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STUDIES ON PROPAGATION OF VIBROACOUSTIC ENERGY AND ITS INFLUENCE ON STRUCTURE VIBRATION IN A LARGE-SIZE OBJECT

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Large-size spaces of general use are usually characterized by atypical acoustic features. The Great Lecture Hall of Warsaw Technical University can be an example, as its maximum crosswise dimension is comparable with its height. When powerful amplification equipment is used for special events, the question that arises is possible negative influence of acoustic signal energy on the building's structure, especially the skylight. The paper presents selected results of studies on acoustically induced vibrations of construction elements and tries to answer the above formulated question.

Keywords: noise excitation, structural vibration, safety of construction.

1. Introduction

On many occasions it is the propagation of vibroacoustic energy that determines the functional qualities of a technical object. These questions result especially important in the process of designing big public spaces as concert halls, theatres and auditoria. However, even the most elaborated computational tools require experimental verification, as the experiment that gives the ultimate answer concerning acoustic qualities of the space (often perceived in a very subjective way) [1, 2].

Methods based on propagation of vibroacoustic energy play a particular role in solving practical engineering tasks, including evaluation of the object's state, improvement of user's comfort, and shaping the acoustic atmosphere [3]. One of the frequent causes of a noticeable change in vibroacoustic signal is the fact that the routes of propagation of vibroacoustic energy have been modified as a consequence of damage or wearing of an element. On the other hand, the meaning of different forms of mechanical vibrations could be hardly omitted in the discussion concerning dynamic loads and structure security issues.

The architectonical qualities of the Great Lecture Hall of Warsaw University of Technology have made it in recent years quite frequently used venue, used for different meetings and gatherings, official events with media coverage, balls and concerts. On the occasions the powerful amplifying equipment is used and the sound level in the hall reaches values never recorded before. An attempt to evaluate the influence of acoustic input on the object has been undertaken because the security of construction in this aspect has not been examined yet. The main objective of the study was an attempt to answer the question concerning the possible danger to the people staying in the Hall: whether a real danger of the acoustically induced vibration provoking damages the bearing structure of skylight existed. The conclusions should also help to understand better the issue of propagation of vibroacoustic energy in large-size spaces and to formulate possible directives concerning environmental restrictions.

2. The studied object

The Great Lecture Hall is a venue of more than 20 000 m^3 of cubic capacity and complex acoustic characteristics. The measurements [4] gave proved that for the medium frequencies the reverberation time exceeds 10 seconds which can result in superimposing of sounds retarded in phase. Complex form of the object, equipped with many strongly reflective surfaces result in relatively level acoustic field, however, the superimposing reflected waves provoke changes in time and space positioning of local signal maximums (what was confirmed during the research).

The ceiling, made of transparent, coloured screens held in iron framework is suspended under the glass roof, approximately 20 metres above the floor. The load is transmitted by a solid steel structure. The issue of propagation of vibroacoustic energy in the aspect of evaluation of state of the object can be crucial for the skylight crowning the Hall. In fact, if the safe exploitation of the hall is concerned, the ceiling and the roof seem to play a decisive role, as the flat surfaces and relatively low rigidity make them particularly vulnerable to quick changes of pressure (caused by sound waves).

3. Research methods

The research consisted in recording responses for input with the broadband noise, the noise in 1/3 octave band, and the harmonic components of frequencies overlapping by the standardized middles of 1/3 octave bands in the range of 20–6300 Hz. Some additional observations were done during the concert of Kombi pop-music band.

The vibroacoustic signals were processed using 2 capacitor microphones GRAS together with several piezoelectric accelerometers working in ICP standards (three triaxial ones among them). Recording was done with 16-channel multi-analyzer SCADAS III under the LMS CADA-X. Acoustic signals were generated by two amplifying sets placed on the floor where the equipment is usually placed during the official events.

The sound in the Lecture Hall was recorded using a microphone placed centrally on the second floor level (Fig. 1). Before the research could start, the distribution of acoustic pressure level during the broadband noise input had been checked between the ceiling and the glass roof of the Hall. Having noted slight differences (less than 2 dB), the microphone placed between the roof and the ceiling was positioned above the geometric centre of suspended ceiling.

