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Potential health effects of standing waves generated by low frequency noise

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Abstract

The main aim is to present the available updated knowledge regarding the potential health effects of standing waves generated by low frequency noise (LFN) from an open window in a moving car where the negative effects of LFN induced by heating components and/or heating, ventilation and air-conditioning are assessed. Furthermore, the assessment of noise in chosen enclosed spaces, such as rooms, offices, and classrooms, or other LFN sources and their effect on the human being were investigated. These types of noise are responsible for disturbance during relaxation, sleep, mental work, education, and concentration, which may reflect negatively on the comfort and health of the population and on the mental state of people such as scientific staff and students. The assessment points out the most exposed areas, and analyzes the conditions of standing wave generation in these rooms caused by outdoor and/or indoor sources. Measurements were made for three different enclosed spaces (office, flat, and passenger car) and sources (traffic specific noise at intersections, noise induced by pipe vibration, and aerodynamic noise) and their operating conditions. For the detection of LFN, the A-weighted sound pressure level and vibration were measured and a fast Fourier transform analysis was used. The LFN sources are specified and the direct effects on the human are reported. Finally, this paper suggests the possibilities for the assessment of LFN and some possible measures that can be taken to prevent or reduce them.

Keywords: Assessment, effects, human, low frequency noise, measurement

Introduction

The adverse health effects of community noise include subjective annoyance, interference with speech communication, disturbance of rest and sleep, impaired psychological function, and negative behavioral effects.[1,2] Besides the psychosocial effects of community noise, there is also concern about the impact of noise on the cardiovascular system.[1,3-5]

In experimental and epidemiological studies, researchers found that low frequency noise (LFN) can be annoying and can create potential health hazards for people exposed to them, especially for highly sensitive subjects.[6-8]

LFN can be more noticeable indoors, which is why it is often associated with disturbed sleep. The sound pressure level (SPL) also increases for some special conditions – standing waves or partial standing waves.[9,10] Another problem is that LFN travels further than higher frequencies, so its source is often difficult to trace. Sleep and mental work may be disturbed by the generation of standing waves.[11,12]

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Goals of the Study

The goals of the study were to investigate standing waves generated by different LFN sources in an office and a flat, to assess LFN in a moving car, review the effects of LFN exposure on human health and discuss methods of LFN assessment.

Investigation and the Measurement Methods

Conditions for the generation of standing waves in enclosed spaces

The generation of the standing waves in an enclosed space due to LFN is a commonly confronted problem in everyday life. The increment of noise in an enclosed area can be caused by standing waves, if some requirements are fulfilled. Usually at these conditions the people complain about insomnia, migraines, lack of concentration, or other, even more serious, health problems.[7,8,12,13] To investigate standing waves, a theoretical model needs to be found. Points of maximal amplitudes are at a distance of[14-16]

$$x = k\frac{c}{2f} = k\frac{\lambda}{2} \qquad \text{for} \quad f = 0 \tag{1}$$

The standing waves or partial standing waves were observed in rooms situated within acoustically-treated enclosed spaces [Figure 1], where the source of LFN was a vehicle located outside. In this case, the dimension of the rooms was identical to half the wavelength of the significant low frequency acoustical vibration.

The Eigen frequency of an approximately rectangular closed space can be found as

$$f_{n_x n_y n_z} = \frac{c_0}{2}\left[\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2 + \left(\frac{n_z}{L_z}\right)^2\right]^{\frac{1}{2}} \tag{2}$$

where c_0 is the phase speed of sound (m/s); L_x, L_y, L_z are the characteristic dimensions of a protected room (m); and n_x, n_y, n_z are equal to 1, 2, 3,…

For first axial mode in x-direction the factors (n_x, n_y, n_z) are in the form (1, 0, 0), that is, Eq. 2 simplifies to

$$f_{n_x} = \frac{c_0}{2}\frac{n_x}{L_x} \tag{3}$$

Assuming that the closed space is approximately rectangular and the walls are of acoustical stiffness (which is an approximation), then for the phase speed of sound c_0 and characteristic dimension of the enclosed space, the first or higher Eigen frequencies of this space can be calculated.

