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Models of Acoustic Resonators in Studies of Sound-Absorbing Structures

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***Abstract*—This paper provides a comprehensive review of four primary models used to represent Helmholtz resonators in sound-absorbing structures. The purpose of the article is to analyze these models in the context of their application, accuracy, and suitability for different types of acoustic problems. The review focuses on: the simple harmonic oscillator model, which provides a basic yet effective approach for estimating resonance frequencies; the wave equation model, which is well-suited for complex geometries and wave propagation phenomena; the electrical analogy model, used to represent resonators in systems with multiple interacting elements; and the Finite Element Method (FEM), offering high precision for detailed simulations of complex acoustic systems. For each model, typical calculation problems are discussed to highlight their practical applications, along with examples from existing research. Additionally, the article provides recommendations for further development of these models. This review serves as a foundation for selecting appropriate modeling methods for various acoustic design challenges and offers guidance for future research in this field.**

Keywords — sound absorption coefficient; Helmholtz resonator; resonator sound-absorbing structures; mathematical model.

I. INTRODUCTION

The issue of studying and developing resonant sound-absorbing structures is due to the wide range of applications — from improving the acoustic properties of rooms to creating specific acoustic effects. In addition, resonant acoustic structures make it possible to control the frequency dependence of their sound-absorbing properties by changing the geometric dimensions of the perforation elements. This allows the creation of more efficient and compact systems for solving several acoustic problems. This paper highlights the main methods of representing Helmholtz resonators, which are used in the principle of resonator sound-absorbing panels.

Resonator sound-absorbing structures are panels of rigid material installed through holes at a certain distance from the rigid enclosing surface. The panels can be made of plasterboard, plywood, metal, and other materials and composites. The openings can be covered with fabric to increase the active component of sound absorption. The gap between the panel and the enclosing surface can be filled with either air or a layer of soft, porous material, which changes the sound absorption characteristics of the structure [1].

The advantage of using resonator acoustic structures compared to other finishing materials is the possibility of controlling the frequency dependence of their sound absorption properties by changing the geometric dimensions of the perforation elements. Many types of these structures are known today, including perforations in holes and slots, which are widely used in architectural acoustics for interior decoration. However, the difficulty lies in the fact that the sound absorption properties of a particular structure can only be found by measuring the sound absorption coefficient of an already manufactured sample. So, the problem arises of calculating the sound-absorbing properties of the resonator structure at the stage of its development, which will allow the designing of a perforated panel with the desired sound absorption.

Such a structure can be represented by Helmholtz resonator arrays, each consisting of an opening (the resonator neck) and a cavity of air behind it (the resonator cavity). Despite the absence of partitions between the cells, this representation is fully justified for the normal incidence of a sound wave [1]. Thus, the problem is reduced to analyzing the absorption of sound energy by a Helmholtz resonator, considering the resonator's physical parameters.

II. MODERN METHODS OF THE STUDY OF HELMHOLTZ RESONATORS

The theory of acoustic resonators has been actively developed since the 50s of the last century in the works of Ingard, Cox, Long, and Fletcher [2]–[5]. However, the primary issue is the model for representing an acoustic resonator.

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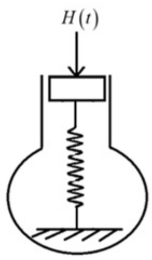

Fig. 1 Mechanical scheme of the Helmholtz resonator

A. Model of a simple harmonic oscillator

The simplest model is the analogy with a harmonic oscillator, where the mass of air in the neck and the elasticity of air in the resonator cavity is used (Fig. 1). In this case, the basic equation for the Helmholtz resonator is as follows:

$$f = \frac{c_0}{2\pi}\sqrt{\frac{S}{Vl}},$$

where f is the resonant frequency, c_0 is the speed of sound in the working medium, S is the cross-sectional area of the resonator neck, V is the cavity of the resonator cavity, and l is the length of the neck.

