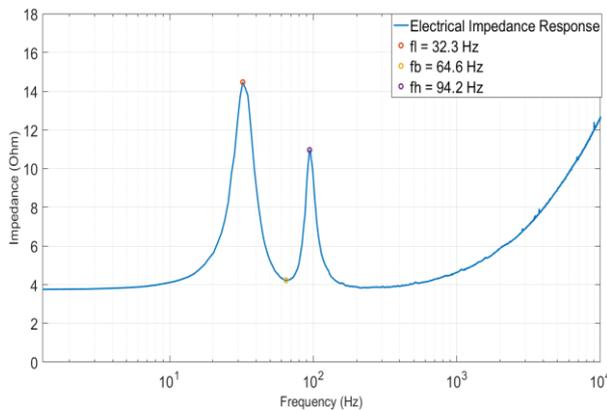


Figure 1 - Typical input impedance curve of a vented box loudspeaker system.

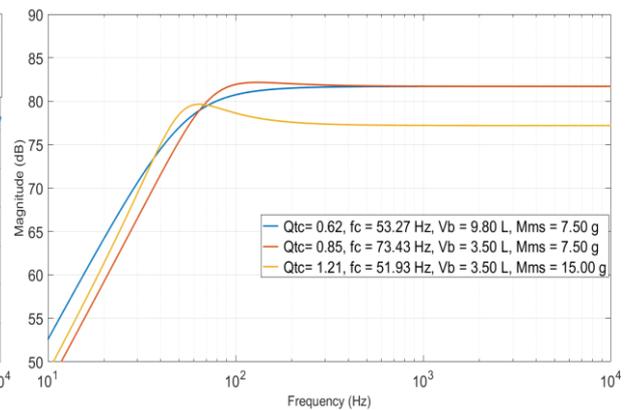


Figure 2 - Design steps of a closed box loudspeaker.

2.2 System design decision

The increase in moving mass reduces the resonance frequency and increases the Q_{TC} . Moreover, the reference sensitivity is decreased (10). However, there is no confirmation that the loudspeaker suspension will withstand the extra mass, or that the diaphragm motion-axis will not be displaced even slightly. The probability of such failures is greater in the case of low- Bl drivers because of the "weak" magnet. Moreover, a possible addition of mass must be done very precisely so as not to change the weight distribution on the diaphragm resulting in the non-linear motion of the cone. In the case of a vented box, the port must be tuned at a low-frequency and the speaker driver must also have a low resonant frequency. The parameters that are at the discretion of the designer to handle are the box volume and the possible addition of mass. Depending on the application, a suitable combination of these parameters leads to different responses.

In the present work, small box volume is the major concern. However, as this is decreased, the f_B increases with the overall quality factor, with the latter to be desirable for greater efficiency near the resonant frequency. It is, therefore, preferable to choose a loudspeaker with as low force factor as possible rather than adding a moving-mass to extend the response to lower frequencies. The 4-inch loudspeaker driver that is used fairly meets the above criteria with $f_S = 37$ Hz and $Bl = 3.43$ T · m.

The volume of implementation to meet the limits and optimize the loudspeaker's low-frequency response must be studied. In order to visualize the changes made by each system modification to the speaker response, a software was developed in Matlab, in which the user can enter the fundamental, the Thiele/Small parameters and the box properties and calculate the transfer function of the loudspeaker. Multiple parameters can be altered and the changes are observed graphically. An example is depicted for the case of a sealed cabinet in Figure 2. The effect of mass-adding is also shown, which is replaced by the port-mass in the final vented cabinets.

An advantage of a vented box is the low cone excursion comparing to a sealed enclosure, i.e. lower distortion, above the tuning frequency. However, this does not stand below the f_B as the excursion rate increases rapidly, meaning a potential rumble noise and cone's destruction, so care must be taken not to drive the speaker in this range (12).