Measuring of the standing waves in an office

In this section, a specific outdoor source is investigated – transportation noise caused by vehicles with diesel engines in idle running while standing at traffic lights. The emitted noise from the engine contains a tonal frequency that coincides with the first resonance mode of the office analyzed, and thus, a standing wave is generated in the office. The problem with standing wave generation in the office was especially observed when public transport busses and some lorries or passenger cars (with diesel engines) idling near the buildings.[16]

Considering an enclosed space having an approximately rectangular shape, the standing wave is generated if at least one of the office's dimensions coincides with a multiple of half of the wavelength (λ/2) of the source's tonal frequency.[16] Then, the location of the nodes may be found from Eq. 4.

$$x = (2n+1)\frac{\lambda}{4} \tag{4}$$

Similarly, having the dimensions of the enclosed space, the natural frequency of the office (for axial closed spaced modes) can be calculated from Eq. 2.

The office room in the building of the Faculty of Mechanical Engineering located close to an intersection with traffic light was analyzed [Figure 1]. An octave-band analysis of the A-weighted SPL in the office using real time octave band analyzer (Norsonic type 114) and fast Fourier transform (FFT) analysis where carried out using PULSE Analyzátor, Dyn-X, FFT, M1 3560-B-X10 (Bruel and Kjaer) platform with measurement points selected according to [Figures 1 and 2]. The A-weighted octave-band analysis [Figure 3a] shows that traffic noise (caused by all three types of vehicles – bus, lorry, and car) contains low frequencies around f = 32.5 Hz. Executing a more detailed FFT analysis [Figure 2b], the tonal frequency

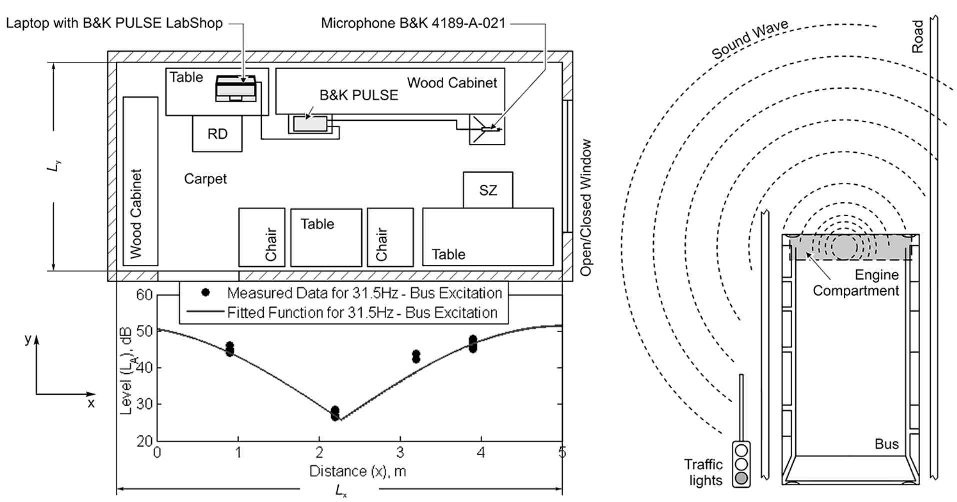

Figure 1: Measurement set-up with results plotted for bus excitation (SOR B 9.5)

$f = 32$ Hz exerted in the office was confirmed, while a diesel engine vehicle waited at the traffic lights. Using Eqs. 2 or 3 the natural frequency of the first mode in the x-direction, that is, the axial mode (1, 0, 0), of the office with length $L_x = 5.4$ m, is $f_{1,0,0} = 31.76$ Hz, is in accordance with measured values.

The fitting curve of A-weighted SPL in the office was approximately created as shown in Figures 1 and 3a, the A-weighting SPL of the standing wave was measured at four measurement points. When using an artificial source (loudspeaker) measurements were taken at six positions within the room. The fitting function is in the form

$$L_A = C_1 + C_2 \left| \cos \frac{\pi x}{L_x} \right| \quad (5)$$

and was used to find the pressure distribution of the sound wave within the office, corresponding to the first mode of the standing wave in the x-direction.

In order to investigate the generation of the standing waves more thoroughly, the source (vehicle) was replaced by a loudspeaker and the first two modes in the x-direction were generated, feeding the speakers with a pure sine signal at $f = 32$ Hz (first mode) and $f = 64$ Hz (second mode), as presented in Figure 3.

