A Comparison of Measurement Standard Methods for the Sound Insulation of Building Façades

Umberto Berardi
Politecnico di Bari, via Orabona 4, Bari, I-70125, Italy
Worcester Polytechnic Institute, 100 Institute Road, Worcester, MA 01609-2280, U.S.
e-mail: u.berardi@poliba.it

This paper focuses on the limits of measurement of the sound insulation of building façades at low frequencies. Three standard methods are compared mainly for the position of the equipment. In particular, the positions proposed by the international standard ISO 140-5 and the national standards ASTM E 966 (USA) and JIS A 1430 (Japan) are considered. The limits of measurement of the sound pressure level in front of the façade are investigated. Different placements of the external source and receiver are considered. Moreover, different placements of the receiver inside small rooms are compared by focusing on corner vs. center room positions. The uncertainties of room averaged sound pressure levels measured according to different standards are discussed. The problems of measurement of the reverberation time in small rooms and of sound insulation in irregular shaped rooms are introduced because these measurements present several critical challenges. Finally, suggestions to improve the future version of the ISO 140-5 are reported.

1. INTRODUCTION

The increasing noise levels in cities are turning the attention to the sound insulation performances of building façades [1]. New requirements are lowering the sound levels admitted inside the buildings worldwide by requiring façades with higher sound insulation [2]. The measurements and the corresponding levels of sound insulation are usually specified in terms of single numbers. These are calculated from values in the frequency range between 100 Hz and 3.15 kHz one-third octave bands according to the procedure described in the standard ISO 717-1 [3]. This frequency range was chosen to measure the potential impact on the people considering speech, music and cars as noise sources. Given the reliability of responses of the measurement equipment in the previous frequency range, it has been reported in every standard of the series ISO 140 for field measurements.

Standards ISO 140 are currently under review. Among other scopes, the review aims to extend the frequency range of measurement to low frequency. In fact, an increasing attention to sound insulation measurements at low frequency has been recorded in recent studies [4-7]. Modern hi-fis, computer audio systems, home cinema equipment and urban noises have an increasing and significant sound power at frequencies below 100 Hz. Moreover, the attention to low frequencies is also due to the recent diffusion in buildings of light weight elements which are more critical below 100 Hz where their resonance frequencies occur. Consequently, there is a request for measurements at low frequency in order to have coherent information with the real disturbance for building occupants.

In this study, measurement methods of the sound insulation of building façades are compared considering both international [8] and national [9,10] standards.

The measurement of sound insulation at low frequency shows several problems: the sound field in typical rooms does not diffuse, and interference effects are significant both inside and outside the building [11,12]. These problems will be investigated through field measurements. The scope is to compare existing methods and to propose some suggestions to reduce the uncertainty in the measurement of the sound insulation of building façades.

This paper is composed by four sections: next section describes standard methods for the measurement of the sound insulation of building façade: section 3 reports the results of field measurements done according to different standards, and section 4 reports a few outcomes of the comparison together with concluding remarks.

2. METHODS FOR THE MEASUREMENT OF THE SOUND INSULATION OF BUILDING FAÇADE

In this section the international standard ISO 140-5 [8], the American standard ASTM E 966 [9] and the Japanese standard JIS A 1430 [10] are described.

Table 1 of ISO 140-5 reports an overview of possible measurement methods for the sound insulation of building façades. These methods can be grouped into element and global methods if a small specimen or a large piece of the façade is considered respectively.

For each method, four types of sound sources can be adopted to assess the external sound: a loudspeaker, road traffic, railway traffic or air traffic noise. The last three can be used when the sound pressure level (SPL) of each source is sufficiently high (10 dB above the background noise) and steady. Although the use of real noise sources has several advantages, these sources are often instable or absent, and field measurements are often performed using a loudspeaker. In fact, the use of a loudspeaker as a sound source in sound insulation measurements represents a method that can always be adopted, and that permits a rapid evaluation of the SPLs. Consequently, in this paper, only measurements with the loudspeaker are considered.

ISO 140-5 specifies where the loudspeaker and the microphone should be placed with respect to the building façade. Paragraphs 5.4, 5.5.2 and 5.7.2 of this international standard state that:

- the distance from the sound source to the center of the test specimen shall be at least 5 m for the element loudspeaker method, and at least 7 m for the global loudspeaker method. The angle of the sound incidence shall be 45 ± 5 °;
- a minimum of five microphone positions shall be used to average the diffuse SPL in each room. Positions shall be distributed uniformly within the maximum permitted space;
- the external microphone should be at a distance of 2.0 ± 0.2 m from the plane of the façade or of 1.0 m from balustrades or similar protrusions, in the global method, whereas, in the element method, the microphone should be almost coinciding with the façade with a distance of less than 17 mm.