This model has been used to create an effective method [6] for designing a soundproof panel to achieve low-frequency noise attenuation in the range of 500 Hz to 1000 Hz and the ability to pass air through the gaps on the panel surface to reduce wind loads. This model also made it possible to calculate the resonant frequency of the Helmholtz resonator in a free field [7] and showed that the resonant frequency changes significantly when the acoustic design changes. In [8], 64 resonant frequencies of the Helmholtz resonator neck were calculated, and in [9], the amplitudes of oscillations of the Helmholtz resonator neck at resonant frequencies were analyzed.

The focus of [10] is on the broadband improvement of the transmission loss of double walls in the low-frequency range by tuning the Helmholtz resonators inside the cavity to frequencies below or above the mass-air-mass resonant frequency of the double wall. This improvement is also accompanied by a reduction in losses at high frequencies due to the decoupling of the Helmholtz resonators. Parametric studies [10] have been conducted to determine the appropriate design parameters to optimize the reduction of transmission losses using Helmholtz resonators.

Paper [11] shows that the study of the resonance half-width is more sensitive to sound penetration into the aggregate substance and attenuation of sound vibrations than the corresponding behavior of the resonance peak. The increase in the resonance frequency depending on the amount of sand is much less important than for water and initially has an almost linear course. More interestingly, for sand with fine grains, there is a rapid increase in the resonant frequency in accordance with the behavior of water. There is also a weaker increase in the resonant frequency when using beads of different sizes compared to water. For smaller beads, the narrow inter-particle channels contribute to an increase in viscous damping and hence the resonant half-width.

The effect of direct and offset arrangement of the necks on the transmission of acoustic waves in a wide frequency range was also investigated [12]. Increasing the number of Helmholtz resonators in a horizontal arrangement makes it possible to increase the number of transmitted frequencies with extraordinary transmission, and the vertical arrangement makes it possible to focus the sound at a certain point. However, this focusing characteristic is observed in a narrow frequency band.

In [13], a broadband sound amplifier based on a multi-tube Helmholtz resonator was proposed to dampen low-frequency sound energy. When the cavity is fixed, the resonant frequency and pressure amplification effect of the resonator increases with decreasing tube length. For a two-tube Helmholtz resonator [13], when the distance between the tubes is odd, the resonator's resonant frequency is slightly lower than when the distance is even. As for the four-tube Helmholtz resonator, the relationship between frequency and sound pressure level has two modes with close peak values, significantly expanding the resonator's operating frequency band.

B. A model based on the wave equations

This model allows considering more detailed characteristics of the acoustic fields inside the resonator. The model is based on the wave equation that describes the propagation of sound waves in the medium:

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0$$

where $\nabla^2 p$ is the Laplacian of the sound pressure p, c is the speed of sound, and t is time.

For this model, it should be noted that the sound pressure p and the particle velocity v are related to each other through the equations of motion and continuity. For a Helmholtz resonator, these equations can be simplified to consider the fundamental vibrations:

$$\frac{\partial \rho'}{\partial t} + \nabla(\rho v) = 0, \quad \rho\frac{\partial v}{\partial t} + \nabla p = 0,$$

where ρ' is the deviation of the density from the equilibrium value, ρ is the equilibrium density of the medium.

For the correct description of the wave model, it is also necessary to consider the boundary conditions on the resonator walls and the neck.

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Based on this mathematical model, the resonator energy emission and dissipation and its interaction with the acoustic shell were thoroughly investigated [14]. The influence of the internal resistance of the resonators and its dominant levels on the energy dissipation process was demonstrated.

The study [14] showed that noise reduction can be maximized by optimally tuning the resonators when their Helmholtz frequency is shifted from the central frequency of the target frequency band. The optimal setting of the internal impedance of the resonators depends on the target frequency region and the bandwidth. Within the resonant region, the optimum internal impedance should increase with increasing bandwidth.

