Improving Design of an Energy-Efficient Lighting System Based on Mirrored Hollow Tubular Light Guides According to the Criterion of Its Soundproofing

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Abstract. This scientific work presents results of energy-efficient lighting systems based on mirrored hollow tubular light guides tests when sound waves of various intensities of low-frequency, mid-frequency and high-frequency ranges pass through them. In addition, technological changes in design of natural lighting systems, which were carried out in order to increase their vibration resistance and noise absorption are shown. Studies have shown high reliability of lighting systems in terms of their soundproofing, especially in mid-frequency and high-frequency ranges, which can significantly reduce harmful effects of noise on human body, leading to fatigue, depletion of brain cells, insomnia, decrease in overall working capacity and human productivity. Conclusions of this work make it possible to further optimize the future prospect of widespread use of energy-efficient lighting systems based on mirrored hollow tubular light guides in construction of residential, administrative and industrial premises.

1. Introduction

Technology of delivering natural light to rooms with constant presence of people is firmly embedded in our lives. We are increasingly equipping our living, administrative and industrial premises with lighting systems based on hollow tubular mirrored light guides. But recently, people using these systems are wondering whether hollow tubular light guides are conductors of various sound signals and noises that are abundantly present around our habitats and work. These questions are not idle, since the desire of people to live, work and rest in comfortable conditions is natural. We have studied this problem in works of various scientists.

Quite a lot of scientific works are devoted to study of sound insulation properties of various materials, study of the processes of sound transmission through various obstacles. For example, M. Garai, P. Guidorzi [1] investigated internal acoustic characteristics (sound reflection and airborne sound insulation) of noise barriers installed in order to check their compliance with design...
characteristics and their quality after several years of operation. Characteristics were measured in-situ according to CEN/TS 1793-5. Highly efficient absorption of low-frequency sounds (<1000 Hz) while maintaining a free flow of liquids, as a serious problem in acoustic engineering, was studied by group of scientists in [2].

Article [3] examines static and dynamic behavior of an elastic disordered system in form of connection between the foundation and the base of a building column under influence of a closed noise signal. And in article [4], studies are presented that answer three questions: (1) How does level of environmental noise, depending on the materials of enclosing barriers, affect perception of people at different amplitudes of sound wave? (2) Does design of anti-sound barrier affect inhabitants’ aesthetic perception? (3) Are safety barriers aesthetically pleasing and perceived as the best noise attenuators? The acoustic characteristics of a semi-closed noise barrier installed on a high-speed railway bridge are considered in this scientific work [5]. Refraction of sound propagating in the open air within homogenization field was studied and investigated by scientists Bartvan der Aa and Jens Forssén in their work [6]. Prospects for use of renewable low-frequency acoustic noise protection barriers on high-speed railways are considered in [7]. This article presents a new noise barrier using a Helmholtz resonator and polyvinylidenfluoride (PVDF) film to convert the acoustic energy of low frequency noise from high-speed railways into an electric energy source. In [8] sound insulation characteristics of expansion chambers with built-in micro-perforated panel construction study was made. Carolina Simón-Herrero, Nieves Peco et al. [9] evaluated effect of adding thermally reduced graphene oxide on physical, thermal, and acoustic properties of finally resulting aerogels. This made it possible to reduce pore diameter, improve thermal stability of aerogels, and also led to an improvement in sound absorption coefficient of aerogels. Theoretical and experimental aspects of fractal approach to sound-absorbing behavior of materials are considered in [10].

It should be noted that much less scientific work has been devoted to study of design features and prospects for practical application of lighting systems based on mirrored hollow tubular light guides. Let’s note the most significant of them. M.Kocifaj in his work [11] generalized theoretical approach, which was originally used to simulate light transmission through a hollow tubular light guide with a Lambert diffuser (HOLIGILM). He also adopted it to light guides with transparent glazing at their base.