Measuring standing waves in bedroom

Low frequency vibration can cause serious damage to building structures as well as serious damage to the health of their residents. Therefore, correct vibro-isolation is necessary to eliminate all potential noise and vibration sources inside dwellings. Otherwise, problems may arise with annoying noise.[11-13]

In Figure 4a, hot-water pipes and heating pipes are suspended from the ceiling of a basement, which also acts as the floor of the enclosed flat above [Figure 4b]. Low frequency vibration at the Eigen frequency of the pipes was generated by water flowing inside.

The frequency spectra was obtained by FFT analyses [Figure 5], using the Bruel and Kjaer PULSE platform for measuring noise with measurement points

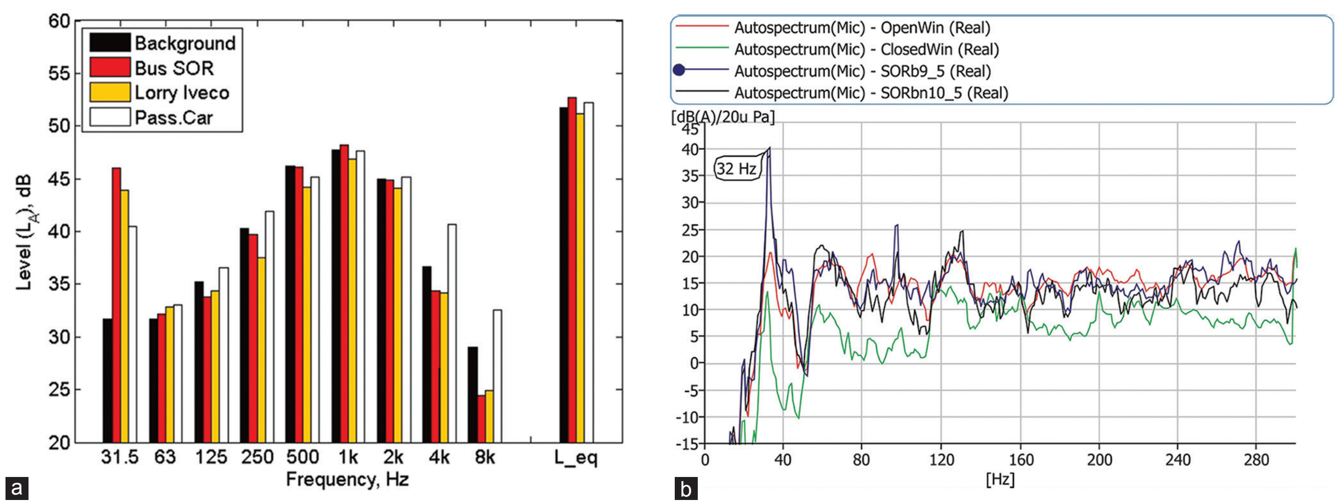

Figure 2: First two modes of the standing wave generated in the office by loudspeaker (a) axial mode (1, 0, 0) and (b) axial mode (2, 0, 0)

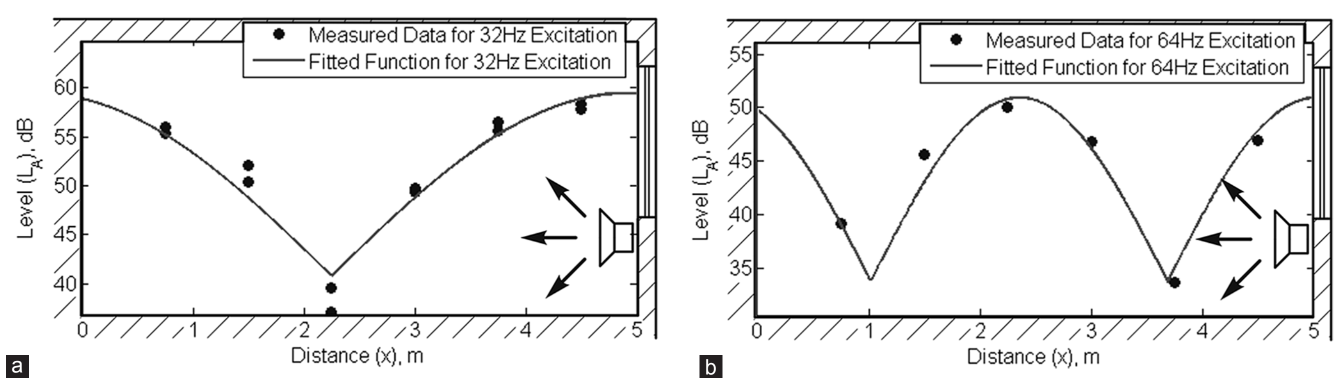

Figure 3: Frequency analysis (a) octave-band analysis of the traffic noise measured in the office, (b) fast Fourier transform analysis of the traffic noise measured in the office