Fig. 1(a) represents the external configuration of measurement as reported in the ISO 140-5. Section 4.2 of this standard outlines that the loudspeaker should ensure local differences of SPLs on the façade below 5 dB in all frequency bands. This condition, which is often neglected in field measurements, should be checked in a free field on a surface that is of the same size and orientation as the façade or element to be tested. However, if the loudspeaker method is implemented with large area façades (e.g. exceeding 5 m), differences in SPLs up to 10 dB can be accepted [8].

To compare different methods for the measurement of the sound insulation of building façade, two national standards are further considered: the American standard

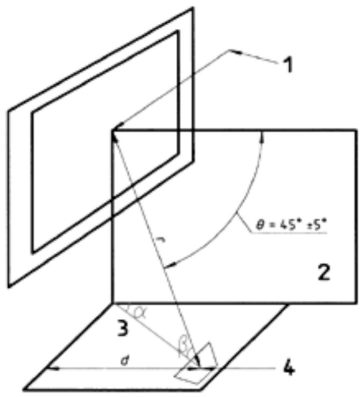
ASTM E 966 [9] and the Japanese standard JIS A 1430 [10].

The standard ASTM E 966 describes several methods for the measurement of the Outdoor-Indoor Level Reduction (OILR). The different methods should be selected according to the scope of the measurement. Par. 8 of the standard contains a detailed description of the requirements for the measurement procedure with an external loudspeaker. The standard suggests arranging the equipment in the following way:

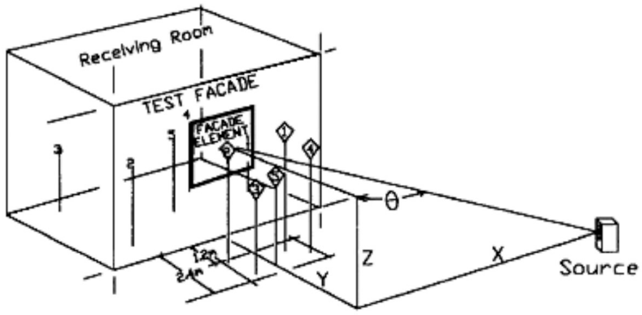
- the loudspeaker should form an angle of 45° with the façade, but the OILR measured with the loudspeaker at one angle is valid for that angle only. The standard remarks the importance of measuring the sound transmission at all incidence angles because a single incident angle cannot simulate a diffuse effect. However, an approximation can be obtained by measuring the SPL at selected angles which should be chosen to represent equal areas (solid angles) of a hemisphere. For three measurement angles, the standard suggests the angles of 34, 60 and 80°, as each of this covers the same hemispherical solid angle. However, in order to have more easily measurable angles, the standard ASTM E 966 suggests putting the loudspeaker at 15, 30, 45, 60 and 75°. In this case, the solid angles are not homogeneous and the standard ASTM E 966 reports the weight factors to average the SPLs measured with the loudspeaker at each angle (0.08, 0.15, 0.22, 0.26, and 0.29 respectively). Obviously, other angles can always be selected provided that this respects the homogeneity of spatial incidence;
- the SPL in the room behind the façade should be measured using a moving microphone which should be located in a minimum of three positions. The standard also suggests reducing the uncertainty by measuring the SPL in more positions in the room;
- the external SPL should be calculated averaging the squared pressure in several positions in order to minimize the effects of wave interferences. Five or more positions should be selected between 1.2 and 2.5 m from the façade element in the nearby average method. The standard suggests selecting the positions within the left, right, upper and lower sides randomly (Fig. 1(b)). Moreover, in the flush method, which corresponds to the element method in the ISO 140-5, the external microphone should be in five positions at less than 17 mm from the façade (Fig. 1(c)).

