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Research on the Possibility of Applying Acoustic Metamaterials for the Protection of Speech Information

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Abstract

The paper analyzes modern methods of technical protection of speech information and proposes a novel approach using acoustic metamaterials. The features of existing passive and active speech protection measures (soundproof constructions, sound-absorbing materials, noise jammers) are considered, as well as the characteristics of traditional sound absorbers and their limitations at low frequencies. The principles of constructing acoustic metamaterials, in particular resonance-based and periodic metastructures are presented, and the physical effects (Bragg band gaps, wave localization, negative effective mass density, etc.) that enable metamaterials to achieve extraordinarily high sound absorption in the speech frequency range are discussed. Recommendations are given for practical implementation of such panels in secure facilities and for evaluating their effectiveness using speech intelligibility criteria. It is concluded that acoustic metamaterials are a promising new means of technical protection of speech information, not yet covered by current standards.

Keywords: Speech information, acoustic metamaterials, sound-absorbing materials, technical information protection

Introduction

Protection of speech information against eavesdropping is an important task of technical security, since oral transfer of data remains one of the most common modes of communication. Malicious actors may attempt to obtain confidential information by intercepting sound, directly through the air (acoustic channel) or indirectly via building structures (vibro-acoustic channel), telephone lines, laser eavesdropping, etc. Therefore, specialists in technical protection of information area have developed a wide range of methods and tools to protect premises against speech information leakage. There are passive methods (aimed at physical attenuation of sound) and active methods (aimed at masking or suppressing the speech signal). In practice, several measures are usually combined to achieve an adequate level of protection – from architectural solutions (soundproof building envelopes) to electronic noise generators.

Conventional approaches to acoustic security have a number of drawbacks. Passive sound insulation requires significant mass and thickness of enclosing structures (walls, floors, ceilings) to effectively block voice frequencies, which is not

always feasible in existing buildings. Active acoustic masking systems can be installed without reconstruction of premises, but their constant noise may reduce the comfort of staff. Moreover, no single method guarantees absolute protection: even when noise is used, an attacker can apply modern digital signal processing methods to extract speech from a noisy recording. Consequently, there is an urgent need for innovative solutions in speech information protection that would improve sound insulation without a substantial increase in mass-dimensional parameters.

One of the most promising directions is the use of acoustic metamaterials – artificially engineered structures capable of controlling sound propagation in unusual ways [1]. Metamaterials form specific frequency responses due to the geometry of the structure rather than only due to the chemical composition of the substance. With the aid of local resonators and periodic elements such structures can create band gaps in which sound practically does not propagate. This opens up the possibility of designing thin sound-insulating panels that effectively absorb or reflect sound precisely in the speech frequency range, achieving the

performance of significantly thicker traditional materials. It is known, for example, that a metamaterial panel can completely absorb low-frequency sound with a thickness tens of times smaller than the acoustic wavelength, significantly outperforming conventional sound absorbers. In this paper, the principles for constructing such metastructures are studied and the possibility of implementing them for speech information protection is evaluated. Crucial to highlight that metamaterials are not yet mentioned in standards and regulatory documents on information security.

Features of existing methods

Ensuring the protection of speech information requires a comprehensive understanding of how acoustic signals propagate within and outside a room, as well as the mechanisms through which these signals can be intercepted. Modern approaches to speech protection combine architectural, engineering, and electroacoustic solutions aimed at reducing the intelligibility of spoken information beyond the boundaries of a secure area. Existing methods include both passive techniques, which focus on improving the physical sound insulation of building structures, and active techniques, which introduce controlled acoustic interference to mask speech signals.

1.1. Passive Protection

When designing secure premises, the primary task is ensuring adequate sound insulation of the room where conversations are held and selecting appropriate sound-protective materials. The most common approach is increasing the insulating capability of building envelopes (walls, ceilings, floors) by increasing their mass and multilayer construction. According to the mass law in acoustics, heavier and thicker partitions provide better sound insulation, especially at low frequencies.

