Airborne sound insulation measurements using gunshot as an impulsive sound source

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Summary
In some cases an impulsive noise source such as a gunshot can be a preferred alternative when investigating building acoustics, including sound insulation measurements, when compared to conventional steady state noise sources. A gun equipped with blank cartridges is an impulsive noise source that is lightweight and small enough to be easily transported. The differences in the noise characteristics between individual cartridges for the same gun are usually small, so the impulsive source can be replicated to a high degree. This paper is focused on the practical application of the sound exposure levels produced by a gunshot with a known sound energy level in the rooms under investigation. In this way, the equipment and methods required by the conventional method are simplified significantly. Furthermore, reverberation times need not be measured, since the equivalent absorption area can be directly obtained from the measured sound exposure levels. Using Green's theorem, the roles of the sound source and measuring microphone were exchanged, which simplified the determination of sound insulation as it was easier to change the position of the gun than the microphone. The results obtained using the impulsive noise source were in agreement with those obtained using the conventional method.

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1. Introduction

The apparent sound reduction index *R*' is usually measured by the conventional method according to the standard ISO 16283 [1] which uses a loudspeaker as a sound source. In some special cases however, like in big rooms, for instance, or when heavily weighted walls are involved or where high levels of background noise at receiving locations are present, it is hard to excite sufficiently high sound levels in the receiving rooms using the conventional method. Furthermore, in very big rooms troubles can appear when trying to excite low frequency modes, by only using a conventional loudspeaker. In addition, the proposal for a new standard for airborne sound insulation, which was initiated by COST Action TU0901 [2], foreseen the determination of sound reduction index also in the enhanced frequency range down to 50 Hz. When determining the transmission loss of a wall or a partition using the conventional method, it is necessary to measure the sound pressure level on both sides of the wall or the difference between the two rooms and the equivalent absorption area in the receiving room. Under the assumption of diffuse sound fields in the two rooms, with a wall separating them, its apparent sound reduction index *R*' in a certain frequency band may be evaluated, using the conventional loudspeaker method described by equation:

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

where $\overline{\boldsymbol{L_1}}$ is the average sound pressure level in the source room (dB), $\overline{\boldsymbol{L_2}}$ is the average sound pressure level in the receiving room (dB), S is the area of the test specimen (m^2), A is the equivalent absorption area in the receiving room (m^2), which is preferably evaluated from measured reverberation time T_{60} (s) according to ISO 3382 [3] and volume V (m^3) measured in this room and using equation:

$$A = 0.16\frac{V}{T_{60}} \tag{2}$$

But, determination of the sound reduction index in the low frequency region, below 100 Hz, is problematic due to a large measurement uncertainty. As already mentioned it is sometimes not appropriate to use commercially available sound generators like loudspeakers, which could also be of enormous size. Such loudspeakers are usually very heavy and can weigh as much as 20 to 30 kilograms. More importantly, such loudspeakers are often not loud enough to be clearly heard over the residual noise. In such cases, impulse noise generators, such as a gunshot, appear to be a more appropriate solution when compared with steady state sources. Such an application can be especially useful when high levels of residual noise are present. Moreover, due to its small dimensions the gun and its cartridges can be considered as a point source in a much larger part of the room than loudspeakers with their large dimensions. In this way its effect of directivity is smaller as well, especially at the low frequency range, down to 50 Hz. Many conventional loudspeakers appear to be weak sound generators, unable to excite this low frequency region. This can be much more easily achieved by using gunshot as a sound source, [4].
Furthermore, an impulsive noise source, such as produced by a gun firing blank cartridges, is usually lightweight and small enough to be carried around easily. In our case, the muzzle blast is by far the predominating source of sound, and it is also omnidirectional similar to a simple acoustic monopole source [6, 7]. Gunshot offers the possibility of removing flanking transmission, a problem which is much harder to realize with a conventional loudspeaker [8]. In addition, such a source is also self-powered and relatively cheap.
In the case of a strong enough impulse sound source, the difference in sound exposure levels, rather than in sound pressure levels, is measured. When the sound energy level of such an impulse sound is known, it is quiet easy to calculate the equivalent absorptive area of the room under investigation, or its corresponding reverberation time [9]. Therefore, the sound energy level of this impulse sound source must first be determined. In this paper a method for the determination of the apparent sound reduction index R' and its validation for in situ measurements is presented, and compared with results obtained by the conventional method using a loudspeaker as a sound source.