In addition, this model has been used to propose a new lightweight acoustic metamaterial panel [15] designed to isolate low-frequency broadband noise effectively. The new design [15], which uses coupled Helmholtz resonators, proved effective in creating a band gap with a characteristic W-shape, which allows precise control of sound propagation in certain frequency ranges. Such low-frequency slots have great prospects for noise reduction systems, effectively reducing sound transmission and attenuating unwanted noise sources.

In [16], an improved design of a Helmholtz resonator with an additional transmission loss peak at high frequency, in addition to the dominant peak at low frequency, was investigated. Ways to improve the high-frequency loss peak were also proposed. It was found [16] that 5-10 dB more loss can be achieved by changing the shape of the resonator neck from the usual shape to an arc-shaped one. This is due to an increase in the equivalent cross-sectional area of the arcuate resonator neck. The change in shape also leads to an increase in the dominant resonant frequency by about 20%.

Also, in [17], a numerical analysis of the effect of geometric parameters and flow Mach number on the ability of a system of twin Helmholtz resonators to suppress noise in the presence of an incoming flow was performed. The results of [17] show that the second resonant frequency and transmission losses increase with the length of the second neck. Compared to a single resonator system, dual resonators can provide a different loss peak and are more suitable as silencers at higher flow rates. The transmission loss results indicate that the flow Mach number has a more significant effect on the first transmission loss peak than the second. The relationship between the noise reduction capability of the two-resonator system and the geometric parameters and flow Mach number may be useful in designing aircraft engine mufflers.

C. A model based on electrical analogies

This model allows us to describe acoustic systems using analogies with electrical circuits. This approach is convenient because it allows the use well-known methods of analyzing electrical circuits to study loudspeakers. The main analogies are the acoustic impedance Z, the mass of air in the cavity (replaced by the inductance of the electric circuit L) and the elasticity of air in the resonator cavity (the capacitance of the electric circuit C). The resonant frequency of a Helmholtz resonator can be determined by analogy with the resonant frequency of an LC circuit:

$$f = \frac{1}{2\pi\sqrt{LC}}.$$

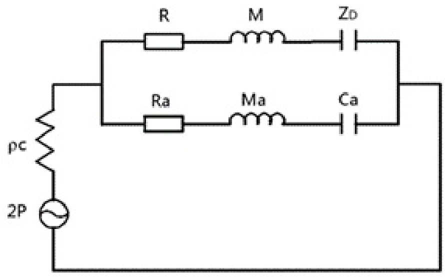

Fig. 2 Equivalent circuit of the MPP with Helmholtz resonators

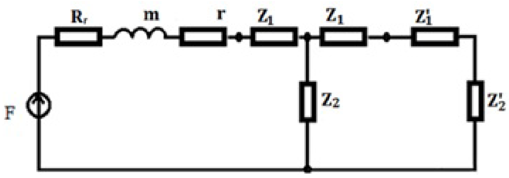

Fig. 3 Equivalent circuit of the Helmholtz resonator (system with distributed parameters)

The representation of an acoustic resonator in the form of an electroacoustic oscillating circuit is somewhat simplified, but for the low-frequency vibration region it gives quite satisfactory practical results. Based on this model and the principle of the electroacoustic equivalent circuit (Fig. 2), the sound-absorbing properties of a microperforated panel (MPP) absorber with Helmholtz resonators were investigated in [18]. The results of modeling and experiments [18] show the presence of two peaks and one resonant frequency. The low-frequency peak depends on the Helmholtz resonators, while the high-frequency peak is close to the peak of a single-layer MPP. Low-frequency sound absorption peaks shift to low frequencies with increasing neck length and cavity of Helmholtz resonators. The high-frequency sound absorption peaks shift to the high-frequency region with increasing volume of the Helmholtz cavity.

The authors of [19] propose a new method for the a priori calculation of the sound absorption coefficient of a perforated resonator structure by representing individual resonators by an electroacoustic oscillatory circuit with distributed parameters (Fig. 3), considering the material of the main panel.

