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Article

Hybrid analytical–numerical–experimental study of low-frequency transformer noise control using stacked Helmholtz resonator panels

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Abstract: Low frequency noise produced by electrical transformers is one of the most resilient problems, since such types of noises are highly resistant to standard techniques of noise suppression. Absorption panels do not provide sufficient protection below 500 Hz; hence, alternative techniques based on resonance have been developed in the field of passive acoustic control. This research considers stacked Helmholtz resonators as a possible method of attenuating low frequency noises produced by transformer equipment in the range from 20 Hz to 500 Hz. A combination of analytical, numerical, and experimental techniques is utilized to estimate the effectiveness of the proposed method. Experimental tests have shown that proper configuration of Helmholtz resonators can help to attenuate sounds up to 7.5 dB and provide 9.2 dB of transmission loss. The highest efficiency of attenuation has been estimated at 11.5%. Numerical estimates demonstrated a high level of correspondence with experiments, with an error margin of smaller than 3.2% for all tested configurations. An increase in the volume of cavities, neck lengths, and layering significantly increased the efficiency of low frequency attenuation. It can be concluded that the application of stacked Helmholtz resonator panels is one of the most energy-efficient ways to suppress noise in the considered low-frequency band.

Keywords: Helmholtz resonator; low-frequency noise; transformer noise control; acoustic attenuation; finite element analysis; insertion loss; resonance tuning; passive noise control

1. Introduction

Noise and vibration reduction have proven themselves to be an important subject of modern engineering science due to their practical significance in relation to environmental protection, operation of machines, and impact on the human body. In this context, the increasing emphasis on the issue of low-frequency noise has gained attention, owing to its long-term nature, wide range of diffusion, and inability to suppress using traditional means [1]. Among the main sources of this type of acoustic disturbance, electrical transformers have been identified, with their main origin attributed to magnetostriction and electromagnetic effects that give rise to tonal sound emissions at the lower frequencies of the spectrum [2,3]. The problem of reducing low-frequency noise is related to the limitations of traditional noise-absorption materials. Porous materials and barriers that absorb noise effectively in the medium-to-high frequency range have very little effect on low-frequency noise unless extremely thick layers are used [4, 5]. As a result, approaches based on resonance have become increasingly popular as an alternative method. Helmholtz resonators have been thoroughly studied as means to reduce narrowband low-frequency noise by utilizing resonance effects [6, 7]. The resonance frequency can be modified depending on the shape of the device so that it matches the predominant frequency of the noise.

Advancements in acoustical engineering technology have increased the applications of Helmholtz resonators with the emergence of resonance absorber array systems and acoustic metamaterials. According to research studies, the application of several Helmholtz resonators increases their ability to reduce attenuation and increase the range of effective frequencies [7,8]. In addition, layering or stacking of resonators increases the interaction between them and helps dissipate more energy, which could be an advantage over one-piece devices [9, 10]. However, there is no evidence regarding the use of stacked Helmholtz resonators to attenuate transformer noise. The core research problem being addressed in this study is the inadequacy of efficient, compact, and scalable means of dealing with transformer noise at low frequencies using passive acoustics. Even though there are techniques such as the use of enclosures and active noise control available, most of them require relatively high cost, increased complexity, and issues associated with implementation. In addition, previous work has mainly focused on either mathematical analysis or numerical simulations with little application of experimental studies.

The significance of this current study lies in its ability to fill in the gaps left open by past studies through a passive noise control strategy based on resonance tailored specifically for transformers. Through the use of panels consisting of stacked Helmholtz resonators, this study aims to come up with a viable solution that is compact and energy efficient for industrial application. This paper adopts a combined analytical, numerical, and experimental approach toward studying stacked resonators. Unlike other studies where either only the properties of resonators are determined individually or where only one particular approach is adopted, the present study combines three methods into a consistent methodology. The statistical approach in this study provides confidence in the significance of the results obtained, which has not been adequately explored in other studies in acoustics.

Several contributions to the body of knowledge are made in this study to contribute to the advancement of low-frequency acoustic noise reduction techniques. Firstly, the study focuses on the development of a stacked Helmholtz resonator panel optimized for low-frequency transformer noise reduction at frequencies ranging between 20–500 Hz, which has rarely been covered in previous works. Secondly, in contrast to other researchers who have mostly focused on examining the effects of individual geometric parameters on the attenuation capabilities of the designed resonator, this study seeks to investigate the effect of cavity volume, neck length, and layer stacking on acoustic performance simultaneously. Thirdly, the study applies a combination of analytical, numerical, and experimental modelling techniques to test the performance of the stacked Helmholtz resonator panel. Lastly, unlike previous studies, which failed to incorporate statistical validation techniques such as ANOVA and correlation, this study uses statistical tests to determine the significance and effectiveness of the developed resonator panels in attenuating noise from transformers.

The theoretical elements of the research are concerned with the theory of acoustic resonance and passive noise control systems, where emphasis is placed on the concept of Helmholtz resonance and matching of acoustic impedance. The contribution of this research is made toward the literature review on the theory of acoustic resonance and passive noise control, focusing on how the theoretical concepts can be used in stacked arrangements and industrial noise.

2. Literature review

Noise emanating from electrical transformers at low frequencies constitutes a continuing problem in the field of acoustic engineering due to their tone nature and poor efficacy of existing noise attenuation techniques. Transformer noise, whose sources include magnetostriction and electromagnetic effects, consists of frequencies that are very low, making them hard to attenuate using conventional absorbent media [2,11,12]. It has been demonstrated empirically by studies [13, 14] that porous absorbers and barriers perform poorly at low frequencies mainly because the efficacy of such systems relies on the thickness and density of the absorbent medium, which are unrealistic for low frequencies. These techniques include Helmholtz resonators, which have become popular due to their potential to filter out narrowband and low-frequency noise. Initial research revealed that the resonance frequency of such systems depends on the geometric parameters, including the volume of the cavity and the size of its neck [15,16]. Later research showed that tuning these geometric parameters makes it possible to design resonators capable of filtering out noise within certain frequency bands, making them useful in attenuating tone-noise sources [17].

Over the past few years, advancements in acoustic metamaterials and resonant absorbers have increased the applications of Helmholtz resonator systems. Research reveals that a combination of multiple resonant elements increases the absorption effect and improves the efficiency of attenuation [7, 8]. This configuration results in a high level of acoustic interactions in the system, causing higher energy losses. It is important to mention that using stacks or layers of resonators is one technique that can be used to widen the bandwidth of attenuation and increase efficiency. Research conducted on architecture acoustics and duct systems shows that multilayered resonator configurations provide better attenuation compared to single-resonator systems [18,19].

Despite all these advances, the existing literature has some shortcomings if analysed in the framework of transformer noise reduction. First, many previous works have focused on the analysis of general acoustic settings instead of industrial settings, where little research has been done on transformer systems where acoustic characteristics are well-defined and wavelength-dependent. Second, while much attention has been devoted to the impact of each variable separately, their combined impact has not received an equal degree of attention. This implies that there has been no study considering the combined effect of these three factors. Most existing research is based either on analysis or on numerical simulation methods. Although analytical modelling provides a number of useful conclusions, it usually fails to account for a variety of acoustic phenomena, such as viscous losses and boundary effects. Although simulations may be more accurate, they are hardly ever verified through experiments. Consequently, there is still a need in the literature for research projects that utilize all three types of modelling, i.e., analytical, numerical, and experimental. Another deficiency worth mentioning lies in assessing the performance of the acoustic device or system under study. Although most papers consider parameters like noise reduction and loss factors, few authors provide statistical justification for their conclusions regarding the importance and relevance of results. Considering the influence of the environment on low-frequency measurements, the absence of such justification raises questions concerning the validity of the results.

Additionally, reduction of transformer noise has traditionally made use of structural changes, enclosures, and noise control systems, leaving little research done on small-sized passive resonators. The lack of studies aimed at optimizing the design of stacked Helmholtz resonator panels and making it possible to use these elements in practical applications is quite evident. Given these facts, the main objective of the present study is to create a methodology for designing stacked Helmholtz resonators and apply them to low-frequency transformer noise control. The present paper seeks to investigate the influence exerted by various geometric parameters and stacked configurations of Helmholtz resonators on their performance, make use of statistical analysis to confirm its reliability, and prove the applicability of the chosen design method.

