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AIRBORNE SOUND INSULATION MEASUREMENTS USING IMPULSIVE SOUND SOURCE

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Abstract: *One of the most important subjects in building acoustics are sound insulation measurements. Airborne sound insulation is usually determined by the conventional method, using loudspeaker. Sometimes however, it is hard to excite sufficiently high sound levels in the receiving room using loudspeaker, especially when background noise levels are high. Furthermore, the frequency range in building acoustics has traditionally been 100 – 3150 Hz, but nowadays there is growing need to include low frequency range as well, down to 50 Hz. Many conventional loudspeakers appear to be weak sound generators for exciting this low frequency components to the satisfactory level.*
In such cases impulsive noise source, such as a gunshot noise can be an appropriate alternative, when compared to sources of steady noise. An impulsive noise source, as produced by a gun with blank cartridges, is usually lightweight and small enough, to be carried around easily. The difference in noise emission characteristics between individual cartridges for the same gun and gun power characteristics are usually small, so such impulsive source can also be reproduced to a high degree.
This paper primarily deals with application of a impulsive sound source in building acoustics. Results obtained with such source are also validated and compared with conventional sound insulation measurements using loudspeaker.

Key words: building acoustics, impulsive sound source, sound energy level, measurement method

1. INTRODUCTION

Airborne sound insulation is usually tested in situ, where the apparent sound reduction index *R'*, defined as a logarithmic ratio of the sound power incident on a wall under test to the total sound power transmitted into the receiving room, mostly serves as a descriptor. It is usually measured according to the conventional method, using loudspeaker. The conventional method is fully described in ISO 16283 [1].
In some special cases, for example when measurements are performed in large rooms, or when heavyweight walls and partitions are being investigated and especially when high levels of background noise are present in the receiving room, it is hard to excite sufficiently high sound levels in the receiving rooms using the conventional method. On the other hand, in very big or large rooms troubles can appear when trying to excite low frequency modes, when using a conventional loudspeaker. The direct use of this method requires namely a powerful loudspeaker operating as a sound generator, which is not always available. In addition new standard for airborne sound insulation measurements, initiated by COST [2], suggests that the sound reduction index should be determined in the enhanced frequency range from 50 to 5000 Hz. Determination of the sound reduction index is especially prone to measurement uncertainty in the low frequency region below 100 Hz.
In such cases impulsive noise source, such as a gunshot noise can be an appropriate replacement, when compared with steady state noise sources. This paper primarily deals with application of a gunshot as a sound source. In addition comparison with results obtained by the conventional method using loudspeaker as a sound source is adressed.

2. GUNSHOT AS AN IMPULSIVE SOUND SOURCE

When determining the transmission loss of a wall or partition by the conventional method, it is necessary to measure the sound pressure level difference between the two rooms and the equivalent absorption area in the receiving room. Under the assumption of diffuse sound fields in the source and receiving rooms, apparent sound reduction index *R'* of a common partition in each frequency band may be evaluated, according to a conventional loudspeaker method using equation (1):

$$R' = \overline{L_1} - \overline{L_2} + 10\log\frac{S}{A} \quad , \tag{1}$$

where $\overline{L_1}$ is the average sound pressure level in the source room (in dB), $\overline{L_2}$ is the average sound pressure level in the receiving room (in dB) and S is the area of the test specimen or common partition (in m^2), A is the equivalent absorption area in the receiving room (in m^2), which is preferably evaluated from reverberation time T (in s) measurements according to ISO 3382 [3] and room volume V (m^3) using equation (2):

$$A = 0.16\frac{V}{T} \tag{2}$$

As already mentioned it is sometimes not appropriate to use commercially available sound generators like loudspeakers, which in addition can be very awkward. Such loudspeakers are usually very heavy and can weigh as much as 20 to 30 kilograms. On the other hand, such loudspeakers are often not powerfull enough to be louder than the residual noise.
When the use of conventional loudspeakers presents such kind of difficulties impulsive noise generators, such as a gunshot appears to be more appropriate solution. Such application can be useful, especially when high levels of residual noise are present, requiring loudspeakers with high sound power levels. Moreover, due to its small dimensions the gun and its cartridges can be considered as a point source in much larger part of the room than loudspeakers with much larger dimensions. In this way its effect of directivity is smaller as well. On the other hand, the frequency range in building acoustics has traditionally been from 100 to 3150 Hz. However, the new standard introduces the need to include the low frequency range as well, down to 50 Hz. Many conventional loudspeakers appear to be weak sound generators to excite this low frequency region. This is much easier and more simple to achieve by using gunshot as a sound source.