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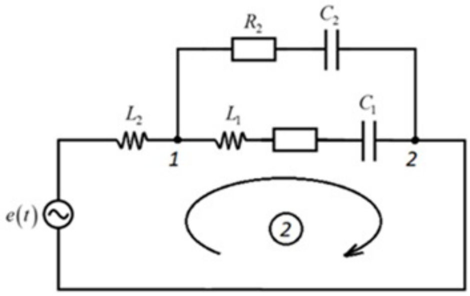

Fig. 4 Electrical model of the resonator (two-circuit system)

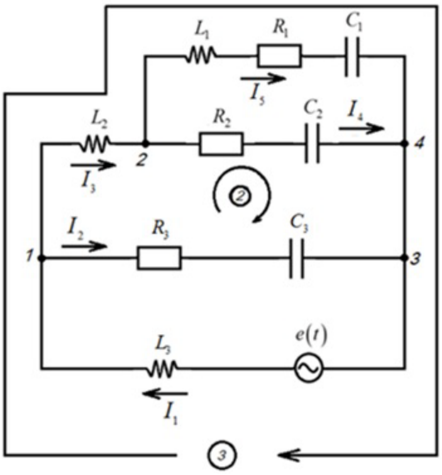

Fig. 5 Electrical model of the resonator (three-circuit system)

By applying the method of electromechanical analogies, the systems of equations of the two-circuit (Fig. 4) and three-circuit (Fig. 5) models of an acoustic resonator were derived and the model of a complex-shaped resonator [20] as a system with distributed parameters was studied for the first time, and the sound fields inside such a system were investigated. We used mathematical analysis methods to solve systems of differential equations and the finite element method to calculate the vibrations of the resonator neck.

In [21], it was demonstrated that the Fibonacci sequence is the optimal candidate for designing a sound absorber resonator array panel to achieve the maximum possible bandwidth in the low-frequency range while trying to keep the absorption coefficient close to unity. The sequence also increases the number of resonant frequencies. And the sound absorption band increases and shifts towards lower frequencies with the addition of two larger resonator blocks, the dimensions of which are determined based on the Fibonacci sequence.

D. A model using the Finite Element Method (FEM)

The Finite Element Method (FEM) is a powerful tool for numerical modeling of physical phenomena, including acoustic processes in a Helmholtz resonator. This method allows us to consider complex geometry, material properties, and boundary conditions. Among the basic principles of FEM are space discretization (dividing the resonator into small elements that together make up a grid and in which simple functions approximate individual physical quantities), the use of the wave equation to describe sound waves and boundary conditions, and the formulation and solution of a global system of equations.

This model was used to develop a meta surface [22] consisting of metaatoms, which are subwavelength Helmholtz resonators with cavities unevenly separated by membranes. The meta surface was designed to satisfy the conditions for impedance matching with air at one or more target frequencies using a theoretical model of frequency-dependent effective acoustic impedance. The theoretical model [22] was matched to physical reality by taking into account the eigenmodes of higher orders of the membrane, visco-thermal losses in narrow holes, and finite corrections for sub wave Helmholtz resonators.

A ventilated two-port asymmetric absorber cell was developed in [23] to achieve almost perfect sound absorption when sound waves incident from the left ports and mainly reflected when sound waves incident from the right ports. A wider bandwidth sound absorption was achieved by placing three asymmetric absorbing elements in parallel. In addition, based on this idea, a multi-asymmetric absorber was developed [23] that allows for broadband asymmetric absorption in the range from 1000 Hz to 1750 Hz (also provides air circulation).

An acoustic sound-absorbing metamaterial has been proposed based on oblique perforations with surface roughness to absorb low-frequency sound [24]. The addition of surface roughness and angular configuration [24] creates additional acoustic impedance and reactance, which allows the impedance to be matched with air without the need to increase the structure's thickness.

Based on this model, the influence of wall sound absorption on the sound absorption of the entire metamaterial was also considered when the calculated structure was perfectly and not perfectly matched [25]. By directly comparing the results of FEM modeling and impedance tube measurements of an example of a metamaterial structure [25], it was demonstrated that the discrepancy between the results of measurements and modeling is caused by the presence of additional sound absorption, the nature of which lies in the imperfectly rigid walls of the prepared sample.