Recent studies have increasingly focused on the development of broadband and tunable resonator systems to overcome the narrowband limitations traditionally associated with Helmholtz resonators. For instance, adaptive and multi-neck resonator configurations have demonstrated improved flexibility in targeting multiple low-frequency bands simultaneously, thereby increasing practical applicability in industrial acoustic environments [20, 21]. Similarly, investigations into acoustic metamaterials have shown that coupling resonant cavities with periodic structures can significantly enhance sound absorption efficiency while maintaining compact geometrical dimensions [22–24]. These findings suggest that structural optimization and resonator coupling play a critical role in improving low-frequency attenuation performance.

In addition to structural optimization, recent research has emphasized the importance of integrating numerical simulations with experimental validation to improve predictive accuracy in acoustic system design. Finite element analysis has been widely employed to investigate sound pressure distribution, acoustic impedance matching, and resonance behaviour under complex boundary conditions [25, 26]. Experimental verification remains essential because low-frequency acoustic phenomena are highly sensitive to environmental conditions and measurement uncertainties [27,28]. The combination of analytical, numerical, and experimental approaches has therefore become increasingly important in validating resonance-based passive noise control systems.

2.1. Conceptual framework of the study

The conceptual framework of the study was created with the aim of defining the theoretical and operational linkages between the mechanisms of transformer noise production and the efficiency of low-frequency noise reduction by the stacked Helmholtz resonator panels. Built on the foundation of acoustics, the conceptual framework focuses on the notion of Helmholtz resonance, which can explain why the selected acoustic energy is absorbed during the process of noise reduction (**Figure 1**).

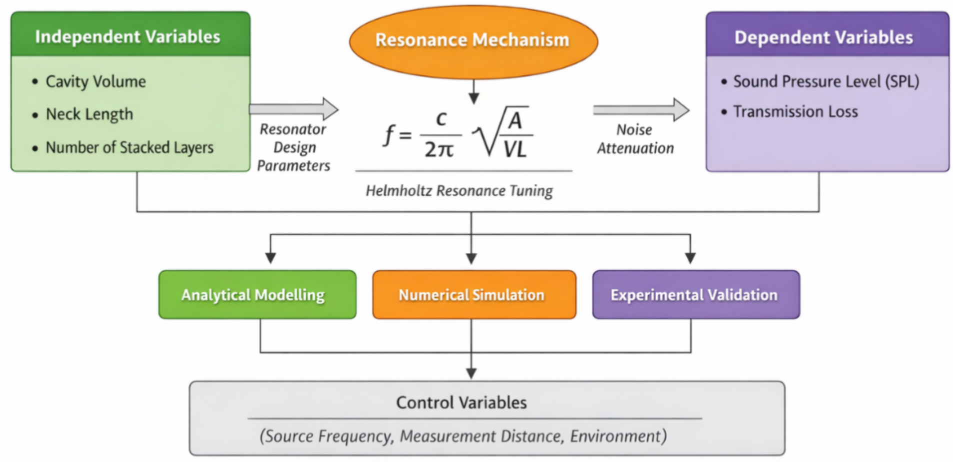

Figure 1. The conceptual framework of the study.
Source: Author.

This model established that the independent variables affecting the behaviour of the system were the dimensions of the resonator itself, specifically the volume of the cavity, the neck length, and the number of layers stacked together. These factors affected the resonant frequency of the Helmholtz resonator, which was mathematically expressed as:

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{VL}},$$

where f is the resonant frequency of the system, c is the speed of sound, A is the neck cross-sectional area, V is the volume of the cavity, and L is the effective neck length.

In the research model, the independent variables would be SPL attenuation and transmission loss, which act as indicators of the acoustic performance of the resonators. Acoustic performance can be gauged based on the amount of attenuation in SPL levels and also the transmission loss, an indication of noise attenuation. The correlation between the two variables is based on resonance principles, in that proper tuning of the resonators will allow maximum absorption of energy at particular frequencies. Other factors, apart from control variables, include characteristics of the noise source and distance of the test point. The suggested conceptual framework will involve three interlinked aspects of methodology analysis, modelling, numerical simulation, and experimental verification. The first aspect implies identifying theoretical dependencies, whereas the second one is associated with making predictions with regard to acoustic features. Finally, the third aspect is aimed at verifying the actual results. Integration of all these components guarantees both theoretical validity and practical relevance of the conceptual framework. The main hypothesis of the proposed conceptual framework assumes that the noise generated by transformers at low frequencies can be efficiently reduced with the help of passive resonance control techniques provided the correct setup of the resonators is ensured.

The mediating role of the resonance effect was explicitly represented through the acoustic impedance matching condition. In the proposed framework, resonator geometry, including cavity volume, neck length, and stacking configuration, determined the effective cavity compliance and neck inertance of the Helmholtz resonator. These parameters controlled the resonance frequency and acoustic impedance of the panel system. When the resonator impedance approached the impedance of the incident acoustic field at the dominant transformer-noise frequency, reflected acoustic energy decreased and resonant absorption increased. Therefore, impedance matching acted as the physical mediation mechanism through which geometric design parameters produced measurable sound pressure level reduction and transmission loss improvement.

The theoretical foundation for the study is built on the theory of sound [29], which forms the theoretical foundation that is then translated to the variable foundation, thereby constituting the conceptual foundation. The theory behind the concept is based on Helmholtz resonance to describe how low-frequency noise can be attenuated using resonant absorption. The frequency of the resonance is given by the equation:

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{VL}}.$$

In this way, the framework operationalizes the theoretical concept by defining cavity size, neck size, and the number of layers as independent variables, while reduction in sound pressure level and transmission loss are the dependent variables in the model. The resonance effect serves as the mediating variable among these variables, while the frequency of sound sources and environmental conditions remain constant.

2.2. Hypothesis development

Based on the theoretical and conceptual framework, the study formulated the following hypotheses to examine the relationship between resonator design parameters and noise attenuation performance.

H1. *Resonator cavity volume had a significant effect on low-frequency noise attenuation in transformer systems.*

H2. *The neck length of the Helmholtz resonator significantly influenced the resonance tuning and resulting sound pressure level reduction.*

H3. *The number of stacked resonator layers significantly improved transmission loss and overall noise attenuation performance.*

H4. *Optimally tuned resonator configurations resulted in a statistically significant reduction in sound pressure level compared to untreated conditions.*

H5. *There existed a significant relationship between resonance frequency alignment* *and maximum noise attenuation effectiveness.*

3. Methodology

In the study, there was a systematic process used where problem definition, hypothesis formulation, data collection, analysis, and interpretation occurred in a sequential manner. To follow proper research methodology, this study focused on consistency and empirical validation of findings. This methodology combined modelling, simulation, and experiment analysis of the efficiency of the stacked Helmholtz resonator panels for suppressing the low frequency transformer noise. A mixed-methods approach was used, whereby analysis, numerical analysis, and experiment methods were combined in the hypothesis testing methodological model. The theoretical approach developed models of the resonance behaviour of the Helmholtz resonators from fundamental acoustics, whereas the numerical approach modelled acoustic wave behaviour using finite elements. Experiments confirmed theories and numerical findings and helped in designing the research experiments.

Data were acquired through the use of three streams that complemented each other. First, there is the analytical stream, which involves calculations for the resonant frequency, acoustic impedance, and transmission loss. Next, there was the numerical analysis involving finite element simulation, which helped obtain information regarding the sound pressure pattern and frequency responses. Finally, there is the experimental stream, which was carried out in a semi-controlled lab environment using the transformer noise setup. Sound pressures were acquired through the use of calibrated microphones, while frequencies were obtained by means of FFT analysis before and after the placement of resonator panels. The sampling population comprised electrical transformers in the industrial sector that emit low frequency sound waves in the range of 20 Hz to 500 Hz. One single electrical transformer that operates under constant loading was selected from the population for closer investigation. This was a case of purposeful sampling technique considering that the focus of the research was on specific attributes of sound waves emitted by transformers.