Furthermore, an impulsive noise source, as produced by gun shoot with blank cartridges, is usually lightweight and small enough, to be carried around easily. The difference in noise emission characteristics between individual cartridges for the same gun and power characteristics is usually small, so such source is reproducible to a high degree. Sound overpressure released during an explosion is proportional to the third root of explosive mass used. By doubling or halving powder mass, the corresponding overpressure level changes for 2 dB only. Although the charges are not fully repeatable, it must be kept in mind that even loudspeakers sound signals show variations as voice coil and magnet heat up. Muzzle blast is here far predominating source of sound, so it is also omnidirectional. On the other hand gunshot offers the possibility of removing flanking transmission, a problem which is much harder to realize with conventional loudspeakers. Additionally, such source is also self powered and relatively cheap. That means, that gunshot as a sound source can play an important role in room acoustics investigations.

In the case of strong enough impulsive sound source the difference in sound exposure levels, rather than in sound pressure levels is measured [4]. When sound energy level of an impulsive sound is known, it is quiet easy to calculate equivalent absorptive area of the room under investigation, or its corresponding reverberation time. Therefore, the sound energy level of impulsive sound source must be determined first. In this paper we present a measurement method for determination of apparent sound reduction index and its validation for in situ measurements.

3. SOUND ENERGY LEVEL

During the duration of the impulse the impulsive noise source releases some sound energy E (in Joules) in the environment.
This energy is proportional to the time variyng sound power *W(t)* and to the time of its duration.
By considering the basic acoustical relationship between sound power, sound intensity I in [Wm^{-2}] and sound pressure p, one can write:

$$E = \int_{-\infty}^{\infty} W(t)\,dt = S\int_{-\infty}^{\infty} I(t)\,dt = \frac{S}{\rho c}\int_{-\infty}^{\infty} p^2(t)dt \tag{3}$$

Here S is an area [m^2] and the product ρc is a specific acoustical impedance, at temperature 20^0C, equal to 415 [kg/m^2s = rayl] under the standard atmospheric conditions. Now, the reference sound energy is defined as energy, passing over such reference area S_0, resulting in a reference sound pressure p_0 in a reference time T_0.

$$E_0 = \frac{S_0}{\rho c} p_0^2 T_0 \tag{4}$$

where S_0 is a reference area, equal to 1 m^2, T_0 is a reference time, equal to 1 s, p_0 is reference sound pressure equal to 20 μPa. Reference sound energy E_0 is then equal to 10^{-12} J.
The logarithmic proportion between the sound energy released and reference sound energy, multiplied by 10 is by definition the sound energy level L_E:

$$L_E = 10\log\left(\frac{E}{E_0}\right) = 10\log\frac{S}{S_o}\frac{1}{T_0}\int_{-\infty}^{\infty}\frac{p^2(t)}{p_0^2}dt \tag{5}$$

After considering the definition of sound exposure level *SEL*, this relation can be written as:

$$L_E = \overline{SEL} + 10\log\left(\frac{S}{S_0}\right) \quad (6)$$

Here *SEL* is the energy, the mean value of *SEL* on the measurement surface *S*. Equation (6) is equivalent to expression (7):

$$L_W = \overline{L_p} + 10\log\left(\frac{S}{S_0}\right) \quad (7)$$

connecting sound power level L_W and sound pressure level L_p in the case of continuous sound source.

4. DETERMINATION OF EQUIVALENT SOUND ABSORPTION AREA

To determine sound reduction index *R'* and also in many other practical cases, the determination of equivalent absorption area or its corresponding reverberation time must be determined. Information about equivalent absorption area is also needed in some passive noise control measures, when the reduction of reverberant effects is required, for instance. Suppose that a loudspeaker, operating as a steady sound generator, with sound power level L_W is installed in such a room, producing sound pressure level L_p at a distance *r*. The basic equation, connecting sound pressure level and sound power level of steady sound generator in diffuse halls can be written as:

$$L_p = L_W + 10\log\left(\frac{Q}{4\pi r^2} + \frac{4}{A}\right) \quad (8)$$

with symbols as follows: L_p sound pressure level (dB re 20 μPa), L_W is sound power level (dB re 10^{-12} W), *Q* is directivity factor (dimensionless), and *A* is equivalent sound absorption area (m^2) of the room under investigation.