Acoustic modeling by FEM was used in [26] to show that the sound absorption property of Helmholtz resonators can be improved by spatially dividing and grouping the chambers, which is called multiple-divided and

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grouped Helmholtz resonators. The effect of the number of separation Ns and the number of groupings Gs on the sound absorption characteristics of multiple-split and grouped Helmholtz resonators was investigated.

An ultra-wideband sound-absorbing structure designed to absorb sound in the frequency range of 800-3000 Hz based on the structure of two-layer resonators with several elongated necks was also developed [27]. The absorber consists of 11 parallel heterogeneous two-layer Helmholtz resonators with numerous perforations. The analytical, numerical, and experimental results [27] showed that the half-absorption band gradually increases with the number of perforations, and additional peaks correlate with the sequential addition of more layers.

The acoustic properties and corresponding theoretical descriptions of the Helmholtz resonator with an integrated cantilever inside the neck were considered [28]. The advantage of this resonator design is the presence of a second resonant frequency, which leads to an additional frequency region with high sound absorption properties. Based on the analytical model [28] for calculating the resonant frequencies and absorption coefficient of the resonator system, a significant influence of geometric parameters on the resonant frequencies and broader sound absorption characteristics of the coupled resonator system was revealed.

In [29], an adjustable Helmholtz resonator with multiple necks was proposed. The simulated results using the FEM have a difference of less than 1% compared to the theoretical results. Study [29] demonstrated that by using an appropriate number of necks, the Helmholtz resonator can be tuned to different desired frequencies depending on the resonator geometry.

III. DISCUSSION

Each of four methods for representing Helmholtz resonators approach offers distinct advantages and limitations, which highlight their applicability in different contexts.

The harmonic oscillator model forms the basis for the initial analysis of acoustic resonators, allowing quick estimations of key system parameters, particularly the resonance frequency [7]–[9], [11], [13]. This model is appropriate for tasks requiring approximate assessments without complex mathematical computations:

- example 1 – estimating the resonance frequency of small rooms with a resonator integrated into the wall to reduce specific frequencies;
- example 2 – calculating the resonance frequency of resonators in portable acoustic panels used to mitigate noise in office spaces;
- example 3 – analyzing the Helmholtz resonator in car exhaust systems to minimize low-frequency noise.

The wave equation approach considers wave processes in the medium and enables the analysis of systems where interference, diffraction, or standing waves are significant [14]–[16]. It is more complex to implement but provides more accurate results:

- example 1 – analyzing interactions between a resonator and the complex geometry of a room, such as concert halls with multi-tiered ceilings;
- example 2 – calculating the behavior of resonator systems in underwater acoustic buoys where wave phenomena have a considerable effect;
- example 3 – studying the acoustic environment in ventilation channels influenced by multiple reflections of sound waves.

Electrical analogies allow the use of circuit analysis methods to study acoustic resonators [18]–[20]. This approach is effective for optimizing designs and analyzing systems where the interaction of multiple resonators is crucial:

- example 1 – optimizing an array of resonators in large-scale sound-absorbing structures, such as those used in industrial facilities;
- example 2 – modeling resonators in musical instruments, such as guitars or drums, to improve sound quality;
- example 3 – analyzing combined resonator systems in active noise cancellation technologies, particularly in aviation engines.

The FEM enables detailed modeling of resonators of any complex shape while considering intricate physical properties of materials [22]–[25], [27], [29]. This model is indispensable for tasks with high precision requirements:

- example 1 – designing custom sound-absorbing structures for architectural objects like theater domes or philharmonic halls;
- example 2 – modeling the effects of defects in resonator construction, such as cracks or material irregularities;
- example 3 – analyzing the acoustic environment in spaces with hybrid sound-absorbing systems where resonators are integrated with porous materials.