The other standard, which is considered in this paper, is the Japanese standard JAS 1430. This has some differences from the ISO 140-5 as described in its Annex JD [10]. Looking at the position of the equipment during the measurement, the main differences are:

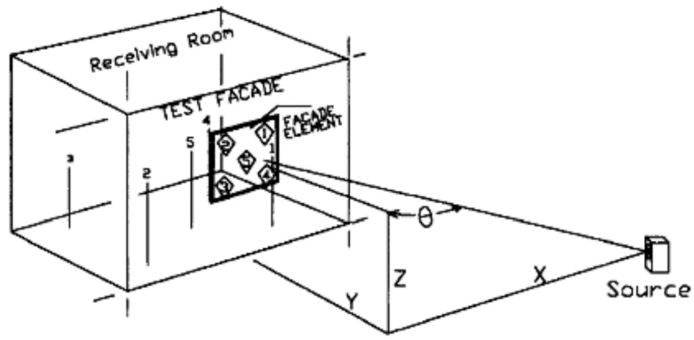
- in addition to the methods described in ISO 140-5, the standard JAS 1430 also allows measurements with the inverse method. Following the reciprocity principle, it is possible to put the loudspeaker inside the room and to measure the sound insulation of the façade from the difference between internal and external SPLs.
- the Japanese standard prefers the use of a loudspeaker as source for measurements in the element method, whereas the ISO 140-5 always gives priority to the use of real field noise sources;
- the external microphone should be at a distance of 1.0 m from the façade. This shorter distance respect to the standard 140-5 is accepted in this standard for balustrades or similar protrusions only.



(a)



(b)



(c)

Figure 1. Measurement positions according to the ISO 140-5 (a), and the ASTM E 966-10 for the global method (b) and element method (c).

A confusing aspect of every standard is the orientation angle of the loudspeaker with respect to the façade (in Fig. 1). This angle is obtained by the perpendicular to the façade and the line connecting the loudspeaker to the center of the façade. This means that when the loudspeaker is at a different height from the center of the façade, this angle is oriented on an inclined plane. Consequently, the horizontal projection of this angle should not be considered when positioning the loudspeaker. In fact, a "horizontal interpretation" results in an angle smaller than 45°. However, given the difficulty to measure that angle on an inclined plane, a "horizontal interpretation" is often considered in field measurements. Recent studies have discussed the error resulting from using an angle of 45° in the horizontal plane when the loudspeaker and the center of the façade state at different heights, obtaining a single index number some dB different from the value measured with the right position of the equipments [11, 12]. These results have contributed showing the high uncertainties of filed measurements [11,13].

Previous standards for the sound insulation of façades differ in the frequency range of measurement. The standard JAS 1430 suggests measurements in octave frequency bands from 100 Hz to 3.15 kHz, whereas the ASTM E 966 asks for measurements in one-third octave band frequencies from 80 Hz to 5 kHz. The frequency range represents a controversial aspect, especially because the revision of the ISO 140-5 is likely to extend the measurement to one-third octave bands below 100 Hz.

Several problems have recently emerged for low frequency measurements of sound insulation of façades [14-17]. Previous standards have hence been compared for the possible configurations for the measurement of the sound insulation of building façade, as reported in the next section.

3. INVESTIGATION OF MEASUREMENT CONFIGURATIONS

Tests were done in a new and empty building to investigate different methods for the measurement of sound insulation of building façades. Fig. 2 reports the plane of the building and the positions of the equipment. Measurements were carried out in two box-shaped rooms which were located on the first floor. The façades of these two rooms had no balconies or architectural decorative elements. The rooms had volumes of 79 m^3 (room 1) and 44 m^3 (room 2).

Measurements were carried out using a calibrated chain consisting of a 01 dB Symphonie system and two GRAS 40-AR omnidirectional microphones. A directional sound source (Lookline FL 301) was used in front of the façade, whereas an omnidirectional sound source (Lookline DL 301) was used in front of the façade, whereas an omnidirectional sound source (Lookline DL 301) made up of twelve 120 mm loudspeakers was used inside the rooms in order to measure the reverberation time (RT). A non-equalized pink noise averaged over 15 s and from 50 Hz to 5 kHz was used as signal. The equipment were calibrated before any session of measurement, and showed stable results. Air temperature was 25.0 °C on average, whereas the humidity showed small variations during the measurement sessions.

Different sessions of measurement were carried out. In this section, the results are reported grouping them according to the problematic aspects of the measurement method. The following four sub-sections describe the investigation of the measurement of SPL in front of the façade, the SPL inside the building, the RT in the room, and the sound insulation of corners and irregularly shaped rooms.

3.1 THE MEASUREMENT OF SPL IN FRONT OF THE FAÇADE

As seen in section 2, ISO 140-5 allows flexibility in positioning the external microphone and loudspeaker: in the global method, a tolerance of 0.2 m for the microphone exists, whereas the loudspeaker can be positioned with an angle from 40 to 50°. The standard ASTN E 966 suggests averaging measurements obtained in different positions both of the microphone and the loudspeaker.