Typical secure rooms are equipped with brick or concrete walls, often with double-wall construction (two walls separated by an air gap), airtight heavy doors with gaskets, and multilayer sound-insulating windows. Building acoustics tables provide sound reduction index values for various constructions: for example, a 250 mm brick wall provides ~ 45 dB of insulation in the mid-frequency range, a 100 mm gypsum-board

partition ~ 35 dB, and a 160 mm reinforced concrete slab more than 50 dB. Requirements for sound insulation levels depend on the protected room category.

To achieve maximum protection, additional measures are often necessary: resilient hangers and dampers for vibration isolation, sealing gaps and utility penetrations (ventilation, piping), installing double-door lobbies, etc. Special attention must be paid to door and window openings, as these are typical weak points. Such openings must be equipped with specialized sound-insulating doors and glazing, since standard structures have low insulation and sound may leak through gaps around them.

1.2. Active Protection

When construction-related measures are difficult to implement (e.g., an already operating facility where wall thickening is impossible), active protection methods are used. The most widespread approach is acoustic masking. Special generators of white (Figure 1) [2] or pink noise are installed in the protected room (ceiling or wall loudspeakers) and create constant background noise that hinders speech intelligibility outside the room. The noise spectrum is adjusted to overlap with the vocal frequency range and achieve sufficient masking.



Figure 1: Generator of white noise “RIAS-2GS”

The effectiveness of such systems is evaluated using the signal-to-noise ratio (SNR) at the boundary of the protected zone: the lower the SNR, the lower the probability of intelligible eavesdropping. Many regulations require maintaining SNR below a certain threshold (approximately 0 dB or a negative value). In Ukraine, the energy parameters of the speech signal at the zone boundary are measured in the 100 Hz – 10 kHz band using one-third-octave filters and compared with normative values.

In addition to noise masking, active noise cancellation systems have recently been proposed which generate an antiphase sound wave to cancel the speech signal (Figure 2) [3].

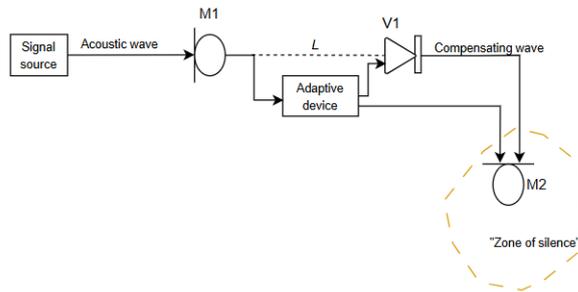


Figure 2: Structure of a one-dimensional adaptive system from acoustic information leakage

Such systems, equipped with microphones and loudspeakers with adaptive filtering algorithms, can form local “zone of silence.” Overall they demonstrate promising development in the field of active protection.

Traditional sound-absorbing materials

To reduce sound levels inside a room and prevent its escape outside, sound-absorbing materials are widely used. They convert acoustic wave energy into heat due to internal friction and resonant losses, thereby reducing sound reflection from surfaces.

1.3. Main types

Porous and fibrous materials. Mineral wool boards (glass wool, basalt wool), polyurethane foam and other foamed polymers are typical porous absorbers. In their porous structure the sound wave causes air and thin fibers to vibrate, and acoustic energy is dissipated due to viscous friction. Such materials effectively absorb mid and high frequencies (above 500 – 1000 Hz), but their performance at low frequencies is limited by the fact that thickness is small compared to wavelength. For example, a 50 mm mineral wool slab has a sound absorption coefficient less than 0.2 at 125 Hz, about 0.65 at 500 Hz and up to 0.9 at 2 kHz.

Perforated and slotted panels. These are resonance-type materials combining a rigid panel with holes and an air cavity behind it, often filled with fibrous material. A classic example is the Helmholtz panel resonator (Figure 3): a rigid board with holes above a closed air volume [4].