Close to the reflecting walls and far away from the sound source generating sound power level L_W, the first term in brackets can be neglected. In this case the sound pressure level is mainly a result of reverberant sound field, which can be further written as

$$L_p = L_W + 10\log\left(\frac{4}{A}\right) \quad (9)$$

In acoustics it is usually more appropriate to deal with logarithmic quantities. When transforming *A* to $L_{abs}=10\log A$, equation (9) can be written as:

$$L_{abs} = 10\log A = L_W - L_p + 6 \quad (10)$$

However, when using these relationships, some practical difficulties can be encountered, especially in big industrial rooms. In such rooms a sound power of commercially available loudspeakers is usually to weak to excite wider set of modes of interest, especially those in the low frequency region. In such cases the application of gunshot can become a solution for this problem, as it can produce high enough energy levels, even in a low frequency region, down to 50 Hz. By measuring sound exposure level of such impulsive noise with known sound energy level L_E, and considering equations (6) and (7), L_{abs} becomes:

$$L_{abs} = 10\log A = L_W - L_p + 6 = L_E - SEL + 6 \quad (11)$$

5. APPLICATION IN SOUND INSULATION MEASUREMENTS

The method using gunshoot as a sound source can be useful for determination of apparent sound reduction index in situ as well, especially when a loudspeaker appears to be unsatisfactory, as already described.

When using a loudspeaker as a sound source in the sound insulation measurements, the average sound pressure levels in the source and receiving rooms are measured at several microphone positions. However, using Green theorem of reciprocity, the source and the receiving positions can be exchanged. Consequently, sound exposure levels generated by gunshot (replacing sound pressure levels as produced by loudspeaker), can be measured with two microphones (one on each side) when gunshot operates as an impulsive source in many positions one after another. As expected, these impulses are generated by gunshots triggered sequentially.

First, one microphone position was fixed in the source room and at least two microphone positions were selected in the receiving room. The gunshots were fired at several (for instance five) different positions in the source room. In this way the a of apparent sound reduction indexes were determined as:

$$R_i^{'} = \overline{SEL_{1\iota}} - \overline{SEL_{2\iota}} + 10\log\frac{S}{A} \quad (12)$$

with average value as:

$$\bar{R}' = -10\log\frac{1}{n}\sum_{i=1}^{n} 10^{-0.1R_i^{'}} \quad (13)$$

here SEL_{1i} is the average sound exposure level in source room during the microphone location at *i*-th position in the receiving room, calculated as

$$\overline{SEL_{1\iota}} = 10\log\frac{1}{m}\sum_{j=1}^{m} 10^{0.1SEL_{1ij}} \quad (14)$$

and similary for SEL_{2i} in the receiving room

$$\overline{SEL_{2i}} = 10 \log \frac{1}{m} \sum_{j=1}^{m} 10^{0.1 SEL_{2ij}} \quad (15)$$

With SEL_{1ij} the sound exposure level measured in source room during *j*-th gun shoot with *i*-th microphone position in the receiving room and SEL_{2ij} the sound exposure level measured in receiving room during *j*-th gun shoot with *i*-th microphone position in the receiving room and m is a number of gun shoot positions in the source room.

6. MEASUREMENT PROCEDURE

6.1. Determination of sound energy level of a gun-shot

Sound energy level of a gun-shot was determined according to procedure described in ISO 3740 [4]. Sound exposure levels (*SEL*) at 10 points, distributed over a spherical surface with radius r = 1m, (so S is equal to 6.28 m^2) were measured. All measurements were performed in one third octave bands from 50 Hz to 5000 Hz. Sound energy levels of a gunshot in each one third octave band were determined using equation (6), with S = 2π m^2. All measurements were done in free field over a reflecting surface. Total sound energy level was determined by summation over one third frequency bands from 50 to 5000 Hz.

6.2. Determination of apparent sound reduction index according to impulsive method

One microphone was fixed in the source room and two measuring positions (n=2) were selected in the receiving room. In the source room five gunshot positions were choosen (m=5). After that the microphone in the source room was moved to another location and the whole procedure repeated, so 20 measurements were performed altogether. Average sound exposure levels in the source (SEL_1) and receiving room (SEL_2) were calculated according to equations (14) and (15).

With conventional measurements equivalent sound absorption area (*A*) (equation (2)) is determined through reverberation time (T_{60}) measurements. With impulsive method sound absorption area is a function of sound energy level and sound exposure level in a room as proposed by equation (11). When sound energy level in each frequency band of interest is known, one has to measure sound exposure levels in the room. We propose at least two microphone positions with three gun-shot positions for single microphone position.