selected according to Figure 4b. Vibration and modal analyses was measured at the points seen in Figure 4a and b and shows the tonal frequencies in a low frequency region that can have a negative influence on building structures and on the comfort of the human beings living close to this or similar sources of vibration. It is, therefore, important to take both of these aspects into consideration; the first is the effect of low frequencies on the building structure, which can lead to, for example, rattling, and the second is its negative effects on human beings. From the frequency spectrum measured using the acoustical signal [Figure 5a], it is possible to recognize a tonal frequency close to 30 Hz, which disturbs the comfort and health of the residents in the flats.

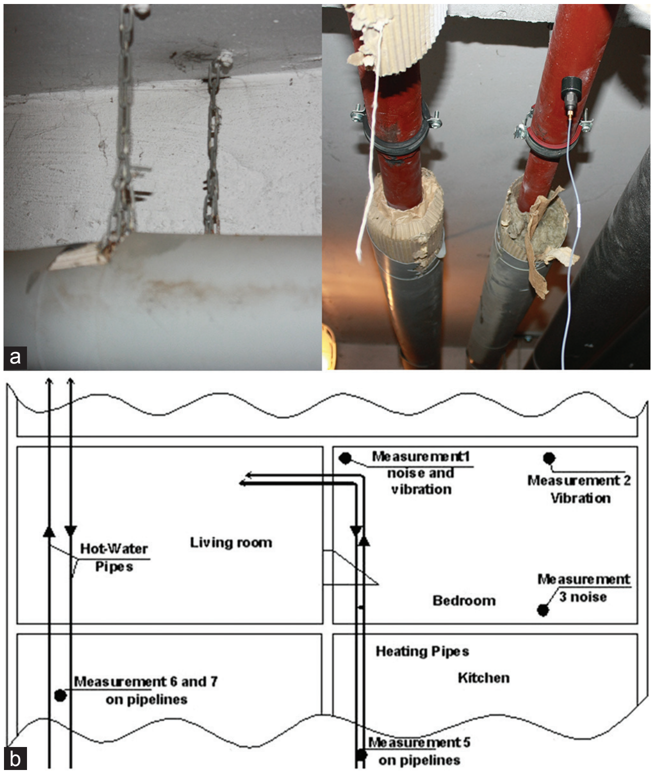

Figure 4: Source of vibration and enclosed spaces (a) suspension of hot-water (in left old) and heating pipes (in right new) and (b) floor plan of the flat

Measuring low frequency noise in a moving car

Many studies have been published about noise emissions from vehicles,[17-20] particularly in urban areas where traffic noise is a big problem, which needs to be addressed. Another viewpoint is to analyze noise inside a car and its effects on driver comfort and safety. When driving a car every day to work or even travelling by car for long distances, acoustic comfort inside the car is a key issue. In designing, car producers pay attention to making environmental noises, noises from the engine, etc., less noticeable inside the car, in order to minimize disturbance while driving.

A specific noise, mostly aerodynamic in nature, is that from an open window. At high speeds, an open window behaves as a source of specific LFN, which can be annoying. Some measurements of this source are presented herein.[20,21] In this paper, the interior noise of a passenger car was measured under different conditions (driving on normal roadways in Slovakia). An A-weighted octave-band analysis was used to evaluate the noise level and its impact on the driver's comfort.