Figure 3: Helmholtz resonator

The air in the holes operates like a spring, and the air mass in the necks of the holes behaves as a pendulum, forming an acoustic resonator. At the resonance frequency such a panel absorber intensively absorbs sound and effectively removes energy from the incident wave. The resonance frequency is tuned by the area and length of the holes and the air-cavity volume: it can be approximated by the formula

$$f = \frac{c}{2\pi} \sqrt{\frac{S}{V(L+\Delta L)'}}$$

where S is the total area of the holes, V is the cavity volume, L is panel thickness (neck length), and ΔL is an end-correction term. Resonant panels allow targeted enhancement of absorption at a specific low frequency without increasing the overall thickness of the structure. However, their effective band is narrow around the resonance.

Combined systems. Modern sound-absorbing systems can combine porous and resonant elements. For instance, a suspended acoustic ceiling usually consists of porous tiles with an air gap above, creating a quarter-wavelength resonator to enhance low-frequency absorption. Another approach is the membrane absorber: a flexible membrane or sheet (thin metal plate, PVC) is stretched in front of an air or wool layer. At its own resonance frequency such a membrane efficiently absorbs sound (by vibrating and dissipating energy as heat through internal damping and radiation losses). Membrane absorbers are mainly aimed at low and mid frequencies (100 – 500 Hz) and often used together with porous layers to extend the effective bandwidth.

1.4. Limitations

The main parameter of a sound-absorbing material is the sound absorption coefficient α , i.e., the fraction of acoustic energy absorbed by the surface. It is frequency-dependent: most materials are more effective at high frequencies and much less at low frequencies. The reason is that low-frequency waves require a larger “path” to be attenuated – absorber thickness should be comparable to one-quarter wavelength. For the voice band ($\sim 300 - 3000$ Hz), quarter wavelength ranges from ~ 0.3 m (for 300 Hz) to ~ 0.03 m (for 3 kHz). Therefore, a 50–100 mm (0.05–0.1 m) thick material performs well from ~ 600 Hz upwards, but poorly below ~ 300 –400 Hz. Another problem with traditional materials is the need to cover all surfaces hermetically: if gaps or untreated patches remain, sound will find the path of least resistance. One must also account for non-uniform frequency response: porous absorbers provide smoother broadband absorption but still underperform at low frequencies; resonant absorbers give sharp peaks of high absorption but may have “valleys” between peaks.

For technical information protection, maximal attenuation precisely in the voice band 250 – 4000 Hz is critical, since this band carries most speech energy and determines intelligibility. Traditional materials can provide high absorption coefficients (> 0.8) in the mid and upper part of this band, but the overall protection against information leakage is often limited by low-frequency “transparency” of building partitions. It is exactly this problem that metamaterial absorbers are intended to solve by combining structural resonances on subwavelength scales to achieve extraordinary properties such as negative effective mass or extremely high absorption in narrow bands. Their basic principle is considered in the next section.

Acoustic metamaterials

An acoustic metamaterial (Figure 4) [5] is an artificially engineered periodic or locally resonant structure that exhibits effective properties beyond those attainable with natural materials. In other words, a metamaterial is not a homogeneous monolithic substance, but a “material made of structure” in which special elements (resonators) of size much smaller than the acoustic wavelength are embedded.

Interacting with the sound wave, these elements introduce phase shifts and additional losses, enabling dramatic changes in the transmission, reflection, or absorption of the wave at designated frequencies.

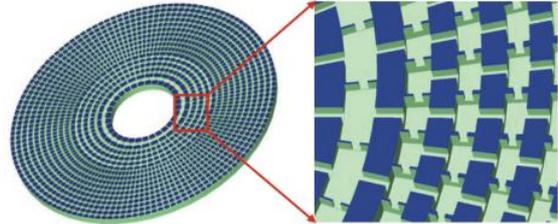


Figure 4: Schematic diagram of acoustic cloaking and the configuration of an acoustic cylindrical cloak

1.5. Concept and operating principle

For example, in a metamaterial based on local resonators the effective sound speed in the medium can be strongly reduced, forming a frequency band with small phase speed, strong dispersion, and high absorption. Another manifestation is negative values of effective parameters: in a band of frequencies just above the resonators’ resonance, the metamaterial may exhibit negative dynamic density or negative bulk modulus. Physically this means that the metamaterial medium responds to acoustic pressure in an unusual way – for instance, it may expand under compression or accelerate opposite to the applied force. As a result, the sound wave cannot propagate (the refractive index becomes imaginary) and a band gap is formed at the respective frequencies.