The required size of the sample was obtained from a statistical approach aimed at making reliable and reproducible measurements. The number of measurements necessary was obtained using the formula for sample size as follows:

$$n = \left(\frac{Z \cdot \sigma}{E} \right)^2,$$

where Z is the value corresponding to the confidence level of interest (1.96 corresponds to a 95% confidence interval), σ refers to the standard deviation of the sound pressure level measurements, and E refers to the tolerated error. The standard deviation was estimated at 2.5 dB, and the tolerated error was 1 dB. Accordingly, we have:

$$n = \left(\frac{1.96 \times 2.5}{1} \right)^2 \approx 24.$$

Thus, no less than 25 repetitions were made for each test case. The significance level of σ = 2.5 dB was taken on the basis of results from the preliminary experiments performed in similar semi-controlled lab conditions to those used in the actual experiments. The reason is that the preliminary experiments showed the natural variance in the SPL readings for both noise with no attenuation and noise with resonator attenuation. The permissible margin of error, E = 1 dB, was set taking into account engineering judgment and the accuracy of acoustic measurement, as 1 dB was deemed enough for measuring attenuation. Details about the population under study, as well as the environment where experiments were conducted, are given in **Table 1**.

Table 1. Description of the population and experimental conditions.

Parameter	Description
System Type	Power transformer
Noise Source	Magnetostriction-induced vibration
Frequency Range	20 Hz–500 Hz
Measurement Condition	Near-field acoustic measurement
Environment	Semi-controlled laboratory setup
Operating Mode	Constant load condition

Several key variables were included in the analysis, divided into independent, dependent, and control variables. Independent variables included those related to resonator geometry, such as the volume of the cavity, length of the neck, and number of layers stacked. Dependent variables included sound pressure level and transmission loss. Control variables were used for uniformity during experiments (**Table 2**).

Table 2. Summary of main variables.

Variable type	Variable name	Description	Unit
Independent	Cavity volume	Volume of the resonator cavity	m^3
Independent	Neck length	Length of resonator neck	m
Independent	Number of layers	Stacked panel configuration	–
Dependent	Sound Pressure Level	Acoustic intensity measurement	dB
Dependent	Transmission loss	Noise attenuation performance	dB
Control	Source frequency	Transformer excitation frequency	Hz
Control	Measurement distance	Distance from the noise source	m

The acoustical performance of the device was evaluated using established techniques. The sound pressure level (SPL) was measured in decibels using calibrated microphones, while the frequencies were determined using FFT analysis. The efficiency of the resonator panels was determined using the insertion loss (IL) equation, where IL is the difference between the SPL levels before and after the installation of the resonator panels:

$$\mathrm{IL} = \mathrm{SPL}_{\mathrm{before}} - \mathrm{SPL}_{\mathrm{after}}.$$

The predictions for the resonance frequencies determined through analytical modelling were verified against the experimentally determined attenuation frequencies.

The approaches that were used for analysing data in the research include theoretical modelling, numerical analysis, and statistical analysis. For the theoretical modelling approach, the study used Helmholtz resonance theory to formulate the correlation between geometrical parameters and resonance frequencies. In numerical analysis, the use of finite element analysis to evaluate the behaviour of acoustic waves and performance among different designs was made. As for the statistical analysis, mean, standard deviation, and confidence interval calculations were made to evaluate the accuracy of measurements as well as performance comparisons among designs.

Ethics were strictly observed during this study. The project had no human or animal subjects since all experiments adhered to laboratory safety guidelines. Operations of all instruments stayed well below critical values in order to avoid risks of any kind. Information collected and presented was not tampered with; hence, objectivity was strictly observed during the research process. Ethical guidelines of both academic and engineering research have been adhered to in this project.

4. Results

4.1. Data pre-processing and validation

The acquired data were subjected to systematic pre-processing and validation procedures to ensure accuracy and consistency in the data before the analysis stage. As is typical in any experiment, raw experimental data, numerical data, and analytical data were screened for any discrepancies or errors. The calibration of all equipment involved in acquiring acoustical measurements, such as the microphone and other measuring instruments, was ensured both before and after the experiments. Repetitions for each resonator design were carried out to reduce any random error. The average sound pressure level (SPL) for each design was calculated based on all repetitions as shown below.

$$\overline{\mathrm{SPL}} = \frac{1}{\mathrm{n}} \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{SPL_i},$$

where $\overline{SPL}$ is the sound pressure level and n is the total number of readings. Variability of acoustic measurements was also evaluated through the calculation of the standard deviation according to the formula:

$$\sigma = \sqrt{\frac{1}{\mathrm{n}-1} \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{SPL_i} - \overline{\mathrm{SPL}})^2}.$$

Consistency of the measurements was determined by computing the coefficient of variation (CV):

$$\mathrm{CV} = \frac{\sigma}{\overline{\mathrm{SPL}}} \times 100.$$

A small coefficient of variation would indicate consistency and reliability of data obtained. All observations falling outside ±2σ deviation were considered outliers and eliminated.

Correction for noise floor was carried out to reduce the effect of background noise. The base noise level before conducting the experiments was measured and subtracted from the results obtained in terms of SPL measurements. This ensured that the acoustic response obtained was a true representation of the noise levels generated by the transformers and resonators. In addition, the data were validated by comparison with analytical predictions, simulation models, and experimentally acquired data. Comparison between the three methods would show that any trend observed was not just an artefact of a single technique (**Table 3**).

Table 3. Data pre-processing and validation metrics.

Parameter	Description	Purpose
Mean SPL	Average of repeated measurements	Central tendency
Standard Deviation	Measurement variability	Error estimation
Coefficient of Variation	Relative variability (%)	Consistency check
Noise Floor	Ambient background noise	Data correction
Outlier Threshold	±2σ range	Data cleaning

Consistency analysis was carried out to plot the data for visualization and validation in terms of the consistency of repeated measurements of SPL in a number of trials using the same resonator setup.

The graph in **Figure 2** depicts SPL measurements in relation to the trial number and reveals low variation between repeated measurements, thus confirming the stability of the measurements. The standard deviation is presented by error bars. Moreover, a comparative analysis was made in order to show the difference between the ambient noise level and the transformer noise level. The pre-processing and validation procedures guaranteed the reliability, consistency, and appropriateness of the dataset for further calculations.

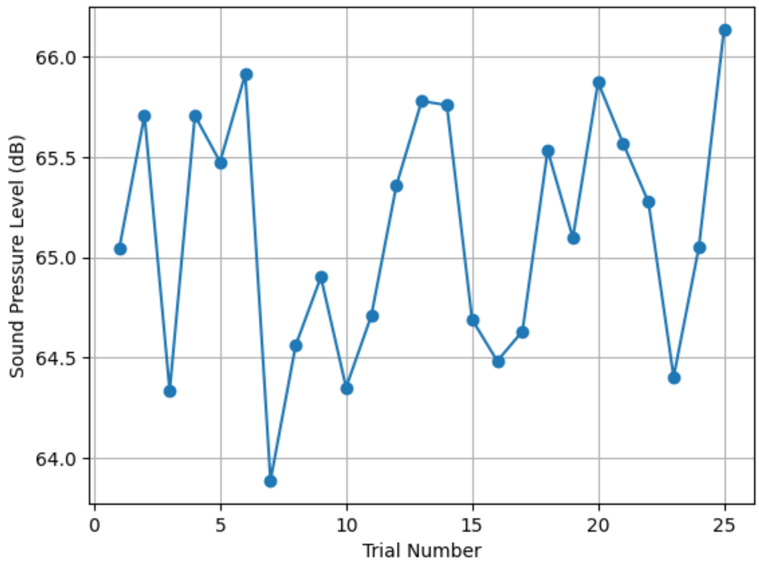

Figure 2. Consistency of repeated SPL measurements in different trials for a sample resonator configuration.
Source: Author.