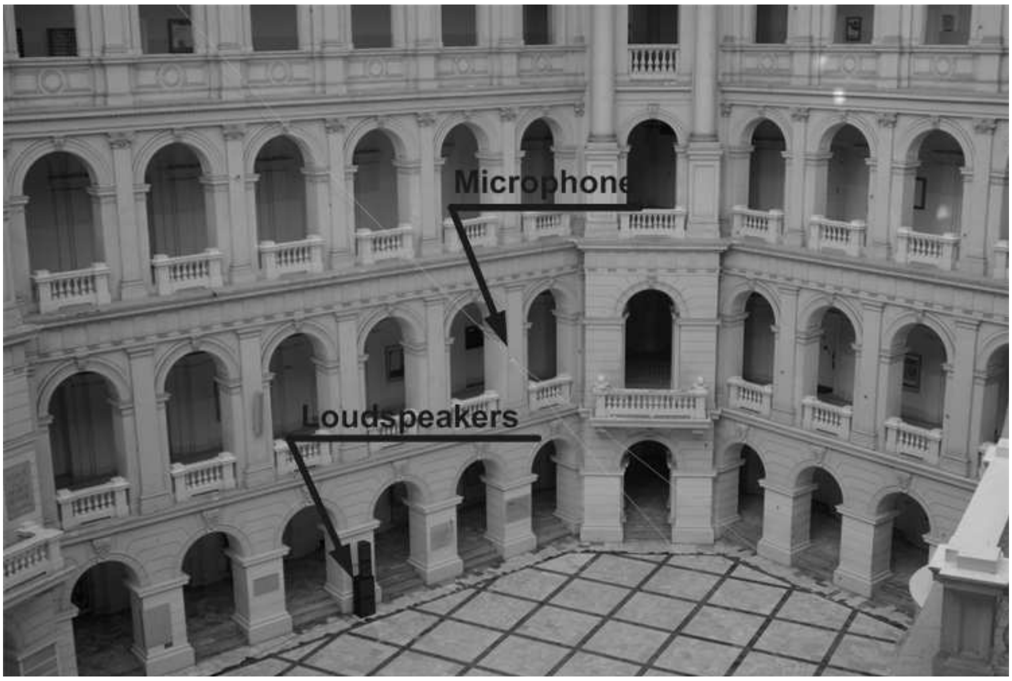

Fig. 1. Positions of the microphone and one of the amplifying sets in the Hall.

The accelerometers were fixed in chosen points of metal structure, as well as in geometric centres of several ceiling panes. Location of some measurement transducers can bee seen in the photographs (Fig. 2).

All slotted sections were calibrated using standard sound and vibration sources (calibrators).

Fig. 2. Location of some selected measurement transducers on the ceiling of the Hall.

4. The results

The experiment has provided very extensive research material. As the analyze of recorded signals has shown, the acceleration of vibrations reached its highest values in consequence of the tonal (harmonic) inputs. At the same time geometry of the Hall made indeed the tonal signal of speaker input vibrations interfered by a polyharmonic signal. Some selected results have been presented in graphic form demonstrating the most disadvantageous cases (the highest recorded rms values of vibration accelerations). All the results are for vertical vibrations – the amplitudes of horizontal vibrations are several times lower.

The Fig. 3 shows the juxtaposed levels of acoustic pressure in the interior of the Hall and above its ceiling. It can be understood from the graph that the ceiling does not work as an efficient acoustic barrier. It is especially apparent for low-frequency sounds.