This principle is the acoustic analogue of electromagnetic metamaterials with negative permittivity and permeability that lead to a negative refractive index. Since 2000 many metamaterial variants have been developed [6]: elastic membranes with attached masses, frame structures with resonators, meta-panels with Helmholtz resonators, etc. The key point is that local resonance at frequency creates a sharp dip in sound transmission near (or a peak of absorption if the structure is damped). Thus, a metamaterial can be “tuned” to the desired frequency by choosing the resonator parameters.

1.6. Types

By structure and mechanism, acoustic metamaterials can be divided into two broad groups: locally resonant metamaterials and

periodic phononic crystals; hybrid approaches combining both mechanisms also exist.

Locally resonant metamaterials. These consist of periodically arranged inclusions (resonators) embedded in a matrix or frame which shown in Figure 5 [7].

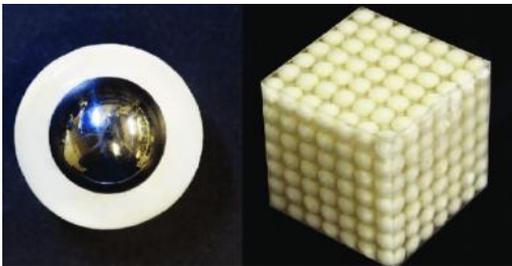


Figure 5: Sample that first realized a local resonance-induced anomalous mass effect

The size of each resonator is much smaller than the wavelength at the target frequencies, so at first approximation sound “does not see” individual elements and the medium appears effectively homogeneous. However, near each resonator’s natural frequency strong interaction occurs; the resonator absorbs wave energy. Examples include mass-spring resonators (heavy elements connected by elastic links to the frame, yielding negative dynamic mass), membrane metamaterials (thin membranes with attached weights that oscillate out of phase with pressure, also producing negative mass [8]), and Helmholtz-resonator-based structures (closed cavities with narrow necks integrated into a panel, acting as acoustic resonators that selectively absorb sound). Locally resonant structures can create wide band gaps even for very small lattice periods ($\lambda/10$ and below). Their drawback is relatively narrow attenuation band around each resonance; the advantage is very strong effect (almost total reflection or absorption) in that band.

Phononic crystals (periodic metamaterials) shown in Figure 6 [9].



Figure 6: Schematic diagram of one-dimensional, two-dimensional and three-dimensional phononic crystals

These are structures where the acoustic impedance varies periodically in space (for example, alternating layers of two materials, or a

lattice of holes/rods in a uniform medium). A classic case is periodic slits or columns in air. When the lattice period $d \sim \lambda/2$, Bragg scattering occurs: waves reflected from adjacent elements interfere and form frequency zones where propagation is prohibited (band gaps). Unlike local resonance, Bragg effects require the structural scale to be comparable with wavelength, so for 1–3 kHz frequencies the period must be tens of centimeters. This is often impractical for limited-thickness panels, therefore phononic crystals are more often used at higher frequencies or in large-scale structures (for example, noise barriers along highways with periodic elements). However, in combination with local resonators, periodicity can enhance the effect and widen the attenuation band.

Hybrid metamaterials. Modern designs often combine different mechanisms. For example, labyrinthine metamaterials use meandering channels cut into a panel (Figure 7) [10]: sound propagating through such a channel travels an effectively longer path in a compact volume, equivalent to locally reducing sound speed.

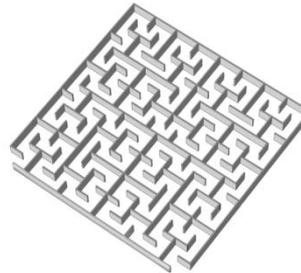


Figure 7: Labyrinthine metastructures with channels along the Hilbert space-filling

As a result, the panel behaves like a quarter-wavelength resonator at much lower frequencies than its physical thickness suggests [11]. Another hybrid example is combining membrane and porous layers: the membrane provides resonant low-frequency absorption, while the backing wool layer attenuates higher frequencies, significantly broadening the effective bandwidth.