In study [12], authors determined dependence for standard distributions of sunlight brightness in overcast and clear skies, as well as effect of this dependence on efficiency of hollow tubular light guides. The findings lead to assessing indoor daylight and developing various daylighting strategies. A team of scientists headed by Stanislav Darula carried out study of theoretical method application to light propagation when illuminating interior spaces with curved hollow tubular light guides [13]. In [14] angular distribution of light emitted from collector of a hollow tubular light guide was studied. The developed concept made it possible to imitate solid light particles for hollow tubular light guides of various diameters and sky brightness diagrams, depending on design of lighting systems. Lighting of premises using straight light tubes in various climatic zones was studied in [15]. Results of calculations showed that light transmission from a light tube can be expressed as a monotonic function of height of the sun, with exception of low angles of its location. In [16] and [17] problem of condensation and thermal bridges formed at hollow tubular light guide junctions when installed on flat roof surface is considered. Lighting systems were compared in two different simulation programs: ANSYS Fluent and CalA. Article [18] presents an analytical study of the optical efficiency of straight hollow tubular light guides. The solution found is applicable to all aspect ratios of hollow tubular light guides, it provides accurate prediction when modeling lighting systems. The new analytical model is validated and compared with HOLIGILM’s precise calculations. Scientific work [19] is devoted to the tracing of daylight passage through circular lighting tubes with anidolic concentrators added to the input port of the light tube. Article by scientists from the University of Technology Thonburi, Bangkok, Thailand [20] presents simulation results of an experiment on transmitting light through rectangular light tubes. Analytical method of direct ray tracing was used to observe passage of the rays from a sunlight source into a bend pipe to a straight section, then through a bend section to an exit.
After analyzing the above and many other scientific publications, we came to a conclusion that no one has studied the problem of the passage of sound waves through lighting systems based on hollow mirrored tubular light guides. Therefore, we assume that this work is unique, and presented conclusions have undoubted scientific novelty.

2. Methods
For the research we used lighting systems manufactured by recognized leader Italian company Solarspot International SRL (tube diameters 250, 530 and 650 mm), which are considered the most advanced in comparison with other similar systems produced in the world. Tests were carried out in one of acoustic test/sound measuring laboratories in Italy in which it is possible to measure all acoustic parameters of the environment: noise levels, general and local vibration, infrasound, ultrasound, acoustic parameters of premises as well as measuring sound insulation of air and noise impact of enclosing structures, measuring reverberation time and other acoustic criteria.

During the tests following modern equipment was used: a precision sound level meter and spectrum analyzer, a 3-channel precision vibrometer-spectrum analyzer, an acoustic calibrator, a percussion machine, an omnidirectional sound source dodecahedron with a power amplifier and a white and pink noise generator, appropriate software and other devices. Layout of the testing laboratory is shown in Fig. 1.

![Figure 1. Scheme of the acoustic laboratory and tests performed.](image)

Legend:
1 - lighting system based on 650 mm tube diameter hollow tubular light guide manufactured by Italian company Solarspot International SRL;
2 - soundproof chamber with sound-emitting equipment of various power;
3 - precision sound level meter and spectrum analyzer;
4 - percussion machine.

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1 Report No. 280962 on the results of comparative tests of hollow tubular light guide systems (measurements of the transmittance of natural light by four different HLG systems of the world's leading manufacturers: Solarspot® D-38, two-layer light capturing units: dome and anti-condensation tray (Solarspot International SRL, Italy); Solarspot® D -38, single-layer light capturing unit, dome without anti-condensation tray (Solarspot International SRL, Italy), Sun Pipe® 450, double-layer diffuser (Monodraught, UK) Brighten Up® 290 OS, double-layer diffuser and reflective notch on the surface of the dome (Solatube International Inc, USA) conducted on August 14th, 2012, in BRE (Building Research Establishment) Office Building, Bucknalls Lane, Watford WD25 9XX Hertfordshire, United Kingdom.
3 - soundproof chamber with a sound receiver, simulating attic of a building;
4 - soundproof chamber with sound receivers.

We tested lighting systems in three generally accepted frequency ranges: low, medium and high. Sound signals of various amplitudes (100 and 80 dB) were used. We calculated sound absorption coefficients ($\alpha$) of individual elements of lighting systems based on hollow tubular light guides using the formula:

$$\alpha = \frac{L_3}{L_1}$$

(1)

where $L_3$ is sound energy absorbed by structural elements (see Fig. 2);
$L_1$ is sound energy falling on structural elements (Fig. 2).

Figure 2. Diagram of sound signal passage through a lighting system based on hollow tubular light guides.

Legend:
1 - dome of the light receiving device (collector, shown in Fig. 10, position 1);
2 - air environment between individual structural elements of the lighting system and anti-condensation trays (their number in a lighting system depends on length of the light guide to be installed);
3 - light-distributing device (diffuser, shown in Fig. 10, position 10);
$L_1$ is energy of sound falling on the obstacle;
$L_2$ is energy of sound reflected from the obstacle;
$L_3$ is sound energy absorbed by structural elements;
$L_4$ is sound energy transmitted through structural elements of the lighting system.