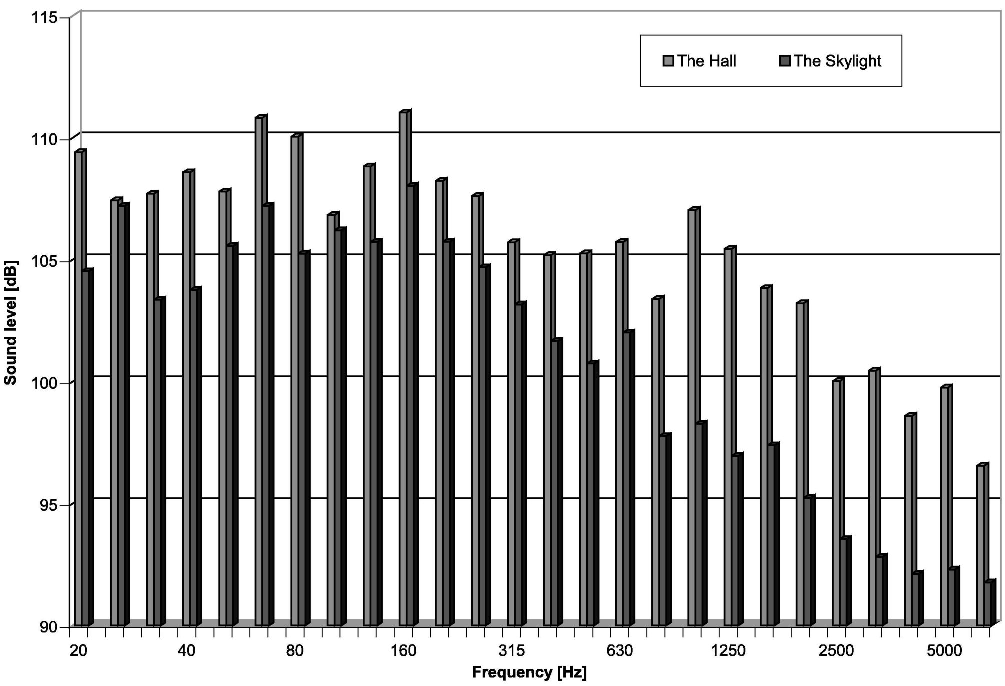

Fig. 3. Acoustic pressure level in the Hall and above the ceiling, the tonal sounds being generated.

In the Fig. 4 we have the rms values of vibration accelerations in three selected ceiling panes, the vibration excited by harmonic sounds. The pane 1 is a sector of a circle forming the centre of the ceiling. Two others are of elongated shape and situated further from the geometric centre of the skylight.

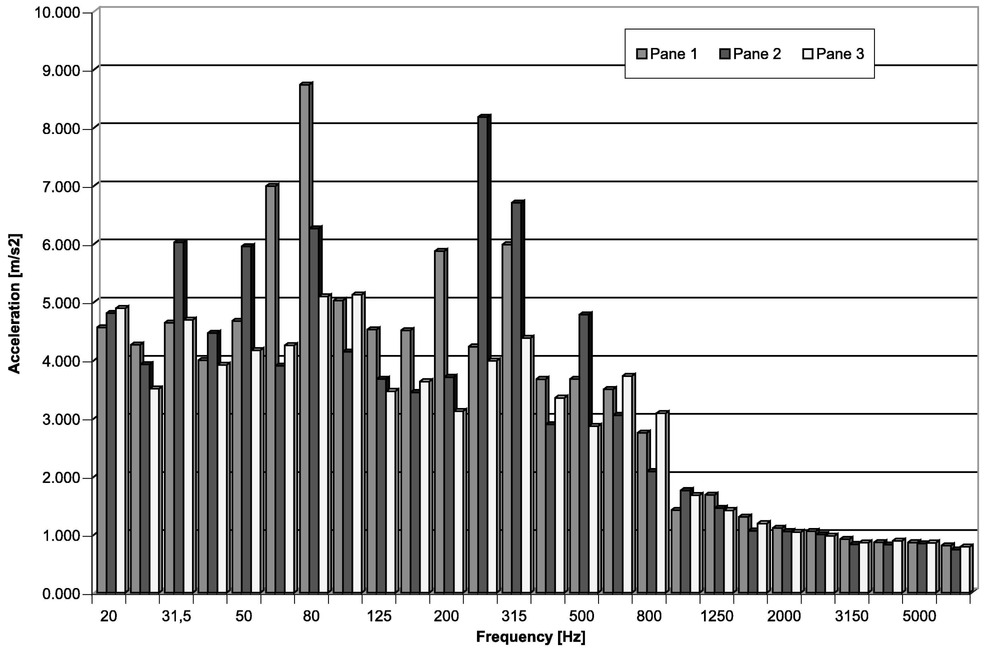

Fig. 4. The amplitude of acceleration of vibrations in the ceiling panes, the tonal sounds being generated.