The underlying physical phenomena, besides Bragg scattering and local resonance, include wave localization near resonant elements. In locally resonant systems, much of the sound energy is “trapped” around the resonators instead of propagating further, leading to local oscillations of small air volumes or structural elements that quickly decay. This is the absorption mechanism: the metamaterial acts as a sound trap. A crucial phenomenon is negative

dynamic mass: when a structural element (e.g., a membrane) oscillates in anti-phase with acoustic pressure, it effectively provides an inertial response of opposite sign. For the external wave this is equivalent to a medium with negative mass, so instead of passing through, the wave is reflected or canceled.

1.7. Prospects of applying metamaterials to speech information protection

Acoustic metamaterials have already attracted attention in noise control, architectural acoustics, automotive and aerospace industries (for reducing noise in vehicles), etc. In the field of technical speech information protection, the following application directions are promising:

- instead of traditional 100+ mm porous liners, metamaterial modules 20–50 mm thick can be used, providing equal or better absorption in the speech band. This saves space and weight (important for mobile secure modules, shipborne or airborne premises with strict weight limits). Metapanel can be mounted on existing walls without major reconstruction;
- metamaterials can be integrated into double-wall partitions or screens around confidential zones. For example, a portable shielding panel containing a layer of local resonators forms an additional sound barrier around a meeting table. Such screens can be relatively light and mobile, unlike heavy traditional shields;
- compact sound-isolated phone booths in open-plan offices are becoming common. Using metamaterials in their walls would allow thinner panels while improving isolation at voice frequencies, increasing the booths' effectiveness for confidential conversations;
- malicious actors may direct a laser beam at a window and detect micro-vibrations caused by internal sound. A metamaterial applied to glass (e.g., a transparent film with micro-resonators) could reduce vibration amplitudes at critical frequencies or introduce chaotic vibrations. This remains an idea at the conceptual level, but follows from the same principles of metamaterial control over wave propagation.

Evaluation of the effectiveness of acoustic metamaterials

The practical applicability of acoustic metamaterials in speech protection systems must be verified through objective, measurable criteria. Since metamaterials are intended to improve sound attenuation and reduce the intelligibility of spoken information outside a protected room, their effectiveness should be assessed using standardized acoustic metrics. This includes examining how metamaterial panels influence speech signal levels, sound insulation properties, and speech intelligibility when compared to conventional materials.

1.8. Methodology

In Ukraine and many other countries, the basis of control is an energy-based approach – measuring SNR at the boundary of the controlled zone. Here, a test speech signal is produced inside the secure room and, outside, the levels of this signal and background noise are measured. The metamaterial is intended to reduce the signal level; if the resulting SNR relative to background falls below the normative threshold (e.g., < -6 dB), then the security level is considered acceptable.

However, as already noted, SNR alone does not account for an attacker's ability to use sophisticated signal processing. Therefore it is advisable to complement SNR with a speech intelligibility coefficient W – the fraction of words correctly recognized from the intercepted recording. Classical methods include STI and CIS, which convert acoustic parameters into a predicted intelligibility percentage. For protective purposes, the goal is to make STI so low that intelligibility becomes essentially zero. For example, $STI < 0.3$ corresponds to poor intelligibility and $STI < 0.1$ to almost unintelligible speech.

In practical terms, a test procedure may include: playing sets of phrases inside the room, recording them outside with and without metamaterial panels, then applying signal-enhancement algorithms (filtering, correlation-based methods) to the recordings. If even after processing the semantic content remains extremely low, the residual intelligibility coefficient can be considered near zero and protection successful.