6.3. Determination of apparent sound reduction index according to conventional method using loudspeaker

The determination of apparent sound reduction index with the conventional method is fully described in ISO 16283 [1]. Reverberation time was determined as proposed by ISO 3382 [3].

7. RESULTS

Sound energy level measurements according to ISO 3740 [4] were done over a large and quiet parking space area in Ljubljana, when no traffic was present.
Apparent sound reduction index (*R'*), reverberation time (T_{60}) and equivalent sound absorption area (*A*) measurements were performed according to the impulsive method as described in this paper and according to conventional method in a medium sized room, which is used as an office at theInstitute for occupational safety.

7.1. Sound energy level of a gun-shoot as a sound source

A starting pistol Ekol special 99 with 9 mm blank cartridges was used as a source of impulsive noise. The results of energy level measurements are shown in figure 1. Gray lines represent sound energy levels at each measuring point, black line is the average sound energy level from the 10 measurements.

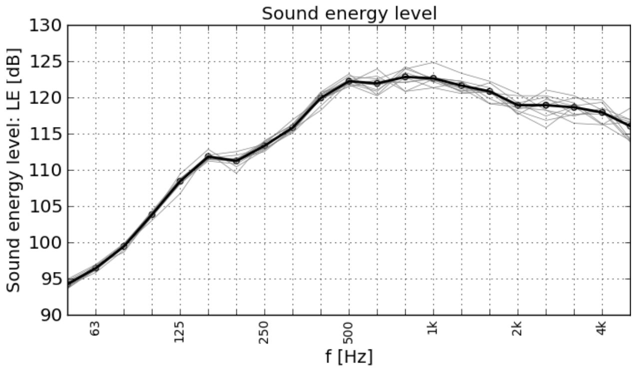

Fig.1. One third octave spectrum of sound energy level of gunshot (gray curves-individual measurements, black curve - average value).

Using equation (6), average values of sound exposure level (*SEL*) can be used to determine sound energy level for each frequency band of interest. By summation over all the frequency bands, the total sound energy level L_E is obtained as:

$$L_E = 10 \log \sum_{f=50\,Hz}^{5000\,Hz} 10^{0.1 L_{E,f}} = 131.8\, dB \quad (16)$$

7.2. Determination of apparent sound reduction index and equivalent sound absorption area in a medium sized room

7.2.1. Determination of apparent sound reduction index and equivalent sound absorption area using impulsive method

Sound insulation

Airborne sound insulation of a common wall between two medium sized rooms was tested, using impulsive sound source method. The test specimen (common partition) was a 100 mm thick plaster wall. The wall was 4.30 m wide and 2.89 m high. A slightly bigger 2.89 high, 4.30 m wide and 8.10 m long room was used as a source room. Three vertical walls including the connecting wall were lightweight constructions, one was a window wall. The floor and the ceiling were heavyweight constructions. The receiving room had the same wall configuration. It had the same height and width as the source room and was 5.65 m long. In order to determine sound reduction index of a common partition the following procedure was used: one microphone was fixed in the source room and two measuring positions (n = 2) were selected in the receiving room. In source room five positions of gun-shots as a sound source were chosen (m = 5). Measurement positions are shown in figure 2.

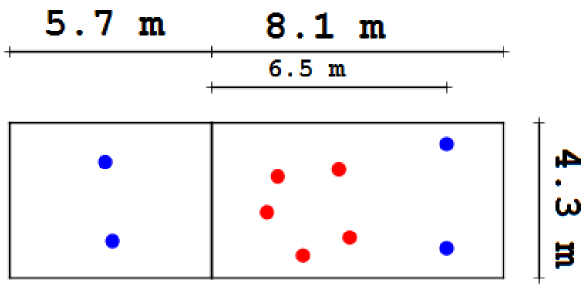

Fig.2. Microphone (blue dots) and sound source (red dots) positions in the source (right) and receiving rooms (left) as proposed by the impulsive method. Room dimensions are also shown.

After that a microphone in source room was moved to another location and the whole procedure repeated, so 20 measurements were performed altogether. Sound exposure level measurements necessary to determine SEL_1, SEL_2 and background noise levels are shown in figure 3.