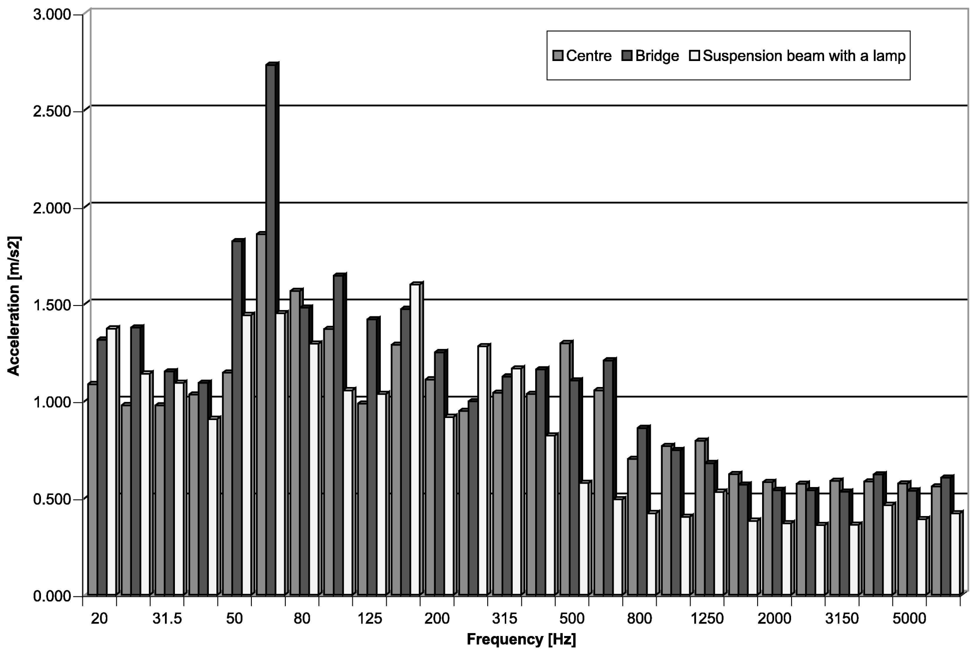

Fig. 5. Amplitude of vibration accelerations in steel construction elements, the tonal sounds being generated.

Vibrations of selected elements of the ceiling structure are demonstrated in the next graph. Taking the highest recorded levels of vibrations acceleration, out of the three measurement points situated on the semi-beam of bridge, the middle one, located in the 1/3 of its length has been chosen for visualization.

5. Discussion of the results

The results presented in the previous section show that the general level of vibrations forced by acoustic pressure during the standard exploitation is not dangerous to the structure. However, the results do not fully describe the phenomenon and therefore do not provide enough background information for a forecast in the case of more powerful sound amplification. What is necessary for this task it is a mathematic model (even approximate) for the input (acoustic pressure) / vibration response transfer function. The Fig. 6 shows the narrowband spectra of acoustic pressure measured under the skylight and above it, together with the spectrum of vibration acceleration input by the broadband noise. It can be observed that at low frequencies (up to 500 Hz) transformation of acoustic energy absorbed by the skylight's structure into mechanic vibrations is necessarily nonlinear in some ranges.