Sánchez Bote *et al.* [18] have recently studied the influence of loudspeaker directivity and measurement geometry on the SPLs on façades. They found that an ideal omnidirectional source has a priori the best directivity because it produces relatively small variation of the direct acoustic level on the façade. On the contrary, the source directivity is always

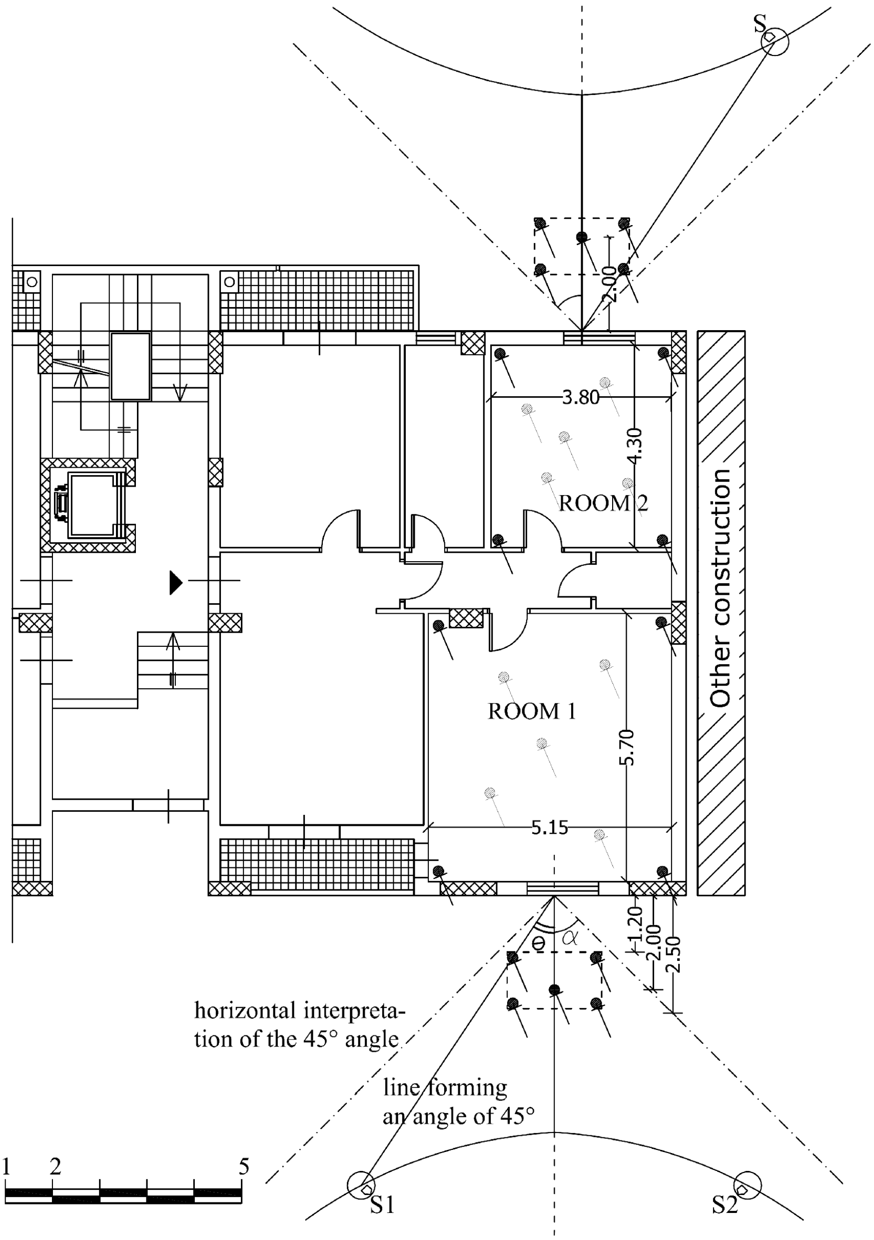


Figure 2. *Plan of the measurement configuration with positions inside and outside the two investigated rooms.*

a detrimental factor for the measurement of the sound insulation of building façades.

Berardi *et al*. [16] have recently published a theoretical study of the effect on sound insulation values of different positions of the instruments in front of the façade. Using the same measurement chain used in the present work, they showed that destructive interferences among waves may occur in different frequency bands depending on the relative positions of the microphone and the loudspeaker. These interferences were particularly evident at low frequencies because at such low frequencies, in-phase reflections did not overlap among bands. That study showed that using different configurations all complying with the prescriptions of ISO 140-5 resulted in differences of the sound insulation values up to 2 dB in single number.