CONCLUSIONS

This review has demonstrated that each model of Helmholtz resonators provides valuable insights into

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the acoustic behavior of sound-absorbing structures. However, their applicability and accuracy vary depending on the complexity of the system and the specific research objectives. Based on the analysis of these models, the following recommendations can be made for future applications and research in this field:

- The simple harmonic oscillator model remains useful for quick approximations and initial design of sound-absorbing structures with simple geometries. Future research can focus on refining this model by integrating more complex acoustic phenomena, such as non-linear behaviors and interactions between multiple resonators, to increase its accuracy in more intricate settings.
- The wave equation model is highly suitable for environments with complex geometries, such as concert halls and large auditoriums. Future research should explore its integration with advanced simulation tools to improve the accuracy of wave propagation predictions in non-ideal environments.
- The electrical analogy method is particularly effective for designing resonator arrays and systems where multiple resonators interact. Further research could explore the adaptation of this model for active noise control systems and its integration with real-time control mechanisms. Expanding its capabilities to handle dynamic and non-linear effects in resonator arrays could make it more applicable for complex acoustic applications in industrial and automotive soundproofing.
- The FEM model offers the highest precision for modeling complex acoustic systems, but it is computationally intensive. Future studies could focus on optimizing FEM algorithms to reduce computational time while maintaining accuracy. Additionally, combining FEM with machine learning techniques could provide more efficient methods for predicting acoustic behavior in highly complex and large-scale systems.

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Анотація—У статті розглянуто сучасні моделі акустичних резонаторів, які знаходять застосування у розробці та дослідженні звукопоглинальних конструкцій. Детально проаналізовано чотири підходи до моделювання резонаторів, кожен із яких має свої особливості, переваги та обмеження, що визначають їхню ефективність у конкретних завданнях. Модель простого гармонійного осцилятора дозволяє проводити базові розрахунки частот резонансу та отримувати уявлення про основні принципи функціонування резонатора. Вона є ключовим інструментом для попереднього аналізу, що дозволяє швидко оцінити ефективність конструкції та її відповідність заданим параметрам. Хоча ця модель не враховує складні геометричні чи фізичні фактори, її простота та інтуїтивність роблять її незамінною на початкових етапах проєктування. Другий підхід базується на рівняннях хвиль і використовується для моделювання складних геометрій, де хвильові процеси значно впливають на поведінку резонатора. Така модель дозволяє враховувати взаємодію акустичних хвиль із поверхнями різної форми, а також досліджувати їх розповсюдження у неоднорідних середовищах. Це робить її ефективною для завдань, пов'язаних із точним налаштуванням акустичних характеристик у приміщеннях зі складною архітектурою. Модель електричних аналогій демонструє себе як універсальний інструмент для аналізу багатокомпонентних систем. Вона дозволяє представити резонатор як частину електричної схеми, що спрощує вивчення його взаємодії з іншими елементами акустичної системи. Цей підхід знаходить застосування у задачах, де важливо враховувати вплив зовнішніх факторів, таких як розташування резонаторів у просторі чи взаємодія між ними. Метод скінченних елементів (FEM) є найпотужнішим інструментом для аналізу акустичних систем із високою точністю. Він дозволяє моделювати складні конструкції, враховувати фізичні властивості матеріалів та геометричні особливості резонаторів. Використання FEM є особливо актуальним для проєктування акустичних панелей, елементів оздоблення приміщень та дослідження впливу зовнішніх умов на ефективність звукопоглинання.

У статті наведено приклади типових задач для кожної з моделей, що демонструють їх практичну реалізацію у дослідженнях. Додатково обговорено напрями вдосконалення існуючих підходів, які можуть сприяти підвищенню ефективності розв'язання сучасних акустичних проблем. Окрему увагу приділено перспективам застосування моделей у майбутніх дослідженнях, включаючи розробку інноваційних типів резонаторів і створення комплексних моделей акустичних систем.

Ключові слова — коефіцієнт звукопоглинання; резонатор Гельмгольца; резонаторні звукопоглинальні конструкції; математична модель.