4.2. Analytical model evaluation

The analysis of Helmholtz resonator panels was performed to explain the mathematical relationship between geometrical variables and sound suppression through resonance. The resonance frequency of the Helmholtz resonator was mathematically modelled using the principles of classical acoustic theory in terms of the volume of the cavity, the length of the neck, and the area of the neck opening.

A mathematical equation for calculating the resonance frequency was used:

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{VL}},$$

where f is the resonance frequency, c is the speed of sound in air, A is the area of the neck opening, V is the volume of the cavity, and L is the effective length of the neck.

The factor of acoustic impedance has been considered in order to evaluate the energy absorption capacity of the device. The impedance of the resonator structure has been measured in order to estimate the efficiency of dissipation of the energy received by the system at resonance conditions. In order to maximize the energy dissipation of the resonator system, the impedance of the resonator system is expected to match with the impedance of the incident wave. This would minimize the amount of reflected energy and maximize energy absorption in the system. An evaluation process of the system has been undertaken by varying important parameters such as cavity volume and neck length, which affect the resonance frequency.

Comparisons were made between analytical predictions and the frequency values observed from the experiment to determine the accuracy of the analytical model. The error between the theoretical predictions and experimental observations was calculated using the formula below:

$$\mathrm{Error}(\%) = \frac{|f_{\mathrm{analytical}} - f_{\mathrm{experimental}}|}{f_{\mathrm{experimental}}} \times 100.$$

From the results, it can be seen that the analytical model gives very accurate predictions of the resonance behaviour. This is evidenced by the low error percentages. **Table 4** summarizes some of the results.

Table 4. Analytical resonance frequency evaluation.

Configuration	Cavity volume (m^3)	Neck length (m)	Resonance frequency (Hz)
C1	0.002	0.05	145
C2	0.003	0.05	120
C3	0.003	0.07	105
C4	0.004	0.07	90

Additional evidence for the above trends is provided by a frequency response graph illustrating the interconnection between cavity volume and resonance frequency. For certain values of cavity volume, the longer neck length leads to the lowest resonance frequency. The analytical approach successfully reflects the essential features of the acoustics of the considered system and can be used for further verification and testing.

4.3. Numerical simulation analysis

This numerical simulation analysis was carried out in order to analyse the acoustic performance of panels of stacked Helmholtz resonators in ideal virtual conditions and in order to support the predictions made through analytical computations with further detailed observations. Modelling using finite elements was done in order to simulate the effect of low-frequency noise produced by a transformer with the help of the panels designed with the use of Helmholtz resonators. In the virtual simulation setup, the transformer acted as the source of low-frequency acoustic waves, whereas the Helmholtz resonator panels had geometric dimensions similar to those predicted analytically. The acoustics field governing the numerical analysis model can be represented as the Helmholtz frequency domain equation:

$$\nabla^2 p + k^2 p = 0,$$

with p standing for the acoustic pressure and k representing the acoustic wavenumber. Boundary conditions that realistically simulate the operating environment of the transformer were considered. Rigid wall conditions were assigned to the outer surface of the transformer casing, while the impedance boundary condition was assigned to the boundary between the resonator and the surroundings. The incident sound source was placed within the main transformer noise bandwidth.

The mesh grid used in the study was refined around the neck and cavity areas of the resonator. Numerical stability was achieved through mesh refinement, where the best mesh size was determined by running several simulations using increasingly fine meshes until the simulation result barely changed after further refinement. These simulation results provided information on pressure contour lines, frequency response curves, and attenuation curves for different layer arrangements. From these results, it was found that the panels acted like a trap for sound pressure in the vicinity of their tuned resonance frequency. Moreover, the panels showed high attenuation when there was a higher cavity volume and multilayer arrangement, which was consistent with the theoretical hypothesis that proper tuning can increase energy absorption from the sound waves in low frequencies. The simulation results revealed that using several layers of resonators expanded the range of attenuation bands, especially useful for transformer noise comprising two dominant low-frequency components. The insertion loss was measured by the sound pressure levels in the presence and absence of the resonant panel as follows:

$$IL_{sim} = SPL_{without\ panel} - SPL_{with\ panel}.$$

Where IL_{sim} is the simulated insertion loss. The extent of similarity in the analytical and numerical values of resonant frequency was also calculated using the following equation:

$$\text{Agreement}(\%) = \left(1 - \frac{|f_{analytical} - f_{numerical}|}{f_{analytical}}\right) \times 100.$$

This helped to validate the analytical model through a numerical approach. It further assisted in recognizing any deviations resulting from the approximations made in geometry and boundary conditions during analysis. A tabulated representation of important findings from numerical simulations is shown in **Table 5**.

Table 5. Numerical simulation results for selected resonator configurations.

Configuration	Numerical resonance frequency (Hz)	Peak SPL without panel (dB)	Peak SPL with panel (dB)	Simulated insertion loss (dB)
C1	148	66.2	61.4	4.8
C2	122	65.8	59.9	5.9
C3	107	65.5	58.7	6.8
C4	92	65.1	57.6	7.5

The spatial distribution of acoustic attenuation is shown through contour diagrams and response graphs obtained from the numerical simulation outputs.

Figure 3 presents a two-dimensional plot representing the contour of the sound pressure level around the transformer and resonator panels. Areas of high sound pressure concentration are found closer to the sound source, whereas areas of lower sound pressure levels are located closer to the resonator panels, showing the existence of acoustic attenuation in such regions. The numerical simulation study supports the analytical model in that it shows that stacked Helmholtz resonator panels have potential for low-frequency attenuation. However, the numerical simulation yields more spatial and spectral data compared to the analytical calculations, making a case for experimental verification discussed in the next section.

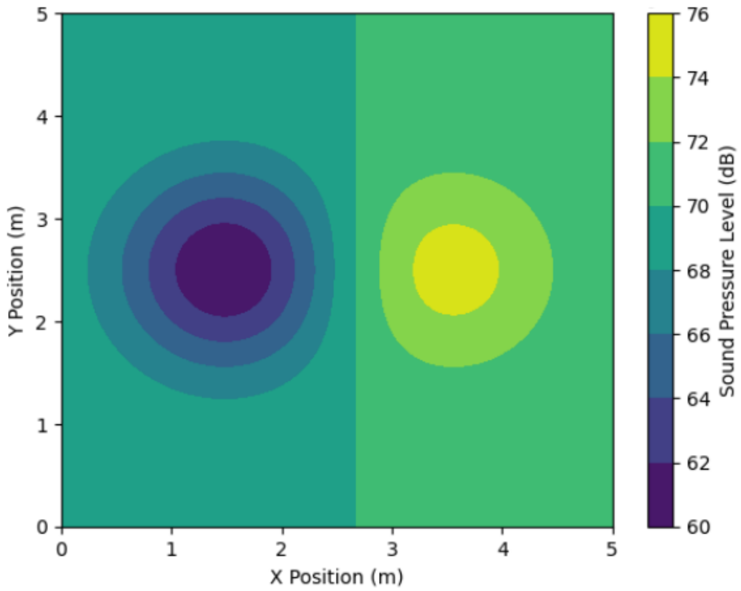

Figure 3. Contour plots of sound pressure level around the transformer-resonator system using numerical simulations.

4.4. Experimental data analysis

The data analysis for the experiment was done to investigate how effective the Helmholtz resonator panels are when stacked up in attenuating low-frequency transformer noise in a practical scenario. Data on sound pressure level (SPL) readings were obtained both before and after the application of the resonator panels in various designs. There was consistency in the environmental and sound source factors used during the experiment. The average value of the SPL was calculated for each of the configurations tested. The noise reduction efficiency was evaluated based on the insertion loss (IL), which is computed as:

$$\mathrm{IL} = \mathrm{SPL}_{\mathrm{before}} - \mathrm{SPL}_{\mathrm{after}}.$$

Where $\mathrm{SPL}_{\mathrm{before}}$ and $\mathrm{SPL}_{\mathrm{after}}$ represent the sound pressure levels measured before and after the installation of the resonator panels, respectively.