2. Sound energy level

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

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

Here S is the area (m^2) and the product ρc is the specific acoustical impedance, which, under standard atmospheric conditions (20 $^{\circ}$C and 1.013 bar), is equal to 415 (kg/m^{2}s=rayl). The reference sound energy is defined as energy passing over the reference area S_o, resulting in the reference sound pressure p_o in the reference time T_o.

$$E_0 = \frac{S_0}{\rho c} p_o^2 T_o \quad (4)$$

where S_o is the reference area (1 m^2), T_o is the reference time (1 s), p_o is the reference sound pressure (20 μPa) and 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 [10]:

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

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 $\overline{SEL}$ is the energy – mean value of SEL on the measurement surface S. Eq. (6) is equivalent to Eq. (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 a continuous (steady state) sound source.

3. Determination of equivalent sound absorption area

For calculation of the apparent sound reduction index R' of a wall, the equivalent absorption area or its corresponding reverberation time must first be determined. The basic equation, connecting the sound pressure level and sound power level of a steady sound generator in diffuse halls can be written as

$$L_{\mathrm{p}} = L_{\mathrm{W}} + 10\log\left(\frac{Q}{4\pi r^2} + \frac{4}{A}\right) \qquad (8)$$

where L_p is the sound pressure level (dB re 20 μPa) at a distance r, L_w is the sound power level (dB re 10^{-12} W) of a loudspeaker operating as a steady sound generator, Q is the directivity factor (dimensionless) and A is the equivalent sound absorption area (m^2) of the room under investigation.

Close to the reflecting walls and far apart from the sound source generating sound power level L_W, the first term in brackets (in Eq. (8)) can be neglected. In this case the sound pressure level is mainly a result of the reverberant sound field, which can be further written as

$$L_{\mathrm{p}} = L_{\mathrm{W}} + 10\log\left(\frac{4}{A}\right) \qquad (9)$$

In acoustics it is usually more appropriate to deal with logarithmic quantities, transforming A to L_{abs}=10 log(A/A_o) (A_o = 1 m^2) and giving, after some rearrangement:

$$L_{\mathrm{abs}} = 10\log A = L_{\mathrm{W}} - L_{\mathrm{p}} + 6 \qquad (10)$$

However, when using these relationships in big industrial rooms, the sound power of commercially available loudspeakers used as a sound generator is usually too weak to excite a wider set of modes of interest, especially those in the low frequency region. In such cases the application of a gunshot can afford a solution for this problem, as it can produce high energy levels, even in a low frequency region, down to 50 Hz. By measuring the sound exposure level of such an impulsive noise with the known sound energy level released L_E, and taking into account Eqs. (6) and (7) gives

$$L_{\mathrm{abs}} = 10\log A = L_{\mathrm{W}} - L_p + 6 = L_{\mathrm{E}} - SEL + 6 \qquad (11)$$

4. Application in sound insulation measurements

When using a loudspeaker as a sound source in the sound insulation measurements, the average sound pressure levels on the source side and on the receiving side are measured at several microphone positions. However, using the Green theorem of reciprocity, the source and the receiving point can be reversed. Consequently, sound exposure levels generated by gunshot (replacing sound pressure levels as produced by the loudspeaker), can be measured by two microphones (one on each side) when these gunshots operate as an impulse 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 manipulated at several (for instance five) different source positions in the source room, [11]. In this way the set of apparent sound reduction index were determined as [1]:

$$R'_{\mathrm{i}} = \overline{SEL_{1\imath}} - \overline{SEL_{2\imath}} + 10\log\frac{S}{A} \qquad (12)$$

with average values

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

here $\overline{SEL_{1\mathrm{i}}}$ is the average sound exposure level in the source room with the microphone location at i-th position in the receiving room, calculated as