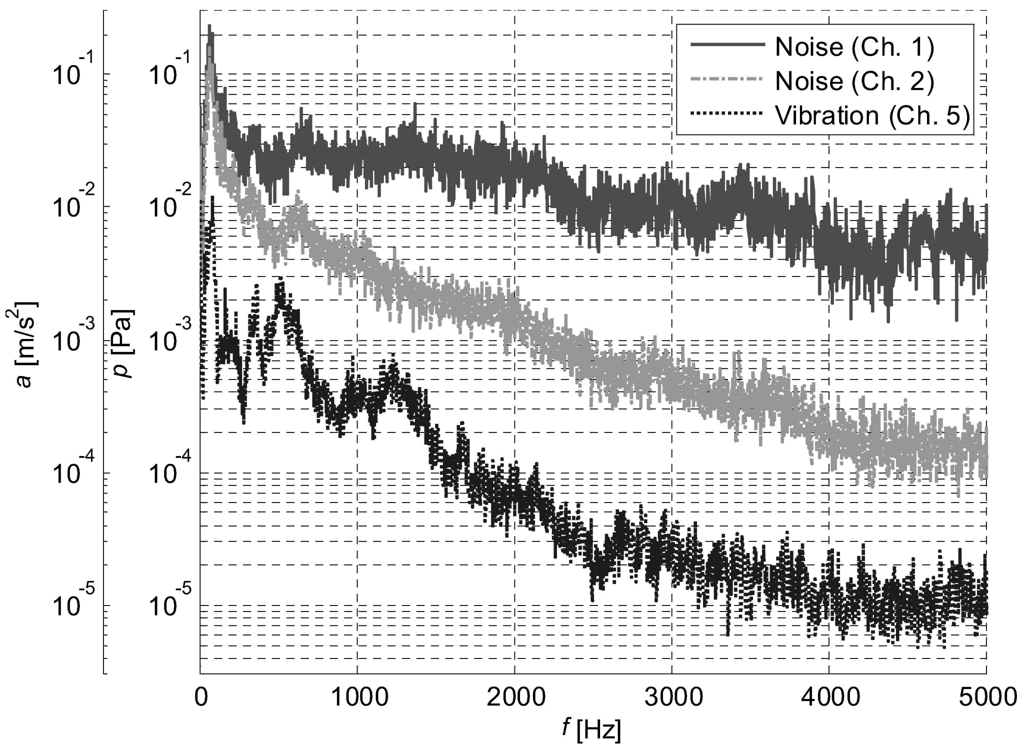

Fig. 6. Spectra of acoustic pressure under the skylight (Sec. 1) and above it (Sec. 2); vertical vibrations in the centre of skylight's structure (Sec. 5) input by the broadband noise.

The correlation analysis was carried out. The subsequent figures (7–9) show some demonstration results for the range of 0–200 Hz for the noise input and the polyharmonic input (into which the tonal input by a speaker tended to be transformed) by the tones of selected frequencies, together with the coherence function. The frequencies

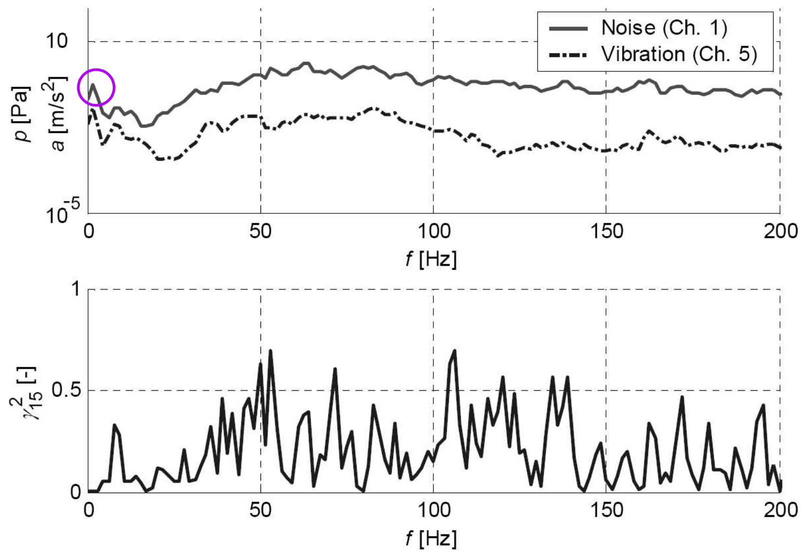

Fig. 7. Spectra of acoustic pressure in the Hall (Sec. 1) and of vertical vibrations in the centre of the skylight's structure (Sec. 5) input by broadband noise; coherence function for the channels.

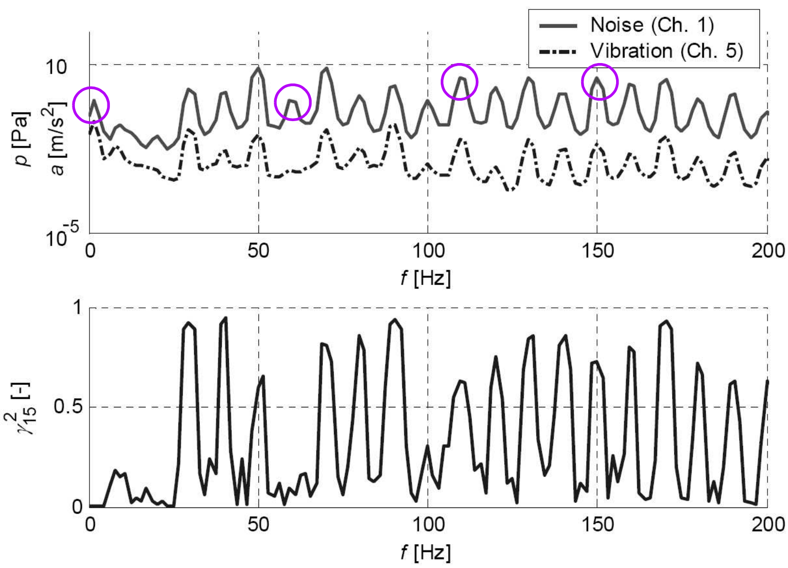

Fig. 8. Spectra of acoustic pressure in the Hall (Sec. 1) and of vertical vibrations in the centre of the skylight's structure (Sec. 5) input by the component 20 Hz; coherence function for the channels.

with discernible nonlinear effects have been marked with a circle. Similar results were also obtained for other input frequencies.