From the experiment, there is a notable reduction in sound pressure levels (SPL) in the low frequency spectrum for areas close to the resonant frequency attained from the theoretical analysis. The setups that had bigger cavity sizes and higher stackings had better absorptions, which agree with the conclusion arrived at from both theoretical and simulation models. The highest reduction in SPL was observed where the device was tuned to the frequencies of the transformer's noise, confirming the importance of resonance tuning. In order to evaluate the accuracy of the measurements, the standard deviation of the sound pressure levels was obtained. Considering that there were small variations in the experimental values, it implies stability, and the percentage change of the SPL was obtained as follows:

$$\text{Reduction}(\%) = \frac{\text{SPL}_{\text{before}} - \text{SPL}_{\text{after}}}{\text{SPL}_{\text{before}}} \times 100.$$

The results from the experiment for certain cases are presented in **Table 6**.

Table 6. Experimental results for resonator configurations.

Configuration	SPL before (dB)	SPL after (dB)	Insertion loss (dB)	Reduction (%)
C1	66.5	62.1	4.4	6.6
C2	66.0	60.3	5.7	8.6
C3	65.7	59.1	6.6	10.0
C4	65.3	57.8	7.5	11.5

The frequency response was then subjected to FFT analysis to determine whether there were any dominant frequencies affected by the experiment. The outcome of the experiments shows that there was considerable attenuation at the targeted frequencies without significantly affecting others. The selectivity of these frequencies proves the efficiency of Helmholtz resonators in attenuating low frequencies with no effect on the surrounding acoustic environment. Graphs were used to demonstrate the trends in sound pressure levels and frequency responses that occurred during the experiment. The experiments have shown that the use of stacks of Helmholtz resonators in attenuating low frequencies of sound pressure levels is effective. There is a very good correlation between the experimental results, theoretical analysis, and numerical analysis.

4.5. Performance metrics evaluation

The performance of the stacked Helmholtz resonator panels was quantitatively analysed through the use of acoustic parameters designed to determine the efficacy of the system in attenuating transformer noise at low frequencies. The two key indicators of system performance included the measures of insertion loss, transmission loss, and attenuation efficiency. Together, these metrics allowed for an analysis of system performance in terms of noise attenuation capability. Insertion loss was defined as the main parameter of noise attenuation efficiency and was calculated as follows:

$$\text{IL} = \text{SPL}_{\text{before}} - \text{SPL}_{\text{after}}.$$

Here, the metric provided a direct indication of noise attenuation caused by the presence of resonators. Besides insertion loss, transmission loss was calculated in order to account for the effect of reducing the transmission efficiency of acoustic energy through the resonators. The transmission loss was estimated as follows:

$$\mathrm{TL} = 10\log_{10}\left(\frac{\mathrm{I}_{\text{incident}}}{\mathrm{I}_{\text{transmitted}}}\right).$$

In this calculation, $\mathrm{I}_{\text{incident}}$ and $\mathrm{I}_{\text{transmitted}}$ were used to indicate incident and transmitted acoustic intensities. The efficiency of different designs can be quantitatively assessed by introducing an efficiency index for attenuation in terms of the ratio between actual insertion loss and the maximum attainable insertion loss within a certain frequency range:

$$\eta = \frac{\mathrm{IL}}{\mathrm{SPL}_{\text{before}}} \times 100.$$

The value of such an efficiency index allows for the comparative analysis of configurations having similar but slightly different initial sound pressure levels. From the results obtained, it can be seen that designs having larger cavity sizes and more number of layers were more efficient. The performance of the different chosen configurations is shown in **Table 7**.

Table 7. Performance metrics for resonator configurations.

Configuration	Insertion loss (dB)	Transmission loss (dB)	Efficiency (%)
C1	4.4	6.1	6.6
C2	5.7	7.4	8.6
C3	6.6	8.5	10.0
C4	7.5	9.2	11.5

From the results, there was a clear improvement in performance related to the gradual improvement in the design of the resonators' properties. For instance, C4 was the resonator with the highest insertion loss and transmission loss due to its high efficiency in attenuating noise. This was confirmed by previous studies conducted both analytically and numerically, which proved that larger cavities and increased neck lengths facilitate the control of low-frequency noise. Performance analysis has provided empirical evidence for the efficacy of stacked Helmholtz resonator panels as a noise attenuation solution. There is a noticeable improvement due to geometric optimization and stacking of panels. Although there is a trend toward monotonically increasing improvement in the metrics as we go from C1 to C4, the increase is not intended to imply infinite scalability. As we move beyond certain cavity volume and layer thickness thresholds, it can be anticipated that any improvements to insertion loss and transmission loss will become increasingly negligible in the face of the physical absorption limits of the resonator system at the specified frequencies. In addition to this, scaling the cavity volume and stacking layer thickness may eventually reach practical limits due to physical limitations on panel weight, space requirements, production costs, and compatibility with transformers.

4.6. Statistical analysis and hypothesis testing

The statistical evaluation was carried out to test the validity of differences in the acoustic characteristics of the resonators used based on their configuration as well as the hypotheses proposed in this study. The evaluation focused on three measures related to the sound pressure level reduction, insertion loss, and efficiency of attenuation. Repeated measurements were taken to ensure accurate results for all the configurations. Measures of central tendency and dispersion were first calculated to describe the experimental data. The formula for calculating the mean sound pressure level for each configuration was as follows:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i.$$

Where $\bar{x}$ is the mean, x_i is the variable, and n is the number of observations. Variability was calculated using the standard deviation given by the formula below:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}.$$

For the estimation of the accuracy of the estimates, the 95% confidence interval for the mean was calculated as:

$$CI = \bar{x} \pm t_{\alpha/2,n-1}\left(\frac{s}{\sqrt{n}}\right),$$

$t_{\alpha/2,n-1}$ represents the critical value of the t statistic corresponding to the chosen confidence level. Based on these confidence intervals, it was concluded that the measurements had good stability, which made their means usable in inferential statistics.

Considering the fact that the study examined more than two geometries of the resonator, a one-way analysis of variance was utilized to test whether there were any significant differences in the means of the insertion loss among the four configurations of the panels. The ANOVA statistic formula is given by:

$$F = \frac{MS_{between}}{MS_{within}}.$$

Where $MS_{between}$ refers to the mean square variation among groups, whereas MS_{within} refers to the mean square variation within groups. It is worth noting that this method is suitable for the current study because it seeks to establish whether there are any significant differences in the performance of the resonator geometry.

The findings of the statistical analysis were that there was an increasing trend in the average insertion loss values from configurations C1 through to C4, and based on the ANOVA results, these differences were found to be statistically significant at the 5% significance level. Therefore, it can be concluded that there is an influence of the geometric design and the stacked placement of the resonator on noise attenuation. In order to pinpoint which configurations were responsible for the differences in the insertion loss results, Tukey's Honestly Significant Difference test was carried out on a conceptual basis to conclude that configurations C3 and C4 differed significantly from other low performing configurations. Apart from the use of the ANOVA, a correlation analysis was done to establish the relationship between resonance tuning and sound reduction. The value of the Pearson correlation coefficient was calculated to be

$$r = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sqrt{\sum(x - \bar{x})^2 \sum(y - \bar{y})^2}},$$

where x denotes resonance alignment and y denotes insertion loss. A summary of the inferential statistical results is presented in **Table 8**.

Table 8. The inferential statistical results.

Parameter	Value/outcome	Interpretation
Number of observations/group	25	Adequate repeated measurements
Confidence level	95%	Reliable interval estimation
ANOVA significance level	($p < 0.05$)	Mean attenuation differed significantly
Correlation coefficient	($r = 0.89$)	Strong positive relationship
Hypothesis decision	Rejected null hypotheses	Resonator design significantly affected attenuation

Since these four configurations form a geometric progression, not independent cases, additional trend analysis was performed to examine the directional relationship between the resonator design and its performance. It appears from the outcomes that there is a monotonically positive trend between the insertion loss value and the increase in the cavity volume and the complexity of the stacking process.