Thus, evaluation of metamaterial efficiency should comprise:

- measuring the spectral reduction of the speech signal level outside the room with metamaterials (in one-third-octave bands 100–5000 Hz).
- calculating *SNR* and comparing it with the normative limit.
- conducting an intelligibility test: human listening or automatic speech recognition on external recordings with and without metamaterials, with estimation of the percentage of correctly recognized phrases.
- assigning a conditional speech privacy class (*SPC*) according to the results (e.g., by analogy with ASTM E2638 [12]).

Note that national regulations may use a simplified criterion: if the required level attenuation (in dB) at a given distance is achieved, intelligibility is assumed to be acceptable. However, with the emergence of new materials (such as metamaterials) and threats (digital post-processing), regulations may be extended with more direct intelligibility-based metrics as proposed in modern studies. Our evaluation will be most complete if we demonstrate both traditional parameters (attenuation, *SNR*) and the effect on actual speech intelligibility.

1.9. Impact of metamaterials on room Security

Assume that additional attenuation provided by metamaterial lining is ~ 20 dB in the 300 – 4000 Hz range (this is realistic: for example, the CNRS panel showed up to 99% sound absorption, equivalent to more than 20 dB reduction). Adding this to existing wall insulation: if the original sound reduction at voice frequencies was ~ 30 dB, after installing metapanel it becomes ~ 50 dB. This corresponds to the highest protection categories. Under such conditions, the distance of speech intelligibility (the distance at which speech remains understandable) is drastically reduced – from several meters to a few tens of centimeters from the wall. In other words, already right behind the wall a person would barely distinguish anything, and at distances >1 m nothing at all.

For quantitative illustration: if previously *SNR* outside was -5 dB (still allowing some speech recognition), then with metapanel it may

become -25 dB, completely burying speech in noise. Even aggressive digital filtering cannot significantly recover a signal at $SNR \leq -10$ dB. Thus, the metamaterial provides a large safety margin.

In *STI* terms, we may expect a drop from $\sim 0.3 - 0.4$ to < 0.1 (assuming sufficient background noise). If there is no background noise (*SNR* determined only by attenuation), metamaterials still reduce the external speech level to < 25 dB *SPL*, close to the hearing threshold or typical building noise floor. Studies show that for unintelligible speech, noise should exceed the signal by at least 6 – 10 dB; in our case the background noise will dominate speech, satisfying this condition.

Compliance with regulations should also be checked. Suppose the standard requires sound insulation $R \geq 45$ dB at 1 kHz for the highest category premises. Our effective value of 50 dB (with metamaterials) exceeds the requirement, i.e., the standard is met with margin. If a regulation is formulated as “intelligibility not more than 5% at 2 m from the external wall”, this is also satisfied, since intelligibility is practically zero immediately behind the wall.

1.10. Compliance with regulatory requirements and recommendations

The analysis shows that using acoustic metamaterials can bring room security parameters to levels that meet or exceed standards and *NDTZI* requirements. In particular, the speech privacy class increases and the intelligibility index drops to a minimum, consistent with best international practices in confidential sound absorption. This indicates that metamaterial solutions have sufficient potential to be included in lists of approved *TPI* tools.

At present, the absence of such tools in official classifiers means each specific product must undergo individual testing and certification according to the national *TPI* expertise procedure. In the future, after enough evidence accumulates, we can expect specific standards on metamaterial sound-absorbing panels or their inclusion as a subtype in existing standards for sound-absorbing materials.

The study has revealed no fundamental contradictions between metamaterial behaviour and traditional protection methods – on the contrary, they can be combined effectively. For example, *NDTZI* requirements for control in one-

third-octave bands can be fully applied to metamaterials, whose band-limited effects are predictable and measurable with standard equipment. Fire safety regulations demand non-combustible materials – metamaterials can be implemented using metal and mineral components to conform.

Therefore, introducing metamaterials does not require revising core principles of the regulatory framework, only supplementing it with new items. The results obtained here – high absorption coefficients and confirmed reduction of speech intelligibility – can serve as a basis for methodological guidelines on testing such devices. In particular, the national regulator could be advised to develop specific instructions or additions to *NDTZI* describing measurement specifics for metapanel (for example, accounting for their narrow-band nature). This would ensure correct comparison of new and traditional tools.