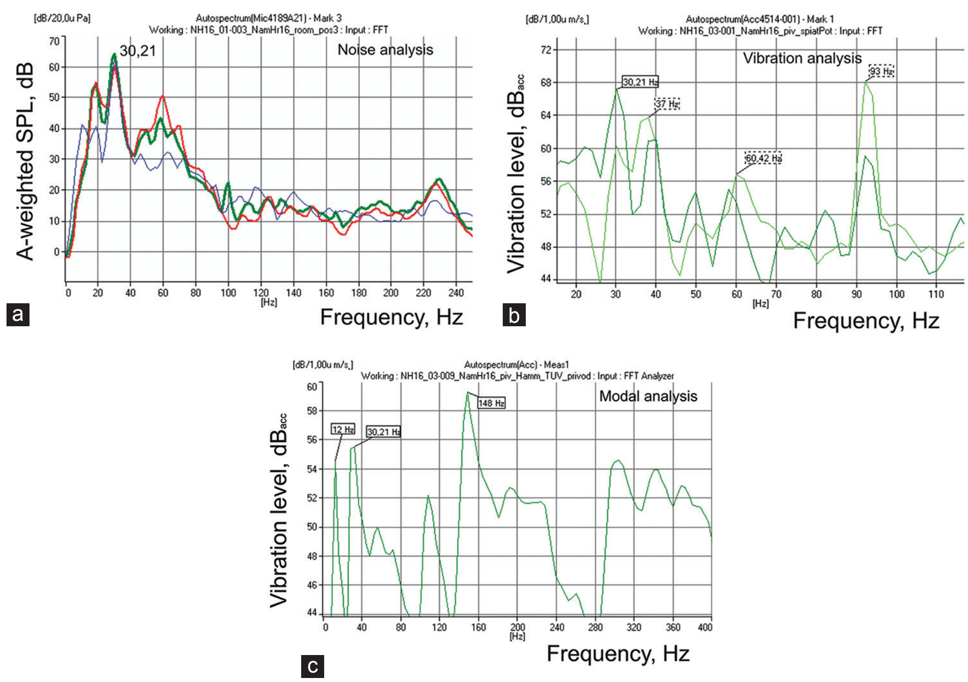

Figure 5: Frequency analysis (a) frequency spectrum of noise in the bedroom, (b) frequency spectrum of the hot-water pipes vibration, and (c) modal analysis of the hot-water pipes

The interior noise was measured inside the passenger car Nissan Tiida (model year 2009). Interior noise level was measured at the driver's ear position, in order to best capture the noises to which the driver is subject to.[18] The sound level meter NORSONIC type 114 was located as shown in Figure 6.

As presented in Figure 7a, when driving on a highway, mid and high frequencies (125 Hz to 1 kHz) of interior noise, which is represented by measured A-weighted SPL, are especially perceived as excessive. Aerodynamic and tire noises become dominant as speed increases. On the other hand, lower frequencies (up to 160 Hz) increase at lower speeds, when the noise from the engine is dominant. In town, the high frequency content from aerodynamic and tyre sources are not significant since the speed is too low to induce them.

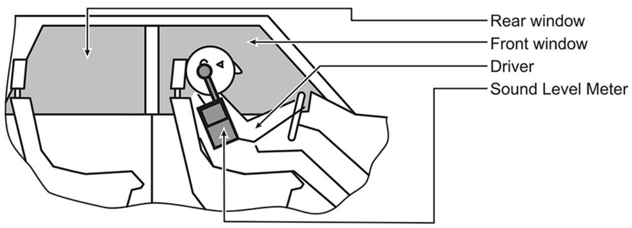

Figure 6: Schematics of the measurement set-up inside a passenger car while driving

Results and Discussion

Standing waves in office

During normal office work, with the window open or closed and facing a road, the standing wave (and consequent annoying noise) was observed while some vehicles stopped at nearby traffic lights[16] [Table 1 for vehicle specifications].

It can be seen that in the case of the first mode [Figure 3a], the middle of the office room is the quietest location, that is, with lowest SPL. In analyzing the second mode however, that same location (middle of the office) exhibits maximal A-weighted SPL. Therefore, choosing the optimal location with the lowest A-weighted SPL is possible provided the frequency content of the sound is obtained.

Standing waves in a bedroom

The main aim of this acoustical problem was the identification of the source (or sources) responsible for emitting this tonal frequency. Moreover, the amplitude of this 30 Hz tone is near the threshold of hearing. The measured A-weighted SPL is