We calculated intensity of a sound signal ($I_1$) that passed through structural elements of the lighting system using the formula:

$$I_1 = I_0 \cdot e^{-\alpha X}$$

(2)

where $I_0$ is intensity of the initial sound signal affecting lighting system
$e$ is a mathematical constant, an irrational number, approximately equal to 2.71828 (Euler's number);

$\alpha$ is sound absorption coefficient of individual elements of the lighting system, which were affected by the sound wave;

$x$ is distance that the sound wave has traveled through the lighting system.

### 3. Results and Discussion

First practical experience, carried out in the acoustic laboratory, was determination of the sound absorption coefficients of individual structural elements of the lighting system. As a basis we took Solarspot system (Solarspot International SRL), diameter 530 mm, since it is, firstly, one of the most frequently used in practice, and secondly, it is medium in diameter among the samples used (from 250 to 900 mm). When checking the empirical values obtained using calculations with formula (1), we found discrepancies of 3.42% - 6.02%, which was considered optimal. Results of the experimental values are shown in table 1.

| Frequency range in which the measurement of the coefficient $\alpha$ was made | Sound absorption coefficients of individual structural elements of the lighting system ($\alpha$) | Light receiving dome (collector) | Anti-condensation trays | Light distribution device (diffuser) |
|---|---|---|---|---|
| Low frequency, 130 Hz | 0.122 | 0.061 | 0.065 |
| Mid-frequency, 1100 Hz | 0.819 | 0.542 | 0.577 |
| High frequency, 5500 Hz | 0.821 | 0.544 | 0.579 |

Next action of the research work was determination of measures to improve design of the lighting systems based on hollow tubular light guides of Solarspot International S.R.L company according to criterion of its soundproofing.

They consisted in installation of additional, previously not provided for in technical documentation, sealing gaskets, installed in places of rigid junction of the lighting system with the building’s structures. Location of the additional gaskets is shown in fig. 11, 12, 13 in black oval and rectangular outlines. Synthetic gaskets are innovative materials, their chemical composition was developed by engineers of Solarspot International SRL company together with specialists from one of Italian chemical concerns. This made it possible to significantly reduce level of vibration of the lighting system, as well as to damp out sound waves that randomly arise outside the buildings where these systems to be installed.

Now we can present results of sound signals intensity measurements of various frequencies that have passed through the lighting systems with diameters 250 and 650 mm (Fig. 3, 4, 5, 6, 7, 8, 9, 10, 14, 15, 16, 17). Dynamics of intensity indicators of sound wave transmitted through the 530 mm system differs very slightly.
In fig. 3, 4, 5, 6 graphs of changes in intensity of a sound wave in low frequency range (130 Hz) are shown. We see that, having completely passed through the lighting system, intensity of a sound wave has decreased slightly (Table 2). This is a natural phenomenon, since low audible sounds with the longest wavelength have a great penetrating ability, are often felt tactiley, "with the whole body". We heard here slow, stringy, sometimes booming and drawn-out sounds, sometimes soft, velvety, "enveloping", having depth and volume.

**Table 2.** Dynamics of changes in intensity of a low-frequency sound wave when it passes through lighting systems with a diameter of 250 and 650 mm.

| Light guide tube diameter, mm | Reduction of the sound wave intensity, % |
|-----------------------------|-----------------------------------------|
| 250                         | 20.55                                   |
| 650                         | 19.36                                   |

The situation changed dramatically when we carried out measurements in mid-frequency range (Fig. 7, 8, 9, 10).
Figure 7, 8. Graphs of changes in intensity of a sound wave in medium frequency range (1100 Hz), passed through a lighting system with diameter of 250 mm. In fig. 7 (left) initial sound intensity of 100 dB. In fig. 8 (right) initial sound intensity 80 dB.

Figure 9, 10. Graphs of changes in intensity of a sound wave in medium frequency range (1100 Hz), passed through a lighting system with diameter of 650 mm. In fig. 9 (left) initial sound intensity of 100 dB. In fig. 10 (right) initial sound intensity 80 dB.
Figure 11. Diagram of an energy-efficient lighting system based on a hollow mirrored tubular light guide with diameter of 650 mm, mounted in a building. On the right detail of a light capturing device (collector) attachment are shown. Black oval and rectangular contours mark installation points for additional sealing materials that reduce vibration of the system and increase its sound absorption.
Figure 12. Diagram of an energy-efficient lighting system based on a 650 mm diameter hollow tubular light guide installed in a building. On the right we can see list of the system’s components. Black oval contours mark points for installation of additional sealing materials that reduce vibration of the system and increase its noise absorption.