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

and similarly for $\overline{SEL_{2\mathrm{i}}}$ in the receiving room

$$\overline{SEL_{2\imath}} = -10\log\frac{1}{m}\sum_{j=1}^{m} 10^{-0.1SEL_{2\mathrm{ij}}} \qquad (15)$$

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

5. Measurement procedure

Two different measurement procedures were used for the determination of the apparent sound reduction index: the conventional method and a new one based on the sound energy level of the gunshot which was determined according to the standard ISO 3740 [10, 13] as was described in [14]. A starting pistol Ekol special 99 with 9 mm blank cartridges was used as the source of impulse noise.

Determination of the apparent sound reduction index according to the impulsive method was performed by measuring sound exposure levels of the gunshots with the known sound energy level in a room as proposed by Eqs. (12) and (13). In this case, one microphone was fixed in the source room and two measuring (microphone) positions (n = 2) were selected in the receiving room. In the source room five positions of gunshots as a sound source were chosen (m = 5). After that, a microphone in the source room was moved to another location and the whole procedure was repeated, so 20 measurements were performed altogether. Average sound exposure levels in the source (SEL_1) and receiving rooms (SEL_2) were calculated according to Eqs. (14) and (15).

Determination of the apparent sound reduction index according to the conventional method using loudspeakers is described in ISO 16283 [1]. Reverberation time was determined as proposed by ISO 3382 [2]. With conventional measurements, the equivalent sound absorption area (A) (Eq. (2)) is determined through reverberation time (T_{60}) measurements. With the impulse method, the sound absorption area is a function of the sound energy level and sound exposure level in a room, as proposed by Eq. (11). We propose at least two microphone positions with three gunshot positions for each of these microphone positions.

The sound energy level of a gunshot as a sound source was determined by measurements over a large and quiet parking space area, when no traffic was present, according to standard ISO 3740 [10]. Measurements of the apparent sound reduction index (R') and equivalent sound absorption area (A) were performed according to the impulse method as described in this article and according to the conventional method in two different types of rooms: medium rooms used as offices and large lecture halls.

6. Measurement results and discussion

6.1. Determination of apparent sound reduction index in medium-sized rooms by using the impulsive method

6.1.1 Use of impulse method. The airborne sound insulation of a wall separating two medium sized rooms was measured, based on the gunshot sound source. The test specimen (a common partition between the source and receiving rooms) was a 100 mm thick plaster wall, 4.3 m wide and 2.89 m high. The source and the receiving room have the same height of 2.89 m and width of 4.3 m. The length of the source room was 8.1 m, and that of the receiving room was 5.65 m. Three walls including the separating wall were lightweight constructions, the fourth was a window wall, while the floor and the ceiling were heavyweight constructions.

In order to determine the sound reduction index of the 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 the source room five positions of the gunshots used as a sound source were chosen (m = 5), Fig. 1. The larger room was chosen as the source and the smaller one as the receiving room.

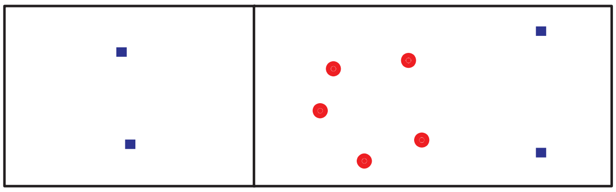

Fig. 1. Microphone positions (blue squares) and sound source positions (red dots) in middle sized rooms.

After that, the microphone in the source room was moved to another location and the whole procedure was repeated, so 20 measurements were performed altogether. Sound exposure level measurements, as required to determine SEL_1, SEL_2 and background noise levels SEL_B.