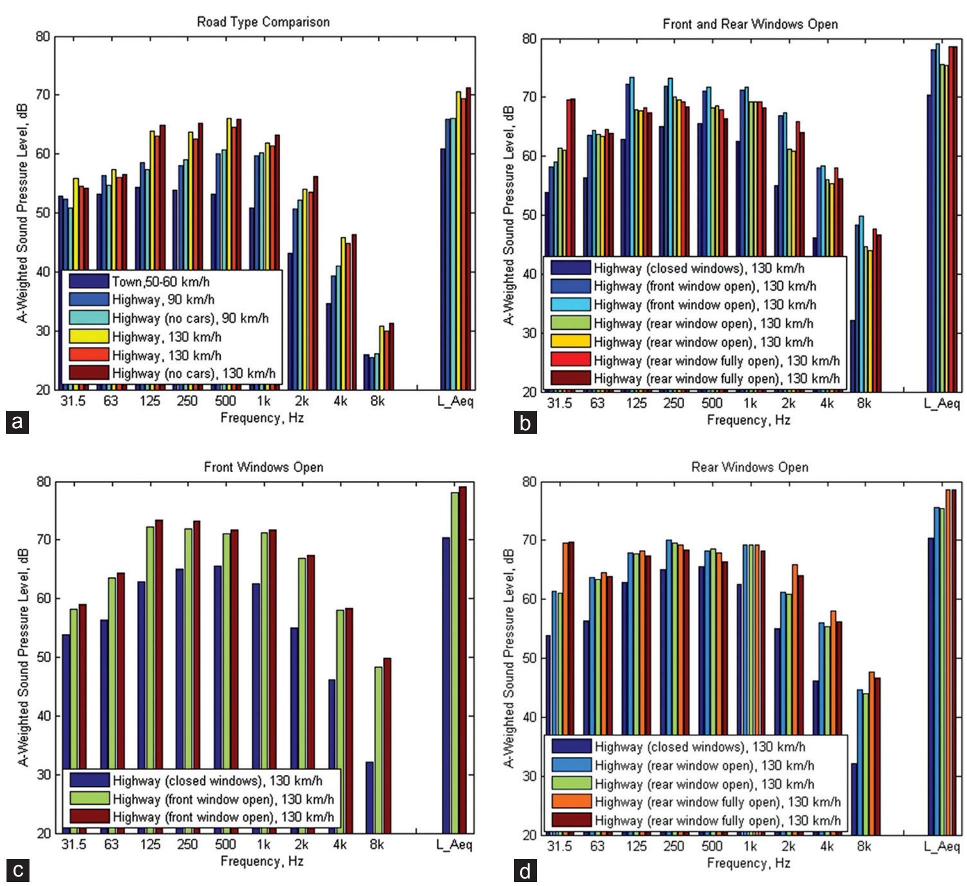

Figure 7: Octave-band analysis: Comparison of measurements (a) for different road types, (b) for rear and front windows open, (c) for front window open, and (d) for rear window open

Table 1: Engine parameters of vehicles measured[16]

Vehicle	Engine	Type of engine	Displacement (cm^3)	Power (kW)
Bus SOR B 9.5	Iveco tector F4 AE 0682C	Water cooled 6 cylinder direct-injection diesel engine	5880	176
Lorry iveco euro cargo	Iveco tector F4AE3481C	Water cooled 4 cylinder direct-injection diesel engine	3920	103
Passenger car	VW 1.9 TDI	Water cooled 4 cylinder direct-injection turbo diesel engine	1896	77

slightly (4 dB) above the threshold of hearing, and therefore, very difficult to identify against normal background noise during the day and evening. However, the problem with standing wave generation in the bedroom, caused by this 30 Hz tonal frequency of LFN, was observed because of the coincidence of the half wave length of this frequency with the characteristic dimensions of the bedroom. The noise was disturbing during the night time, especially for older residents living in this flat.

The source of the unpleasant noise was the Eigen vibration of hot-water pipes, where the maximal amplitude of the low frequency vibration (vertical axis) was at a frequency of 30.21 Hz [Figure 5b]. This vibration was transferred through the buildings structure and emitted to the flat above, thus perceived as an annoying noise. From the frequency and modal analysis [Figure 5c] of the hot-water pipes and the frequency analysis of noise in the bedroom [Figure 5a], a clear coincidence between the dominant natural frequency of the pipes and the Eigen frequency of the enclosed space is observed [Figure 5].

These results demonstrated the need to eliminate noise at a frequency of 30.21 Hz in order to avoid human discomfort or to locate the working place or place of relaxation in the middle of the room [Figure 1], where the effect of the noise has a minimal effect when sleeping.

Noise in a moving car

Comparing the equivalent A-weighted SPL (L_{Aeq}), increased speeds equated to an increasing noise level [around 60 dB at 60 km/h, 65 dB at 90 km/h and 70 dB at 130 km/h], so driving became less pleasant. On the other hand, even 70 dB at highway speed was not perceived as very annoying for longer travel times.