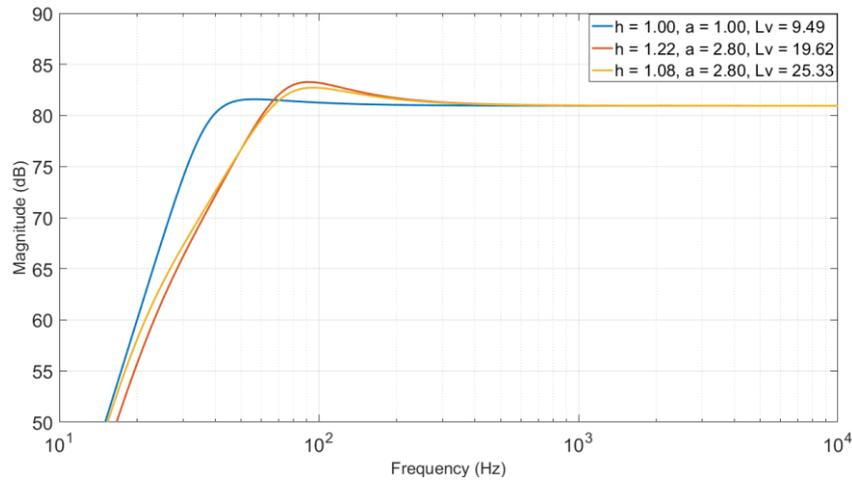


Figure 3 - Effect of α and h in the response of a vented box loudspeaker.

Table 1 - Effect of L_V on f_B in a one-port test box with $d = 3.2$ cm

L_V [cm]	f_B [Hz]
16	52.1
18	47.1
20	44.4
38	44.0

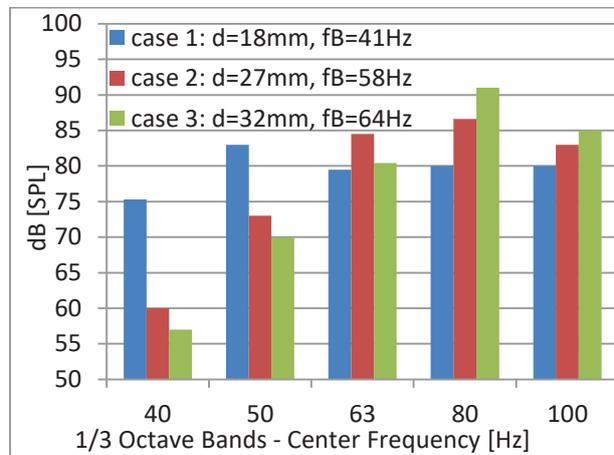


Figure 4 - Maximum SPL of a low- Bl speaker in vented box with two tubes of $L_V = 19$ cm

3. LOW- Bl LOUDSPEAKER IMPLEMENTATION

3.1 Loudspeaker design

In a test box, aluminum pipes of 32, 27 and 18 mm diameter were used. According to Eq. 6 and as can be seen from Table 1, for reducing the f_B in a given enclosure the tube's length must be increased. However, this can be achieved as the length increases up to a certain point, in which the air inside the vent resonates and the f_B is reduced. It seems that an impractical length of a pipe must be used within a one-port box for the f_B to be at 44 Hz. Moreover, the loudspeaker was tested under increasing the input voltage from 2 V (=1 W for 4 Ω drivers) at a step of 0.1 V until the driver started showing non-linear function or fluid noise from the tube was coming. The sound pressure level was tracked with a calibrated sound level meter.

After not so satisfactory results, it was decided to create a second port in the box which was measured with several pipe diameters having the same length, with some results given in Figure 4. It is observed that a lower f_B of 41Hz can be achieved with two vents of much shorter length and diameter. Especially at the center frequencies of 1/3-octave bands of 40 and 50 Hz, the only case with a satisfactory output is the first one, i.e. two pipes of $L_V = 19$ cm and $d = 18$ mm. In Figures 5 and 6, the input impedance with the tuned-box frequencies are depicted and transfer function for four combinations of L_V and d are shown respectively for a double-port box, in order to get the optimum low-frequency response. The effect upon the f_B is apparent. Thus, the choice of the above dimensions for the ports is considered to be suitable, aiming at greater sensitivity to frequencies in the range 40 – 60 Hz.

Finally, two low- $B1$ loudspeakers with outer dimensions of $20 \times 18.5 \times 18.5$ cm were constructed in double-port vented boxes ($f_B = 41$ Hz) with 15mm-thick plywood as shown in Figure 7. The total volume is 5.8 l. Without the driver and ports, the approximate internal volume is 3.5 l.