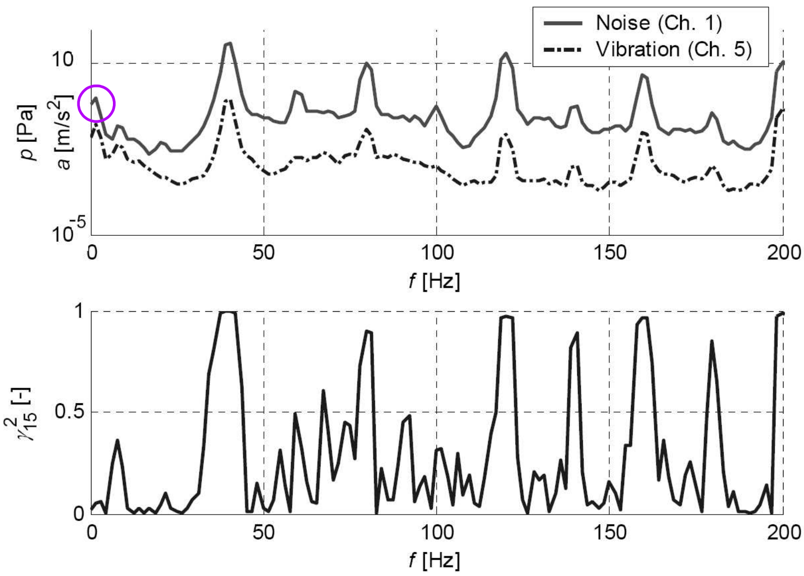

Fig. 9. Spectra of acoustic pressure in the Hall (Sec. 1) and of vertical vibrations in the centre of the skylight's structure (Sec. 5) input by the component 80 Hz; coherence function for the channels.

The response that endangers structure most is undoubtedly the high non-coherent vibration response for the lowest frequencies (3 Hz) corresponding with the free vibration of the structure. As participation of the linear part of transmittance module (close coherence 1) is quite important, we can assume, according to the reasoning presented for instance in [5, 6] that if the external disturbances do not occur, and the nonlinear ones are weak

$$\gamma^2(t) = \frac{\gamma^2_{\text{lin}}}{1 + \Delta(f)},$$

where $\Delta(f)$ means a "correction" function that transforms a linear transmittance into transmittance of the slightly nonlinear system, according to the relationship

$$X(\omega) = \sum p_i(\omega)\, H_{i_{\text{lin}}} + \Phi \cdot \Delta(\omega) + \Psi,$$

where $X(\omega)$ – spectrum of slightly nonlinear system, p_i – input, $H_{i_{\text{lin}}}$ – "linear" transmittance, Φ – scale operator, Ψ – disturbance in measurement.

Subsequently finding the vector of correction $\Delta(f)$ can give an approximate model of response of the system to the selected polyharmonic input. Obviously, the error of such an approximation increases with the value of coherence function falling down, so in our case the assessments done for low-frequency response are substantially overestimated. However, it gives a certain factor of safety.

6. Conclusions

The highest amplitudes are of vibrations forced by acoustic sounds of low frequency. This conclusion was confirmed by the observations done in real conditions during the concert. Visibly higher vibration amplitudes were recorded for the panes than for the steel elements of supporting structure. Large, flat surface of the elements of relatively insignificant mass are susceptible to acoustic input. However, further propagation of acoustic energy finds natural barrier resulting from density of steel, higher rigidity of the structure, dumping on pane-framework joints.

The skylight structure proved stable; the loads are transmitted via strong steel girders. Generally, high amplitudes of sounds force vibrations of smaller rigidity. Therefore, the whole structure is not in danger as the main carrying elements are rigid enough.

Possibility to damage the polycarbonate panes mounted in metal frames by acoustically generated vibration wave is minimal. However, the vibrations of ceiling can provoke alterations of characteristics of the joints, especially slackening of screw joints. Therefore, periodical controls of state of joints are recommended, as well as considering possibility of limiting vibrations forced by sound waves of frequency lower than 100 Hz.

The simple model that has been proposed allows us to forecast the most dangerous vibrations (3 Hz and 80 Hz) in the case of predicted acoustic overload of the structure.

The studies also confirm that the examining of propagation of vibroacoustic energy in the objects previous to the introduction of powerful PA systems is indispensable.

Acknowledgment

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