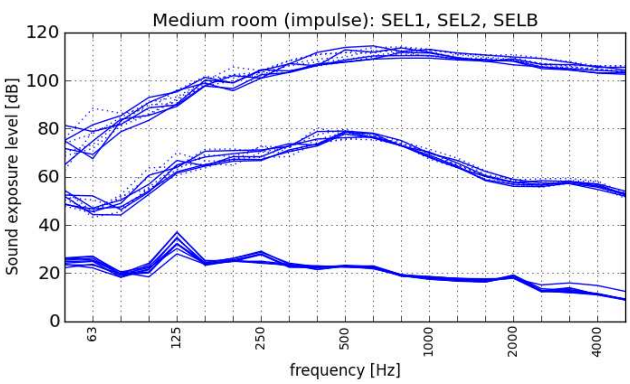

Fig.3. Sound exposure level measurements in the source (SEL_1) and receiving rooms (SEL_2) with background noise measurements. Dotted lines represent measurements when microphone in the receiving room was at the first position, while full lines represent measurements when microphone was at the second position.

Equivalent sound absorption area

When sound energy levels are known and measurements of corresponding sound exposure levels in room under investigation done, the equivalent sound absorption area can be calculated according to (11). For this purpose another set of sound exposure levels (*SEL*) was measured in a mostly diffused receiving room, where two microphone and three gunshot positions were selected. *SELs* were measured for each source - receiver combination, so that 6 gunshots were produced altogether. Reverberation time was calculated from equation (11) and (2) as:

$$T_{60} = 0.16 \cdot V \cdot 10^{-0.1(L_E - SEL + 6)} \qquad (17)$$

Reverberation time and equivalent sound absorption area of the receiving room are shown in figures 4 and 5.

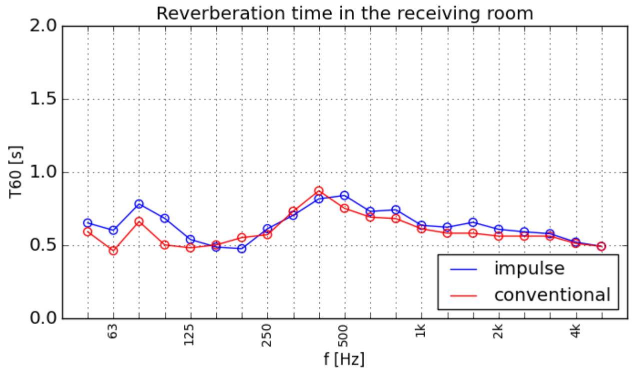

Fig.4. Reverberation time in the receiving room as measured by the conventional (red line) and impulsive (blue line) method.

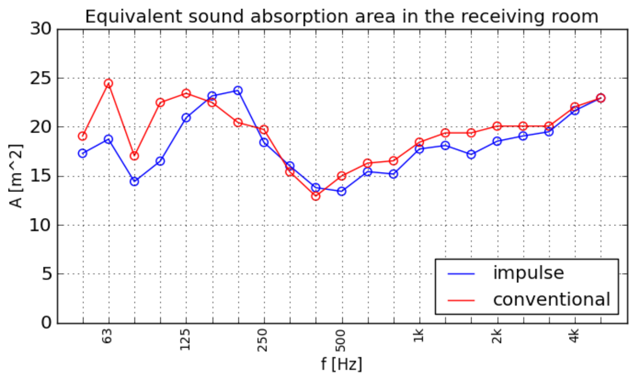

Fig.5. Equivalent sound absorption area in the receiving room as measured by the conventional (red line) and impulsive (blue line) method.

Using equation (12) apparent sound reduction index (R') can be determined from sound exposure level measurements in the source and receiving rooms and reverberation time measurements in the receiving room. Apparent sound reduction index in 1/3 octave frequency spectrum for centre frequencies 50 Hz to 5000 Hz is shown in figure 6.

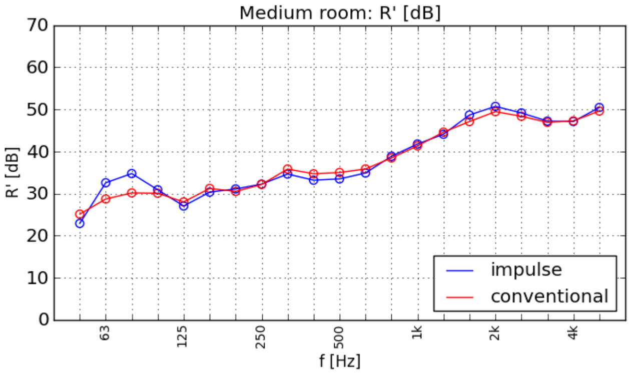

Fig.6. Apparent sound reduction index of common lightweight partition between two medium sized rooms.