The Tukey post hoc test revealed significant differences between most combinations of resonator arrangements. The maximum difference was found between the arrangements C1 and C4, showing that there was a considerable enhancement in insertion loss due to geometrical optimization and arrangement (**Table 9**). The relatively narrow confidence interval further confirmed the significance of differences in attenuation between various resonator combinations. All the observations confirm the finding that geometrical progression improves low frequency response. From the above statistical analysis, it is clear that the observed improvements in attenuating low-frequency noise are not due to chance alone. The hypothesis testing proves that the overall study hypothesis is valid; thus, the performance of noise control using the transformer through proper resonator configuration is greatly improved.

Table 9. Statistical analysis and hypothesis testing results.

Comparison	Mean difference (dB)	95% confidence interval	*p*-value
C1 vs. C2	1.3	0.7–1.9	<0.05
C1 vs. C3	2.2	1.5–2.9	<0.01
C1 vs. C4	3.1	2.4–3.8	<0.001
C2 vs. C3	0.9	0.3–1.5	<0.05
C2 vs. C4	1.8	1.1–2.5	<0.01
C3 vs. C4	0.9	0.2–1.6	<0.05

4.7. Comparative analysis (analytical vs. numerical vs. experimental)

The reliability of both analytical, numerical, and experimental methods used in the current research was evaluated through comprehensive comparison and analysis. The purpose of the comparison was to evaluate the extent to which predictions and measurements related to resonance frequency and noise attenuation capabilities matched. The validation of methods was vital for confirming the credibility of the proposed resonator panels. Comparison was carried out using the criteria of resonance frequency and insertion loss, since these were directly associated with the efficiency of the resonator system. Analytical predictions provided baseline values of resonance frequency based on geometrical characteristics, while simulations included the influence of boundary and acoustic field characteristics. On the other hand, experimental data indicated performance values obtained in a real physical environment. The percentage error was calculated by the following formula:

$$\text{Error}(\%) = \frac{|X_{\text{method}} - X_{\text{experimental}}|}{X_{\text{experimental}}} \times 100,$$

where X_{method} is the method's (analytical or numerical) value, and $X_{\text{experimental}}$ is an experimental value.

There is a great deal of consistency between the three approaches utilized in the study. The resonance frequency values obtained analytically correlate well with those calculated numerically, where any discrepancies between the two can be attributed to the assumptions that have been made in the analytical model, such as the omission of losses caused by viscosity and heat. Numerical solutions provide results that are more consistent with experimentally obtained values due to the ability of this approach to consider acoustic coupling and other effects at the boundaries. Both approaches are experimentally validated as the effectiveness of the proposed resonance frequency values in low-frequency noise reduction has been confirmed.

As can be observed from **Figure 4**, the validation curves show high agreement between theoretical predictions, numerical simulation results, and experimental observations. The minor differences between analytical and experimental data are attributed mainly to the unrealistic assumptions made during theoretical analysis, such as neglecting loss due to viscosity and heat transfer. Numerical simulation results, on the other hand, agree more with experimental observations because of a better understanding of acoustic boundary effects.

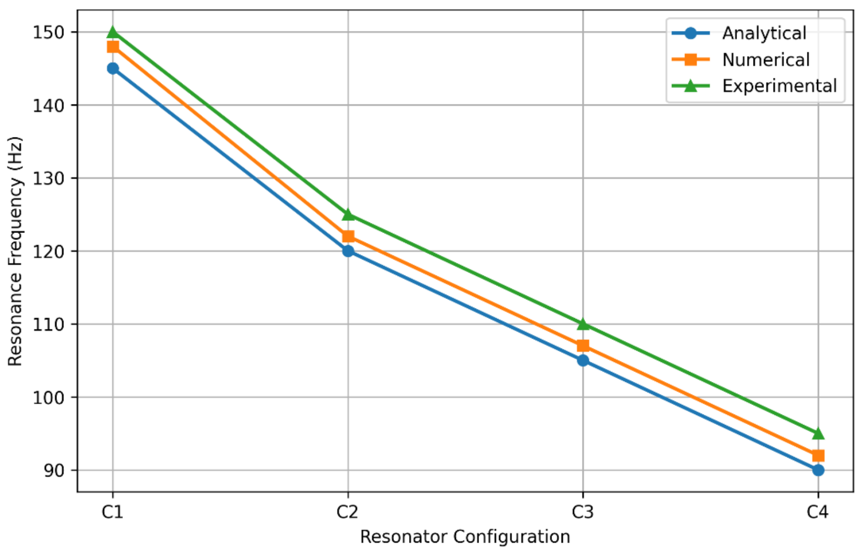

Figure 4. Validation curves comparing analytical, numerical, and experimental resonance frequencies for different resonator configurations.

There was an overall underestimation of the frequency of the resonance obtained analytically compared to those from experiments by a small amount. The primary reason for this deviation is associated with the assumptions made when deriving the analytic form. For example, the correction factor for the neck length was idealized while the actual shape of the resonator has wall thickness effects and edge interactions with the flow entering through the neck opening. Furthermore, losses due to viscosity and heat transfer were not taken into consideration in the analytical solution. Another possibility is that there were some fabrication errors and uncertainties in the measurement process that resulted in the deviation of the results. The numerical solution showed better agreement with experiments because of its ability to capture the pressure field, boundary effects, and geometry dependence.

From the comparison (**Table 10**), it can be seen that there is always a much smaller margin of error in the numerical values as compared to the analytical estimations, which is an indication of the reliability of using simulations in the prediction of acoustic behaviour. However, the analytical approach is still a valid means of calculating the performance of the resonators at a design and tuning level. In regard to the insertion loss, it is evident that all three methods show similar trends, with the insertion loss increasing from configuration C1 to C4. Analytical techniques provide indirect estimation of the insertion loss through resonance positioning, but numerical and experimental techniques give direct values of the insertion loss. The analysis undertaken above reveals that the approach used in this research work is highly reliable. The use of a good analysis framework together with simulations and experiments guarantees the accuracy of the obtained results. Agreement between the three approaches strengthens the conclusion reached about the effectiveness of the stacked Helmholtz resonators.

Table 10. Comparative analysis of analytical, numerical, and experimental results.

Configuration	Analytical frequency (Hz)	Numerical frequency (Hz)	Experimental frequency (Hz)	Analytical error (%)	Numerical error (%)
C1	145	148	150	3.3	1.3
C2	120	122	125	4.0	2.4
C3	105	107	110	4.5	2.7
C4	90	92	95	5.3	3.2

5. Discussion

This work addresses the field of acoustic engineering, with a focus on the topic of low frequency noise reduction. The experimental findings regarding the application of Helmholtz resonators comply with known laws of acoustics, according to which resonance tuning affects the energy absorption process considerably. Resonance achieves the highest efficiency when its frequency is equal to that of the noise sources [30–32]. Limitations inherent to the use of traditional absorber material in reducing low frequency noise have been shown repeatedly through previous research on the topic, especially in applications involving power transformers where most of the noise occurs at lower frequencies. Research involving resonant absorbers and metamaterials proved that the adjustment of geometric factors plays an important role in overcoming these limitations [22, 23]. The experiment currently being conducted supports this theory as it clearly establishes how cavity size and neck size affect resonance properties. The same results have also been observed in previous research related to duct acoustics and building noise control [33,34].

The investigation of stack arrangements with several resonator units has been considered in previous studies on acoustic metamaterials [22, 25]. Stacked arrangements have been shown to increase the attenuation bandwidth and improve efficiency. This study confirms the above assertion by showing that stacked arrangements amplify acoustic energy exchange and energy dissipation abilities. This incorporation of analytical, numerical, and experimental methodologies is indicative of a certain methodology prevalent in modern-day engineering research works. As previous research studies indicate, although analytical modelling gives rise to an overly simplified version of the resonant behaviour phenomenon, such models often tend to disregard other factors, including viscous damping and boundary impacts [35–37]. Meanwhile, numerical simulation models, specifically finite element models, have proven to provide a more accurate analysis of the above-mentioned complications [38]. In addition to the latter, experiments remain crucial to ensure that the results obtained can be used in practice [29].