By opening the front window, the noise from mid and especially high frequencies was generated (125 Hz to 8 kHz), as shown in Figure 7c. The increment of equivalent A-weighted SPL at 8.5 dB was observed, whereas the level at 8 kHz increased to 16 dB. The high frequency content is caused by the aerodynamic fluctuations from opening the window. Tyre noise can also contribute to this increment to an extent which can be neglected.

Similar results in the region of mid and high frequencies were obtained also for open rear windows, with a significant increment of A-weighted SPL from 2 kHz to 8 kHz, as shown in Figure 7d. When fully opening the rear window, low frequency content at 31.5 Hz significantly increased by 16 dB as compared to closed windows. From a subjective view point, the induced low frequency content was more disturbing than higher frequencies, and more than two minutes of measurements were too annoying for the driver and operator.[21] The LFN is caused by impacts due to periodic changes in pressure within the interior, where the air flowing over the bodywork attempt's to escape to the low pressure interior. Its frequency content is dependent on the speed, which will be demonstrated by FFT analyses in the near future.[22]

As presented in Figure 7b, on opening the front windows (50 mm gap) the equivalent A-weighted SPL increased by 8 dB (compared to the A-weighted SPL with closed windows). Opening the rear window (also 50 mm gap) the equivalent SPL increases by only 5 dB. If the rear window is fully open, approximately the same equivalent A-weighted SPL is reached as with the front windows partially open (8 dB increments in A-weighted SPL compared to closed windows). More importantly, the low frequency content increased from 5 dB for open front windows to 7 dB for partially open, and 16 dB for fully open rear window. Subjectively, the open rear window condition was the most annoying from all the analyzed cases.

Health Effects and Assessment of LFN

Effects on human beings

If a person working or resting in a closed space has his/her workplace or place of relaxation located exactly in the mode [Figure 1] of the generated standing wave (for the first mode – at the window or on the opposite side of the room, at the wall), then he/she is exposed to excessive A-weighted SPLs of a tonal character, which may be observed as disturbance and de-concentrate him/her from their work. From experience, it can be concluded that working and resting in such an environment can lead to headaches, and unpleasant feelings which, in turn, can lead to a reduction of working or relaxing efficiency.[16]

The low frequencies induced in the interior of a car (e.g., from open windows) can cause nausea, loss of concentration, and a general discomfort of the driver as well as the passengers.[21,23] From a traffic safety point of view, driver discomfort is undesirable. Therefore, leaving car windows open for long periods of time is not recommended, especially when driving at higher speeds. Instead, it may be preferable to ventilate the car using either an air-conditioning or internal ventilation system.

Low frequencies of sound and infrasound in different vehicles, building equipment and aerodynamic noise, which were analyzed as a whole, can be perceived if they are sufficiently intense. In general, it has been found that if people are exposed to very low frequencies of sound and infrasound, they may experience difficulties in performing mental work, as well as a general sense of discomfort. As the intensity increases or exposure continues for longer periods of time, dizziness, nervousness, fatigue, irritation, nausea, and headaches may occur.[7,23,24]

Assessment of the LFN and measurement

With respect to a theoretical analysis of enclosed spaces (see above) in every enclosed space there are conditions for the formation of standing waves or partial standing waves. It is, therefore, important to assess enclosed spaces from the viewpoint of the potential to generate standing waves. If only the first closed space mode can be generated (in the case of a larger closed space), the working or relaxation area could be located in the node where minimum sound energy is measured. Another possible way to eliminate the generation of standing wave is by building rooms with no perpendicular walls or with dimensions which are not multiples of $\lambda/2$ of source characteristic wavelength (although this would require a deeper study of possible noise sources). Furthermore, passive means of noise reduction may be used to solve the problem of standing wave generation induced by external sources (windows with higher transmission loss factor, or using sound barriers). Yet another way to solve the problem of standing wave generation due to traffic noise is to design the windows of offices and relaxation rooms away from traffic, located in a quieter setting, which is usually a problem in urban areas.

One of the key parameters of acoustical performance of structural panels is transmission loss. For this type of dynamic loading, criteria should be established for equipment vibration to determine the excessive forces that adversely affect the performance or life of the equipment.[9] The isolator provides separation between the source of vibration and the building structure, where the magnitude of transmitted energy to the building structure is a function of the magnitude of the vibrating force.[15,25]

Investigations have shown that the perception and effects of sounds differ considerably at low frequencies as compared to mid or high frequencies.[11,13,26-28] The main reasons for these differences are as follows:

- A weakening of pitch sensation as the frequency of the sound decreases below 60 Hz;
- Perception of sounds as pulsations and fluctuations;
- A much more rapid increase in loudness and annoyance with increasing SPLs at low frequencies than at mid or high frequencies;
- Complaints about feelings of ear pressure;
- Annoyance caused by secondary effects like rattling of buildings elements, windows, and doors or the tinkling of ornaments;
- Less building sound transmission loss at low frequencies than at mid or high frequencies.