When the sound energy levels are known and measurements of corresponding sound exposure levels in the rooms under investigation have been done, the equivalent sound absorption area using the impulse method can be calculated according to Eq. (11). For this purpose another set of sound exposure levels (SEL) were measured in a mostly diffused receiving room. For this purpose two microphone and three gunshot positions were selected, with SEL measurements for each such combination, so 6 gunshots were produced altogether.

Using Eq. (12) the apparent sound reduction index (R') can be determined from the sound exposure level measurements in the source and receiving rooms and the equivalent sound absorption area, as calculated in the receiving room. The apparent sound reduction index in the 1/3 octave frequency spectrum for centre frequencies 50 Hz to 5000 Hz is depicted in Fig. 2.

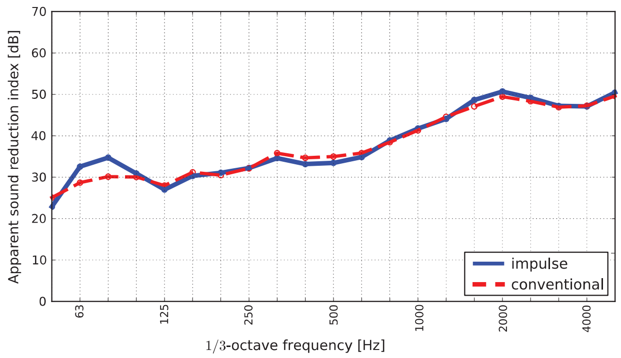

Fig. 2. Apparent sound reduction index of common lightweight partition between two middle sized rooms obtained by the impulse method (full blue lines) and by the conventional method (hatched red lines).

6.1.2. Use of conventional method. In order to validate our proposed method using gunshots, measurements using the conventional method with a loudspeaker were performed in the same rooms as well (see Fig. 1) The measurements were carried out according to ISO 16283, [1]. The default procedure with a fixed microphone, which was moved from one position to another, was used. A single pink noise omnidirectional Brüel & Kjaer 4296 sound source (with 12 loudspeakers) was used and placed in the source room near the opposite wall. The measurement positions in the source room were the same as with the impulse method (Fig. 3), with the roles of the sound source and the microphones being reversed, so five microphone positions in the source and receiving rooms were used.

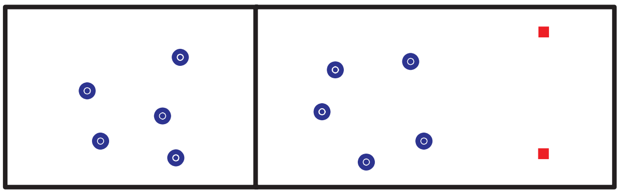

Fig. 3. Five microphone positions (blue dots) in the source and receiving middle sized rooms and two sound source positions (red squares) in the source room.

The sound pressure levels in the source room (L_1) and in the receiving room (L_2) for the first and the second loudspeaker positions and the background noise (L_B) in the receiving room were first measured, and then the apparent sound reduction index was calculated by using Eq. (1). The results are presented in Fig. 2 (red curve) for comparison with the impulse method.

The reverberation time in the receiving room was measured using the interrupted noise method, as described in ISO 3382, [3]. 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. The equivalent sound absorption area was then calculated using Eq. (2).

6.2. Determination of apparent sound reduction index in large rooms

The same procedure as described in Chapter 6.1 was used for large lecture rooms. The source room was a bigger lecture room with dimensions L x B x H = 14.1 x 8.4 x 3.95 m and the receiving room was a smaller lecture room with dimensions L x B x H = 7 x 8.4 x 3.95 m.

Measurements of the apparent sound reduction index were done using the impulse method, where gunshots were used, and the conventional method using a loudspeaker as the sound source. A sketch of the sound source and microphone positions for the impulse and conventional methods are shown in Figs. 4 and 5.

Due to the large volume of the source room, 10 microphone positions for each of the two loudspeaker positions were chosen when using the conventional method and 10 sound source positions were chosen when the impulse method was used, respectively.

When the shooting method was used, the location of the sound source and of the microphones were exchanged so two microphone positions were chosen in the source and receiving rooms, with 10 gunshot positions in the source room selected for each of the two microphone positions.