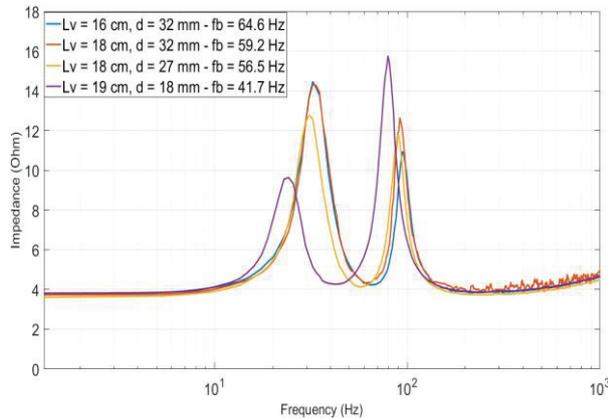


Figure 5 – Measured input impedance with two ports of different lengths and diameters.

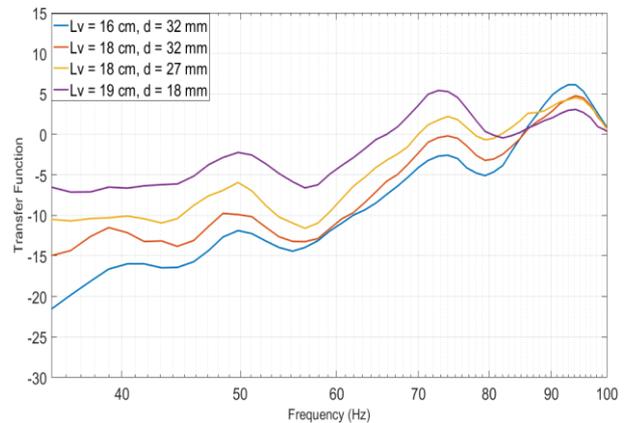


Figure 6 – Measured transfer function with two ports of different lengths and diameters.

3.2 Constructed loudspeakers acoustic measurements

The measurements to obtain the response results and polar patterns of the constructed speakers were conducted in a fully anechoic chamber. The input signal to measure the transfer functions was a pink noise filtered from 35 Hz to protect the loudspeaker from over-displacement. The speakers were also driven by sine waves of certain frequencies to obtain their polar pattern.

The two loudspeakers were measured independently first and then combined in various dipole set-ups to obtain their radiation pattern. The microphone was stationary throughout the measurements, positioned 1.5 m from the sources' acoustic center. As the latter, the center of the box was chosen for the case of one source and the middle of the distance of the two centers for the case of two sources. In Table 2, it is shown that the two sources have the same sensitivity at 1 kHz. The sound level was measured also with sine waves of 40, 80 and 200 Hz. From the monopoles' polar patterns in Figure 8, it seems that their behavior at low frequencies is essentially that of an omnidirectional source with a small deviation (less than 1-2 dB). As these monopoles present an almost identical response with only slight deviations, the next step was to be combined in dipole configurations.

Several dipole set-ups, with the two loudspeakers driven by inverse signals in a distance much smaller than the radiated wavelength, were measured regarding their directivity pattern as seen in Figures 9-10. For example, the FB set-up is the usual dipole with 15 cm distance between the two monopoles. The microphone corresponds to 0° in the patterns. The purpose of the several set-ups was their directivity behavior to be tested for different driver diaphragm and ports orientations of its comprising monopoles.

Table 2 - Loudspeakers responses

f [Hz]	Loudspeaker 1 [dB] (1W@1m)	Loudspeaker 2 [dB] (1W@1m)
40	66.3	66.7
80	80.9	81.1
200	79.2	79
1000	81.3	81.3



Figure 7 - The constructed loudspeakers.