1.11. Practical aspects of implementation and testing

The first stage is laboratory measurement of the sound absorption coefficient. Standard methods may be used: impedance tube to determine α at normal incidence and a reverberation chamber for average α under diffuse field conditions (according to IEC 60268-16:2011 [13] or a national equivalent). In addition, the sound reduction index of the panel should be measured by installing it into a test wall opening and using standard noise sources. These data will enable direct comparison of the metapanel with conventional building materials.

The next stage is field tests in conditions close to real information activity facilities. A typical room (e.g., 20 m² with two similar walls) can be chosen. One wall is fitted with metamaterial panels, the other kept standard as control. A speech-like test signal (recorded conversation or special speech noise) is played inside, and sound is recorded outside at various distances. Comparing levels and spectra shows how much additional attenuation the metamaterial provides. Experts or automatic speech recognition software can then evaluate whether the text is intelligible through the standard wall and through the improved wall. The expectation is that some phrases will still be recognized through the standard wall, but none through the wall with panels. This experimentally confirms the security gain.

An important practical issue is durability and stability of performance. The metamaterial should be subjected to cyclic temperature/humidity changes and mechanical vibration (simulating real conditions) to verify that its parameters remain stable. If all is satisfactory, it can be recommended for use.

Finally, test results must be documented according to *TPI* certification requirements. Measurement protocols and listening test reports can be submitted to the competent authority in charge of state expertise. If certification is successful, the new material can be added to the list of approved tools and deployed widely. This would be a significant step forward in speech information protection technologies, introducing a tool based on metamaterial acoustic engineering.

Conclusions

The research confirms the fundamental feasibility of using acoustic metamaterials to enhance speech information security in premises. Analysis of modern protection methods shows that traditional passive and active tools have physical limitations (requirement for massive, thick constructions at low frequencies, side-effect noise from masking systems, etc.) and do not always provide the necessary confidentiality under advanced threat scenarios. In contrast, metamaterials enable engineered frequency properties of building envelopes: they provide selective absorption and reflection of sound precisely in the speech band, as demonstrated by models of resonant panels. Due to their subwavelength structure, metamaterials achieve extremely high absorption (up to 99%) at target frequencies with very small panel thickness, thus solving the low-frequency sound insulation problem without massive walls.

Based on literature and regulatory review, requirements were formulated for a metamaterial panel for speech protection: broadband absorption in ~ 0.3–4 kHz, average α of at least 0.8, non-combustibility, structural stability. A matching design was proposed – a panel with a complex of resonators of various types (volumetric Helmholtz resonators, slotted channels, membrane elements) combined with a conventional damping layer. Modelling of this panel showed the possibility of achieving 15 – 25 dB additional attenuation of speech compared to standard sound-absorbing cladding of the same

thickness. This directly translates into a reduction of external speech intelligibility: according to estimates, the metapanel can reduce *STI* below 0.1 and provide a speech privacy class corresponding to the strictest confidentiality requirements.

Implementation of the proposed solutions requires further experimental research. Prototype metamaterial absorbers must be fabricated and tested with standard methods. It is expected that practical measurements will confirm the theoretical results, consistent with global publications reporting ultrathin low-frequency metamaterial absorbers. Successful deployment of acoustic metamaterials in secure premises will reduce materials consumption and energy usage in *TPI* systems (less reliance on active noise generators) and increase comfort and protection efficiency.

The obtained results fill an existing scientific-technical gap: it is shown that metamaterial sound-insulating structures can significantly improve room sound insulation without increasing mass-dimensional parameters – an aspect previously not addressed in Ukrainian standards and scientific literature. The practical value of the work consists in developing design recommendations for metamaterial panels and methods for evaluating their effectiveness, which can serve as a foundation for further implementation of this technology in *TPI* systems. In the long term, development of this direction will promote the emergence of new standards and requirements that take metamaterial achievements into account, thereby raising overall information protection to a qualitatively new level.

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