7.2.2. Determination of apparent sound reduction index and equivalent sound absorption area using conventional method in a medium sized room

Sound insulation

In order to validate our proposed method using gun-shot, measurements according to the conventional method using loudspeaker were performed in the same rooms as well. The measurements were carried out according to [1]. Default procedure with fixed microphone moved from one position to another was used. A single pink noise omnidirectional Bruel and Kjaer 4296 sound source (with 12 loudspeakers) and five microphone positions in source and receiving room were used. The measurement positions in the source room were the same as with the impulse method (figure 7), with the roles of sound source and the microphones reversed.

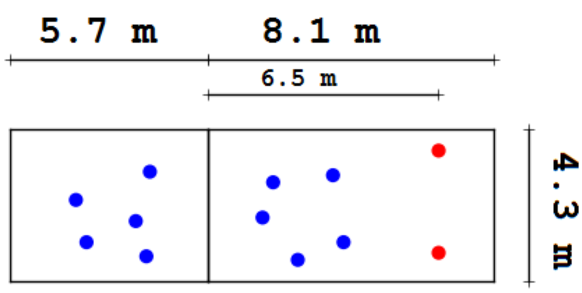

Fig.7. Microphone (blue dots) and sound source (red dots) positions in the source and receiving rooms as proposed by conventional method [1]. Five microphone positions were chosen in each room separated by common partition. Two sound source positions were chosen oposite common wall. The dimensions of both rooms are also shown.

The sound pressure levels in source and in the receiving room for the first and the second loudspeaker position, background noise in the receiving room and reverberation time (using the interrupted noise method) were measured and are shown in figure 8. Apparent sound reduction index was calculated, using equation (1).

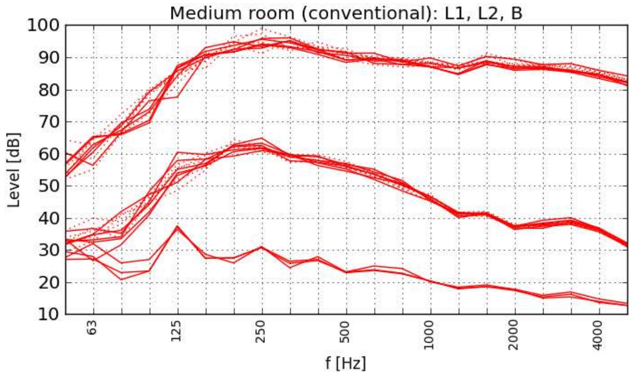

Fig.8. Averaged sound pressure levels as measured in the source and the receiving room by the conventional method. Dotted lines represent measurements when sound source in the sourceroom was at the first position, while full lines represent measurements when sound source was at the second position.

Equivalent sound absorption area

The reverberation time in the receiving room was measured using the interrupted noise method, as described in [3]. The equivalent sound absorption area was calculated using equation (2). Three fixed microphone positions with one loudspeaker position were used. Two measurements were done at each microphone position, meaning that six measurements were required for each frequency band between 50 Hz in 5000 Hz. Reverberation times are shown in figure 4, equavalent sound absorption area is shown in figure 5. Apparent sound reduction index was calculated using equation (1). Airborne sound insulation of common partition between the two rooms is shown in figure 6.

8. CONCLUSION

The comparison between conventional and impulsive method shows some discrepancies in reverberation time (figures 4, 5), especially in the lower frequency bands. On the average they are less than 10 % apart. The biggest difference (about 25 %) occurred at the lowest frequency bands 50 to 100 Hz. However when transformed to a logarithmic scale, as commonly used in sound insulation calculations, these differences become almost negligible. The difference of 25 % on linear scale transforms to only 1 dB difference on logarithmic scale. Differences in sound insulation measurements between two methods are even smaller (figure 6). In this way, one of the biggest problems, how to increase sound level in the receiving room well above the background level, especially in the lowest frequency bands, has been solved by using impulsive method. Using gunshot as a sound source, its sound exposure level increases more than 10 dB above the corresponding background level in the receiving room, even at the lowest frequency bands of 50 to 100 Hz (figure 3). In this way the background criteria was been fully satisfied. It was shown, that impulse method using gunshoots gives more reliable results in the lowest frequency bands, when compared to conventional method, while in mid and high frequencies both methods give very similar results (figures 4,5 and 6).

9. FUTURE WORK

In the future, impulsive noise method will also be investigated and validated against conventional method using loudspeaker in large room or hall. Uncertainty analysis of the new method using impulsive noise source will also be performed.

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