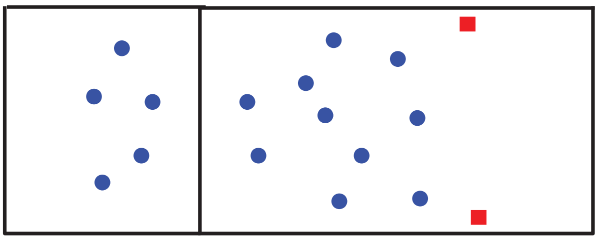

Fig. 4. Microphone positions (blue dots) and sound source positions (red squares) in the source and receiving large rooms when using conventional method.

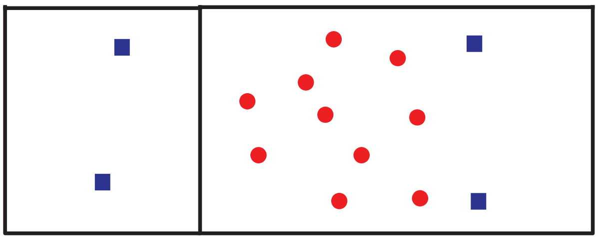

Fig. 5. Microphone positions (blue squares) and sound source positions (red dots) in the source and receiving large rooms when using the impulsive method.

Conversely, 10 microphone positions in the source room and five microphone positions with each of the two sound source positions in the receiving room were used for the conventional method.

The apparent sound reduction index of the partition wall between the two lecture rooms obtained by the impulsive method using gunshots (blue curve) and by the conventional method using the loudspeaker (red curve) are presented in Fig. 6 for comparison.

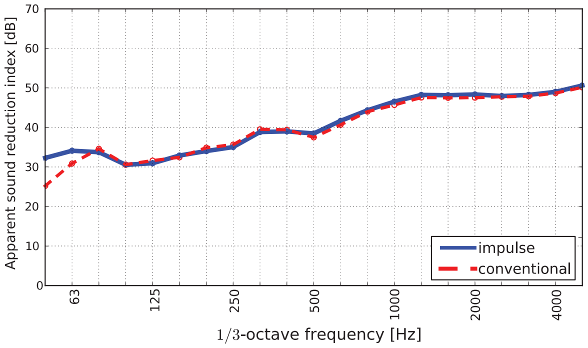

Fig. 6. Comparison between the apparent sound reduction index of the common partition between two lecture rooms obtained by the impulse (full blue curve) and conventional methods (hatched red curve).

Carrying out field tests thus reveals small discrepancies in the results obtained by the impulse gunshot and conventional loudspeaker methods; noticed differences are in the low frequency region, i.e. in the frequency bands where the measurement uncertainty is high by default. On the other hand, the sound exposure levels produced by a shooting noise are at least 25 dB higher in the middle sized room and 13 dB higher in the large room than the corresponding background levels in the receiving room, even for these low frequency bands. In this way the impulse method using the gunshot noise appears to be more reliable for the determination of the apparent sound reduction index, especially in the low frequency range.

7. Conclusions

One of the biggest problems in sound insulation measurements is how to increase the sound level in the receiving room well above the level of background noise, especially in the lowest frequency bands. This problem was successfully resolved by using the proposed impulsive method. Using a gunshot as an impulsive sound source, its sound exposure level increases in many cases more than 10 dB above the corresponding level of background noise in the receiving room, even at the lowest frequency bands, below 100 Hz, which was not possible when using the conventional method with a loudspeaker. In this way the background noise criteria has been fully satisfied. For this reason, the impulse method using gunshots gives more reliable results in the lowest frequency bands, when compared to the conventional method, while in mid and high frequencies both methods give very similar results. However, there are further advantages when using the impulsive method in comparison with the conventional method. For instance, a gunshot as an impulsive sound source offers the possibility of removing flanking transmission; it is sufficiently loud and self-powered, is also small, light, and relatively cheap, therefore it can be used effectively in room acoustics investigations.

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