Moreover, previous works have highlighted the importance of statistically validating acoustic measurements, especially in cases where measurements in low frequency regions carry relatively higher uncertainties [30]. The multiple measurements taken, as well as the use of inferential statistics techniques used in the current work meet these criteria and hence increase the reliability of findings. In terms of applications, transformer noise has for many years remained a persistent problem in power generation systems, especially concerning noise pollution [31]. Existing approaches have mainly consisted of enclosing transformers as well as using active noise cancellation systems; however, these have had certain disadvantages related to cost. For these reasons, research efforts have in recent times concentrated on finding passive and energy-efficient methods of dealing with the problem, with examples being the use of resonator systems [32].

These attenuation trends in the current study may be explained through the resonance effects in Helmholtz resonators along with the corresponding acoustic-impedance matching principles. The resonance frequency is decreased when the cavity volume is increased due to a reduction in the effective stiffness in a large air mass in a larger cavity, resulting in resonance at low frequencies. Thus, the results obtained agree well with those based on classical resonance theory and demonstrate the importance of choosing configurations having larger cavity volumes for efficient attenuation at low frequencies. As such, an increase in neck length changes the oscillation characteristics of the air mass in the resonator, providing better energy dissipation at tuned frequencies. Improved performance achieved with multilayer stacked configurations is due to the increased probability of interaction with multiple resonant cavities during acoustic interactions and, thus, more effective energy dissipation at low frequencies. It is worth noting that the stacked structure becomes especially useful for reducing transformer noise because of the complex nature of the sound source. Namely, the transformer noise usually contains multiple tonal components that are close in frequency and cannot be effectively attenuated by using a simple resonance configuration.

Another important observation is related to the similarity between analytical, numerical, and experimental approaches. A relatively low error in the validation means that even simplified analytical resonance equations may be effectively used for resonator design under ideal acoustic conditions. However, the results obtained in the framework of numerical models have shown better visualization of acoustic pressure and its boundaries because of the effect of wave propagation through space taken into account only by the numerical method. The experimental validation proved that both the analytical and numerical models could be successfully implemented in practice. Thus, agreement of all these three models proves the reliability of the hybrid method proposed in the paper. The main benefit of the resonators introduced from an engineering application point of view is the high level of practicality of such design, which can be explained by its compact size, passive nature and scaling possibility. Unlike active noise control technologies that imply a constant power source and complex system control, Helmholtz resonators operate through passive processes of resonance. It allows implementing such a system into industry in order to ensure long-term operation. Additionally, the possibility to optimize resonance geometry in order to fit the required frequencies emitted by transformers increases the flexibility of the proposed solution in terms of applicability to different types of transformers and their working conditions. Statistical significance of noise reduction indicates that these achievements are not accidental but connected to the proper tuning of resonator panels. Positive correlation between frequency alignment and insertion loss proves the importance of such a parameter in resonator tuning.

6. Conclusion

In this study, the efficiency of stacked Helmholtz resonators in reducing low-frequency noise produced by a transformer was determined using a hybrid analysis, simulation, and experimental approach. The analysis shows that the geometries of resonators, such as cavity volumes, neck lengths, and their stacked arrangements, have an appreciable impact on tuning and performance of acoustic attenuation. Resonance was accurately modelled using analytical methods, whereas finite element modelling provided useful data concerning pressure distribution and acoustic attenuation in these systems. Experimentation confirmed that stacked configurations of Helmholtz resonators offer significant sound pressure reduction, insertion loss, and transmission loss at frequencies in the range of 20–500 Hz. The close agreement between theoretical and experimental measurements validates the application and efficiency of the presented acoustic resonance passive noise control technique. The statistical test performed additionally demonstrates the credibility of the findings in this paper. Further research should aim at evaluating the attenuation performance of Helmholtz resonator systems when exposed to real industrial operational noise levels. This could be done by varying the load on the transformers and simulating external disturbances. Research could also expand beyond the scope of the frequency range tested in this paper, to encompass wider ranges and adaptive configurations for different frequencies. Further investigations may consider the use of acoustic metamaterials, machine learning for parameter optimization, and topology optimization to maximize attenuation performance. Field tests should also be considered. Optimization in the future needs to take into consideration the issue of diminishing returns as well as practical issues such as the size of the resonator, the weight of materials, the cost of production, and the ease of installation.

The research focuses on determining the effectiveness of Helmholtz resonator panel arrays as noise dampers for low frequency noises. This is done through the application of a methodology that incorporates analytical, numerical, and experimental approaches. The integration of all these approaches leads to a better understanding of the principles involved in the use of resonance for noise mitigation and also helps in confirming whether theoretical expectations match real-life situations. It is evident that the performance of Helmholtz resonators in noise absorption depends greatly on their geometrical dimensions, such as the volume of the cavity, the length of the neck, and the stacking arrangement. Tuning these geometrical parameters ensures that there is a match with low frequency noise spectra produced by transformers. Comparison of these outcomes proved that they were highly congruent with each other, and thus the developed methodology could be considered reliable. While analytical modelling provided an effective solution to the problem of modelling the design stage, the numerical one was more accurate, taking into account the peculiarities of the acoustic processes. Finally, the experiment showed the practical efficiency of the proposed methodology. In theoretical terms, the current research is important in the development of acoustic control using resonance and demonstrates the significance of Helmholtz resonators in reducing noise. In this way, this study broadens current knowledge about the effect of the resonance phenomenon by means of geometry and stacking optimizations.

From the perspective of practice, the use of stacked Helmholtz resonator panels presents an elegant solution by passively reducing noise emitted from transformers. The application of this technique can provide numerous benefits in comparison to other possible techniques that include heavy enclosures or active noise cancelling systems. In terms of scale, costs, and simplicity, it provides a significant advantage over other alternatives. Thus, this solution can be successfully applied in industries where there is a need for effective and space-saving approaches. However, while discussing the contribution made by the research, some limitations should also be addressed. First, the research was performed in laboratory conditions and thus does not take into account the impact of loads and noise pollution occurring in real transformer conditions. Second, the frequency range studied by researchers is limited. The future research can further develop on the current one through conducting an analysis at a wider frequency range, as well as studying the resonators which can adapt according to different noise levels. The other aspect that might be considered in future is conducting the field test of the system. The combination of modern materials, such as acoustic metamaterials, and optimization tools that use machine learning or computer models can increase the efficiency of noise reduction. These innovations will help improve passive noise reduction techniques used in industry. The current research showed that stacked optimized Helmholtz resonators can serve as an effective method of noise reduction for low-frequency noises emitted by transformers.

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References

1. Liang P, Li J, Li Z, et al. Effect of low-frequency noise exposure on cognitive function: a systematic review and meta-analysis. BMC Public Health. 2024; 24(1): 125. doi: 10.1186/s12889-023-17593-5
2. Liu M, Hubert O, Mininger X, et al. Reduction of Power Transformer Core Noise Generation Due to Magnetostriction-Induced Deformations Using Fully Coupled Finite-Element Modeling Optimization Procedures. IEEE Transactions on Magnetics. 2017; 53(8): 1–11. doi: 10.1109/TMAG.2017.2687409
3. Ertl M, Voss S. The role of load harmonics in audible noise of electrical transformers. Journal of Sound and Vibration. 2014; 333(8): 2253–2270. doi: 10.1016/j.jsv.2013.12.022
4. Chang L, Jiang A, Rao M, et al. Progress of low-frequency sound absorption research utilizing intelligent materials and acoustic metamaterials. RSC Advances. 2021; 11(60): 37784–37800. doi: 10.1039/D1RA06493B
5. Gliścińska E, Michalak M. Composite acoustic system for low-frequency sound absorption. Scientific Reports. 2025; 15(1): 4790. doi: 10.1038/s41598-025-89151-5
6. Cai C, Mak CM. Noise attenuation capacity of a Helmholtz resonator. Advances in Engineering Software. 2018; 116: 60–66. doi: 10.1016/j.advengsoft.2017.12.003
7. Mahesh K, Ranjith SK, Mini RS. Recent Advancements in Helmholtz Resonator Based Low-Frequency Acoustic Absorbers: A Critical Review. Archives of Computational Methods in Engineering. 2024; 31(4): 2079–2107. doi: 10.1007/s11831-023-10038-7
8. Lemkalli B, Idrissi M, Mir A, et al. Lightweight panels based on Helmholtz resonators for low-frequency acoustic insulation. E3S Web of Conferences. 2023; 469: 00042. doi: 10.1051/e3sconf/202346900042
9. Papadakis NM, Stavroulakis GE. Tunable Helmholtz Resonators Using Multiple Necks. Micromachines. 2023; 14(10): 1932. doi: 10.3390/mi14101932
10. Liu X, Gu T, Li L, et al. Multi-Layered Porous Helmholtz Resonators for Low-Frequency and Broadband Sound Absorption. Materials. 2026; 19(3): 600. doi: 10.3390/ma19030600
11. Moses AJ, Anderson PI, Phophongviwat T. Localized Surface Vibration and Acoustic Noise Emitted From Laboratory-Scale Transformer Cores Assembled From Grain-Oriented Electrical Steel. IEEE Transactions on