Given the above, for the assessment of sounds with relatively strong low frequency content, the rating procedures should be modified. The measurement location may be changed and the frequency weighting affected, since sounds with strong low frequency content engender greater annoyance than is predicted by the A-weighted SPL.

In the assessment of LFN the main factors are as follows:[22,28]

- The frequency range of interest appears to be about 5 Hz to about 160 Hz (max. 200 Hz);
- One of the issues in LFN assessment is that room resonances at low frequencies can create situations that may be hard to predict from outdoor measurements. This can be especially important in evaluating specific residences. However, for the purposes of estimating the prevalence of high annoyance in a large community population, outdoor measurements may be sufficient;
- Sound-induced rattles in building elements are important determinants of the annoyance caused by low frequency sound;
- At the strong low frequency content (about 20 Hz) of a sound it would be better (or more precise) to use C-weighted SPLs. At the present time, more experiments are being carried out regarding assessment of a noise close to the infrasound region.[22]

Noise limits are set by the responsible authorities on the basis of knowledge about the effects of noise on human health and well-being (especially dose-response relationships on annoyance), taking into account social and economic factors. Such limits depend on many factors, such as the time of day, the activities to be protected (e.g., outdoor or indoor living, scientific work, communication in schools, relaxation time, recreation in parks, sleeping), the type of sound source, the situation (e.g., new residential developments in existing situations, new industrial or transportation installations near existing residential areas, remedial measures in existing situations).[28] The investigations show that these limits are not sufficient from viewpoint of human health in the generation of specific LFN.[22,26-28] Therefore, it is needed to define the limit values and procedures describing the circumstances under which compliance with the regulations can be verified. These procedures can be based either on calculations from sound prediction models or on measurements.[22,28]

Conclusions

Low frequency traffic noise, especially caused by idling diesel engines, and vibration of building equipment can cause the generation of standing waves of LFN in enclosed spaces, if the dimensions of the space are multiples of $\lambda/2$ or λ of the source's characteristic wavelength. This can occur in buildings with windows located close to intersections, bus stops, parking lots, flats close to building equipment etc., The standing wave is especially annoying if the working/rest place is located in the modes where maximal acoustic energy occurs.

In the case of tonal noise, as measured in the enclosed spaces describes herein, the standards penalize such a source by +5 dB. Therefore, in many situations the work and relaxation place does not fulfill the standardized requirements, and modifications of the enclosed space are required by the authorities.

From the measurements it can be concluded that it is not a prerequisite that the vibration source be located directly at the window, because the source (in this case a vehicle) can be considered as a point source from which noise propagates in the form of a spherical wave. More so, LFN is not attenuated as fast as higher frequencies, and thus it can be a problem in offices/dwellings located close to intersections, bus stops, building equipment, etc.

The generation of standing waves was proved experimentally (using a loudspeaker as a sound source) also for a larger lecture room. However, the wavelengths of the generated standing waves are larger, which excludes traffic noise as the cause for inducing them. On the other hand, other low frequency sources (as, e.g., hot-water pipes, heating, ventilation and air-conditioning, etc.) can cause the generation of particular frequencies to induce a standing wave, even in larger closed spaces, such as lectures rooms.[16]

The influence of the interior noise of a car on driver comfort was analyzed. Interior noise measured in towns and on highways has shown that with increasing speed, the aerodynamic and tyre noise become increasingly responsible for the increment of the interior noise. However, the 10 dB difference between equivalent A-weighted SPL measured on city roads and on highway is not sufficient to cause driver discomfort.

The aerodynamic noise from open windows proved that when driving on a highway, the car interior should be ventilated by either air-conditioning or ventilation. Opening windows generates low frequency impact noise which is very annoying not only for longer exposure times. Better results were obtained by opening a window slightly (only high frequency noise generated). On the other hand, by opening a rear window fully, significant impact LFN is induced. At the present time, research into the optimal assessment for LFN (closely to the infrasound region) is being conducted using FFT analyses.

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