In the average frequency range of sound wave, we already see clear exponential dependence of sound wave intensity dynamics on length of a tubular light guide (see formula (2)). Calculations of sound wave intensity using formula (2) gave discrepancies with experimentally obtained values from 1.12 to 3.41%, which, in our opinion, is an acceptable result. We also see here that design of the lighting system under study makes it possible to almost completely extinguish sound waves (Table 3) that arise outside the building. Intensity of mid-frequency sound penetrating through the lighting system into a room corresponds to rustling of leaves, whispering or the movement of a wall clock. People in the room do not experience noise discomfort.

We see similar result when testing lighting systems with tube diameter of 250 and 650 mm when exposed to sound waves of high (5500 Hz) frequency, which have ”airiness”, transparency, purity and clarity (Fig. 14, 15, 16, 17). High-frequency sound waves lose from 84.40 to 85.83% of their energy, passing through lighting systems of Solarspot International SRL company (Table 4).
Figure 13. Diagram of an energy-efficient lighting system based on a hollow tubular light guide with diameter of 530 mm, mounted into a building through a sloping roof. Black oval outlines mark installation points for additional sealing materials that reduce vibration and increase sound absorption of the system.

Table 3. Dynamics of changes in intensity of a sound wave in the medium-frequency range when it passes through lighting systems with diameter of 250 and 650 mm.

| Light guide tube diameter, mm | Reduction of the sound wave intensity, % |
|-----------------------------|------------------------------------------|
|                             | Initial sound wave intensity level 100 dB | Initial sound wave intensity level 80 dB |
| 250                         | 85,55                                    | 84,77                                    |
| 650                         | 84,36                                    | 84,12                                    |
Figure 14, 15. Graphs of changes in intensity of a sound wave in high frequency range (5500 Hz), passed through a lighting system with diameter of 250 mm. In fig. 14 (left) initial sound intensity of 100 dB. In fig. 15 (right) initial sound intensity 80 dB.

Figure 16, 17. Graphs of changes in intensity of a sound wave in high frequency range (5500 Hz), passing through a lighting system with diameter of 650 mm. In fig. 16 (left) initial sound intensity 100 dB. In fig. 17 (right) initial sound intensity 80 dB.

Table 4. Dynamics of changes in intensity of high-frequency sound waves when it passes through lighting systems with diameter of 250 and 650 mm.

| Light guide tube diameter, mm | Reduction of the sound wave intensity, % |
|-----------------------------|------------------------------------------|
|                             | Initial sound wave intensity level 100 dB | Initial sound wave intensity level 80 dB |
| 250                         | 85,83                                     | 84,98                                     |
| 650                         | 84,82                                     | 84,40                                     |

4. Conclusions

Test results presented in this work and calculations performed allow us to draw the following conclusions.

1. Energy-efficient lighting systems based on hollow mirrored tubular light guides prevent penetration of sound waves of various amplitudes and frequencies into the premises where these systems are installed. In low-frequency range the sound waves energy loss is up to 20%, in medium and high frequency ranges the sound wave absorbed by the lighting system is up to 85%, which fully complies with the requirements of regulatory documents governing noise level in residential, administrative and industrial premises adopted in the Russian Federation ( [21], [22], [23] and others).

2. The technological changes made in design of lighting systems based on hollow tubular light
guides manufactured by Solarspot International SRL company have made it possible to increase their vibration resistance and absorption of sound waves of various amplitudes and frequencies.

3. Diameter of lighting systems tubes practically does not affect the transmission of sound waves of different frequencies through it. Light guide with diameter of 250 mm transmits 5.8% less low-frequency wave energy than a similar light guide with diameter of 650 mm. In mid-frequency range of sound waves, the difference is 1.39%, in high-frequency range - 1.18%.

4. Initial level of a sound wave intensity affecting the lighting system does not significantly change its sound absorption by the system. In particular, level of sound the wave intensity changes by 3.75% in low frequency range when its initial value decreases from 100 to 80 dB. In mid-frequency range of waves, the difference is 0.90%, in high-frequency range - 0.99%.

5. Results of the study performed allow us to confidently optimize further prospects for use of lighting systems based on mirrored hollow tubular light guides in the energy-efficient construction of residential, administrative and industrial buildings, since they prevent penetration of sound waves of various amplitudes and frequencies (noise) into rooms. Thus, minimizing harmful effects on the central nervous system of people, reducing overwork and depletion of brain cells. Design features of high-tech lighting systems, excluding the effect of noise, help reduce fatigue of people, increase their overall performance and productivity.

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