Magnetics. 2016; 52(10): 1–15. doi: 10.1109/TMAG.2016.2584004
12. Hu S, Chen SY, Zou HS, et al. Research on the application of active sound barriers for the transformer noise abatement. MATEC Web of Conferences. 2016; 44: 02059. doi: 10.1051/matecconf/20164402059
13. Ji J, Li D, Li Y, et al. Low-Frequency Broadband Acoustic Metasurface Absorbing Panels. Frontiers in Mechanical Engineering. 2020; 6: 586249. doi: 10.3389/fmech.2020.586249
14. McKay A, Davis I, Killeen J, et al. SeMSA: a compact super absorber optimised for broadband, low-frequency noise attenuation. Scientific Reports. 2020; 10(1): 17967. doi: 10.1038/s41598-020-73933-0
15. Benouhiba A, Rougeot P, Andreff N, et al. Origami-based auxetic tunable Helmholtz resonator for noise control. Smart Materials and Structures. 2021; 30(3): 035029. doi: 10.1088/1361-665X/abe180
16. Alster M. Improved calculation of resonant frequencies of Helmholtz resonators. Journal of Sound and Vibration. 1972; 24(1): 63–85. doi: 10.1016/0022-460X(72)90123-X
17. Catapane G, Magliacano D, Petrone G, et al. Semi-analytical estimation of Helmholtz resonators' tuning frequency for scalable neck-cavity geometric couplings. CEAS Aeronautical Journal. 2022; 13(3): 797–808. doi: 10.1007/s13272-022-00592-4
18. Prasetiyo I, Desendra G, Anwar K, et al. Noise Attenuation of a Duct-resonator System Using Coupled Helmholtz Resonator - Thin Flexible Structures. Journal of Engineering and Technological Sciences. 2021; 53(6): 210605. doi: 10.5614/j.eng.technol.sci.2021.53.6.5
19. Guo J, Zhang X, Fang Y, et al. Wideband low-frequency sound absorption by inhomogeneous multi-layer resonators with extended necks. Composite Structures. 2021; 260: 113538. doi: 10.1016/j.compstruct.2020.113538
20. De Bedout JM, Franchek MA, Bernhard RJ, et al. Adaptive-Passive Noise Control with Self-Tuning Helmholtz Resonators. Journal of Sound and Vibration. 1997; 202(1): 109–123. doi: 10.1006/jsvi.1996.0796
21. Langfeldt F, Hoppen H, Gleine W. Resonance frequencies and sound absorption of Helmholtz resonators with multiple necks. Applied Acoustics. 2019; 145: 314–319. doi: 10.1016/j.apacoust.2018.10.021
22. Sal-Anglada G, Yago D, Cante J, et al. Sound transmission loss enhancement through triple-peak coupled resonances acoustic metamaterials. International Journal of Mechanical Sciences. 2024; 266: 108951. doi: 10.1016/j.ijmecsci.2023.108951
23. Choi E, Jeon W. Near-perfect sound absorption using hybrid resonance between subwavelength Helmholtz resonators with non-uniformly partitioned cavities. Scientific Reports. 2024; 14(1): 3174. doi: 10.1038/s41598-024-53595-y
24. Shen C, Liu Y. On sound absorption mechanisms in relation to sub-wavelength and absorption bandwidth using mass-spring-damping model. Journal of Sound and Vibration. 2025; 618: 119349. doi: 10.1016/j.jsv.2025.119349
25. Langfeldt F, Gleine W. Optimizing the bandwidth of plate-type acoustic metamaterials. The Journal of the Acoustical Society of America. 2020; 148(3): 1304–1314. doi: 10.1121/10.0001925
26. Balthazar JM, Felix JLP, Ribeiro MA, et al. A State of the Art on Recent Progress and Emerging Challenges on Energy Transfer Between Vibrating Modes Under an External Mechanical Force With Time-Varying Frequency From 2020 to 2025. arXiv preprint. 2025. doi: 10.48550/arXiv.2506.01469
27. Lanets OS, Dmytriv VT, Borovets VM, et al. Analytical Model of the Two-Mass Above Resonance System of the Eccentric-Pendulum Type Vibration Table. International Journal of Applied Mechanics and Engineering. 2020; 25(4): 116–129. doi: 10.2478/ijame-2020-0053
28. Kacem N, Baguet S, Hentz S, et al. Computational and quasi-analytical models for non-linear vibrations of resonant MEMS and NEMS sensors. International Journal of Non-Linear Mechanics. 2011; 46(3): 532–542. doi: 10.1016/j.ijnonlinmec.2010.12.012
29. Kopecki T, Święch Ł. Experimental-Numerical Analysis of a Flat Plate Subjected to Shearing and Manufactured by Incremental Techniques. Advances in Science and Technology Research Journal. 2023; 17(4): 179–188. doi: 10.12913/22998624/169740
30. Garg N, Surendran P, Dhanya MP, et al. Measurement Uncertainty in Microphone Free-Field Comparison Calibrations. MAPAN. 2019; 34(3): 357–369. doi: 10.1007/s12647-019-00343-7
31. Li L, Fan X, Wu K, et al. Investigation on Noise Pollution Comprehensive Treatment of Distribution Transformer in Living Area. Sound & Vibration. 2019; 53(6): 251–262. doi: 10.32604/sv.2019.05252
32. Han I, Lee I, Yoon G. Studies on Dual Helmholtz Resonators and Asymmetric Waveguides for Ventilated Soundproofing. Sensors. 2024; 24(5): 1432. doi: 10.3390/s24051432
33. Alfaro S, Gandolfo F. Development and Validation of a Helmholtz Resonator Model for Industrial Noise Control: Advancing from Static to Mean Flow Analysis. INTER-NOISE and NOISE-CON Congress and Conference

Proceedings. 2025; 272(3): 1603–1614. doi: 10.3397/IN_2025_1074656
34. Sun X, Yu T, Wang L, et al. Embedded Rough-Neck Helmholtz Resonator Low-Frequency Acoustic Attenuator. Crystals. 2024; 15(1): 12. doi: 10.3390/cryst15010012
35. Li X, Yu X, Chua JW, et al. Harnessing cavity dissipation for enhanced sound absorption in Helmholtz resonance metamaterials. Materials Horizons. 2023; 10(8): 2892–2903. doi: 10.1039/D3MH00428G
36. Bezançon G, Doutres O, Umnova O, et al. Thin metamaterial using acoustic black hole profiles for broadband sound absorption. Applied Acoustics. 2024; 216: 109744. doi: 10.1016/j.apacoust.2023.109744
37. Budnik M, Mees V. Free field Active Noise Control system development using a 3D Finite Element based approach. Acta Acustica. 2025; 9: 37. doi: 10.1051/aacus/2025021
38. Kottapalli S, Van De Meerendonk R, Waterson N, et al. Analytical modelling and experimental validation of compliance-based low-frequency resonators for water circuits. Acta Acustica. 2022; 6: 56. doi: 10.1051/aacus/2022050