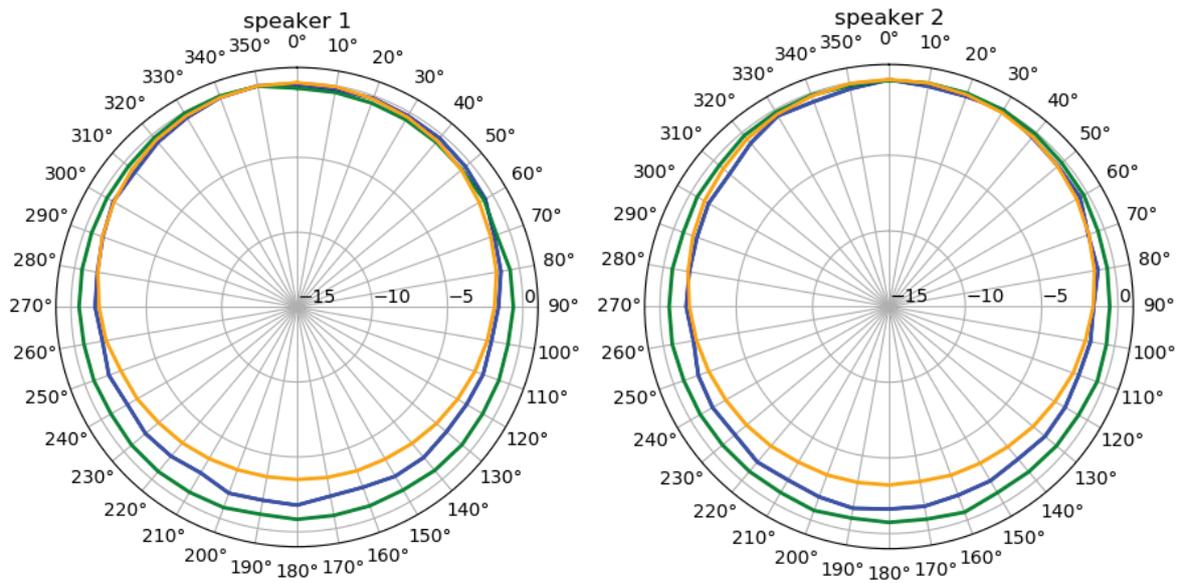


Figure 8 - The measured polar patterns of the constructed speakers for the frequencies of 40 Hz (blue), 63 Hz (green) and 100 Hz (yellow).



Figure 9 – Dipole measurement in a fully anechoic chamber

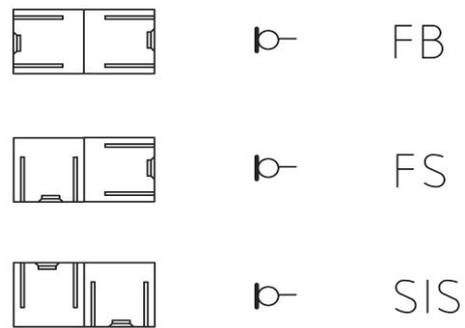


Figure 10 - Dipole configurations. FB: front-back, FS: front-side, SIS: side-inverse side.

4. DISCUSSION

In Table 1, it is observed that in the operation range between 44 and 52 Hz, the length of the port tubes can be changed keeping the loudspeaker volume constant. However, a minimum distance of the tube end from the loudspeaker inner back side must be considered, because of the expected noise. Another notable comment regarding the use of vented box loudspeakers is that care must be always considered not to drive them with high-level signals on frequencies below the f_B , as in this frequency region the diaphragm excursion is increased rapidly and the danger of destroying the driver is severe.

Regarding the FB set-up, it leads to a dipole polar pattern (Figure 11). Sufficient reduction of the

radiated sound is observed at perpendicular directions of the dipole's axis in all frequencies. As far as the other two set-ups are concerned, an expected turning of the pattern in relation to the microphone is presented. Especially in the two lower frequencies, the dips in the dipole shape are weaker than in the case of 100 Hz. This is probably due to the maximized operation of the ports for frequencies close to the f_B , as can be observed for the case of 40 Hz (blue line). The ports function as extra acoustic centers in addition to the diaphragms; therefore more radiation axes in different directions are defined from their combinations. These result in the polar patterns not to have the figure-of-eight shape.

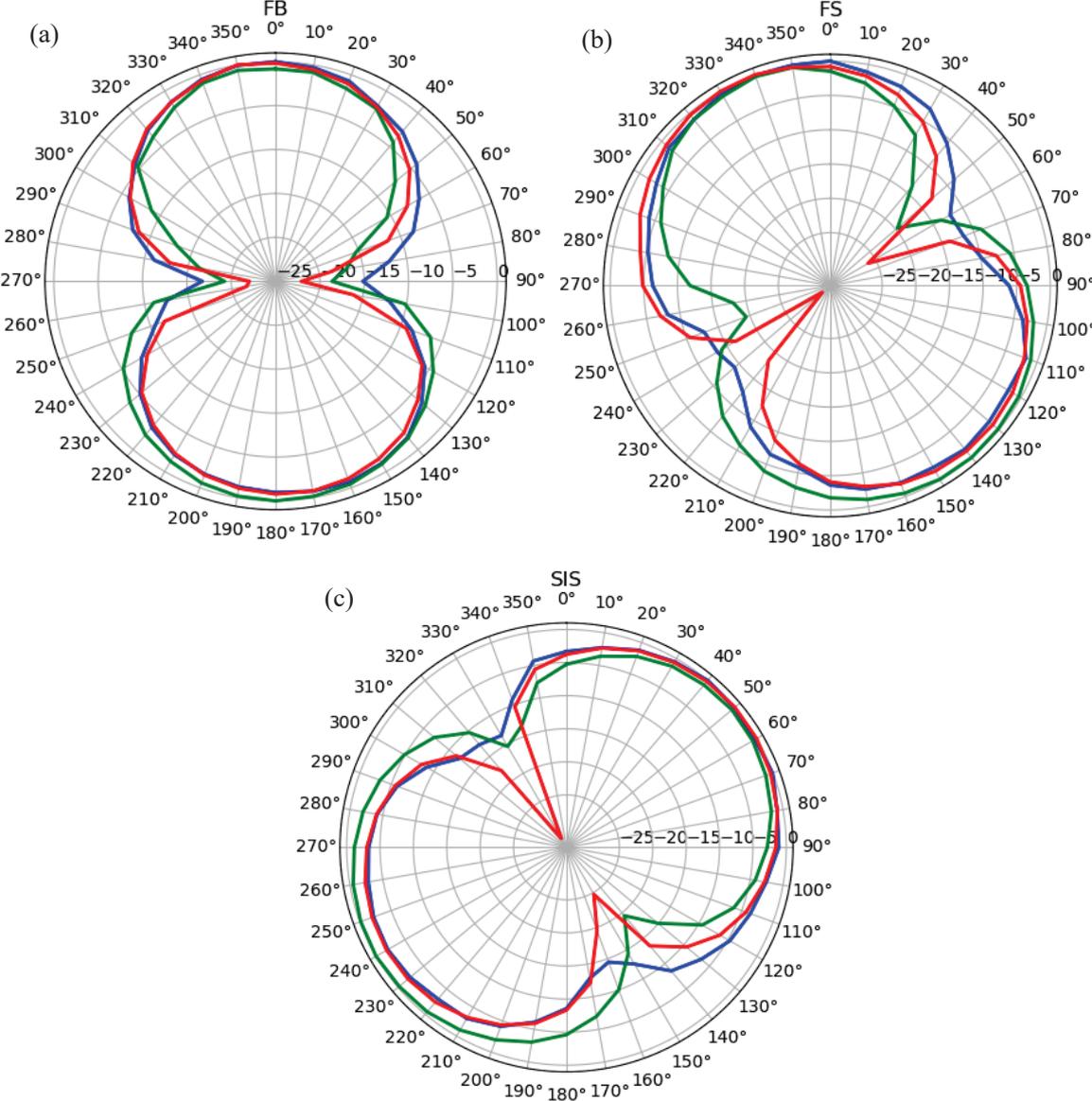


Figure 11 - The measured polar patterns of three dipole configurations (a: FB, b: FS, c: SIS) for the frequencies of 40 Hz (blue), 63 Hz (green) and 100 Hz (red).

5. CONCLUSIONS

This work presents the study and construction of loudspeakers with low-*Bl* drivers for low-frequency applications such as ANC in small closed spaces. Utilizing a low force factor driver with higher suspension compliance, lightweight and small vented box loudspeakers are constructed. Vented box design offers better performance at the lower frequency range than closed boxes, giving the designer the ability to reduce the volume of the speaker cabinet. By increasing the number of ports, better performance in the low-frequency region is obtained. Moreover, the f_B can be tuned in a narrow low-frequency range by changing only the vents while keeping the same cabinet. The designed speakers were tested in dipole set-ups. The polar responses were satisfying in the frequency region

where the loudspeakers radiated through the driver diaphragm, but when the radiation was through the port tubes, it deviated from the typical figure-of-eight response.

The potential implementation of such loudspeakers in combining dipoles or more compound sources is the next step, as they offer the flexibility to configure numerous topologies and provide an alternative to the common bulky monopole sources, especially in small rooms with big restriction in positioning. The requirement that the frequency response to be flat is relaxed as the performance of the speaker in the pass-band is of no concern. The efficient ANC at a narrow low-frequency band in small spaces leads to amplify the speaker response around the f_s and keep it as low as possible along with the enclosure's size. Nonetheless, further investigations including combinations of more-than-one dipoles in different topologies should be made for their radiation patterns, as the design of such compound sources is an advantage for ANC applications.

ACKNOWLEDGEMENTS

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