The problems due to interference effects in front of the façade should hopefully be resolved. The theoretical analysis of the interference phenomenon has suggested reducing the distance between the loudspeaker and the façade or similarly, increasing

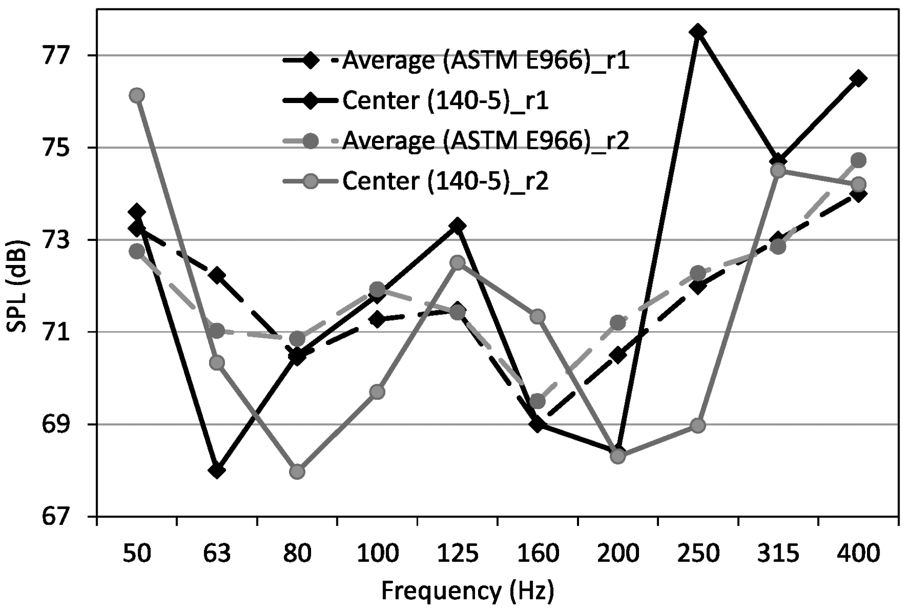


Figure 3. Outdoor SPL measured in the positions given by the ISO 140-5 and the ASTM E 966, for the loudspeaker global method in room 1 (black) and room 2 (grey).

the distance of the external microphone from the façade [16]. Both these solutions reduce the frequencies at which interferences occur, and may help shifting the interference below the interval of interest for sound insulation measurements.

In order to increase the reliability of external SPL measurements, the ASTM E 966 recommends an average of five points of measurement in front of the façade. Fig. 3 reports the SPL average in the positions proposed by the ASTM and the measurement at 2 m in front of the façade for the two rooms. As expected, interferences are evident in the low frequency bands: in particular, interferences resulted at 63 and 160 Hz for measurements in front of room 1, and at 80 and 250 Hz in front of room 2. Results in single band differences differ from the expectation up to 10 dB. Conversely, the average among five measurements significantly mitigates the SPL variations which are caused by destructive interferences. These peaks were compared to the measurements in the center and the average value around the center, as prescribed by the ASTM E 966: standard deviations up to 4 dB were recorded in some frequency bands among values around the center of the façade. Measurements with the microphone at 1 m were also done (data not shown, but the reader may look at Ref. [16] for these): in this case, the peaks reduced, but the interferences were still evident.

Finally, the results in Fig. 3 suggest that the standards which require an average of measurements in several points in front of the façade are more reliable, especially at low frequencies.

3.2 THE MEASUREMENT OF SPL INSIDE THE BUILDING

The SPL measurements inside the building are critical at low frequencies given the not diffusiveness of sound fields. This problem is particularly evident in empty and small rooms where the absorption is low and flat surfaces face each other emphasizing the modal response of the room. Hopkins [17] has proposed the measurement of the SPL inside rooms through manually-scanned microphone paths. This methodology has then been reported in the standard prISO 16283-1[19] which has introduced the possibility of measuring the SPL inside the room using paths forming a circle, a helix, a cylindrical-type or 3 semicircles.

The SPLs in the two investigated rooms were hence measured using these paths. Moreover, the SPLs were measured in five random positions in the room, as prescribed in the ISO 140-5.

Fig. 4 reports the SPL measured with the manual scanning method and the average values in fixed positions in the two rooms. The manual scanning method generally gave higher values than the fixed microphone position method. In fact, a large difference occurred at low frequencies. The plots show that the results measured considering the cylindrical path and semicircles paths were almost identical, whereas the circle path gave lightly lower values than the other manually-scanned paths.

To investigate the possibility of noises related to the manual scanning method, they were repeated, but similar results were obtained. The results in Fig. 4 prevent drawing final conclusions about the difference between fixed positions and scanning methods because in some frequency bands the

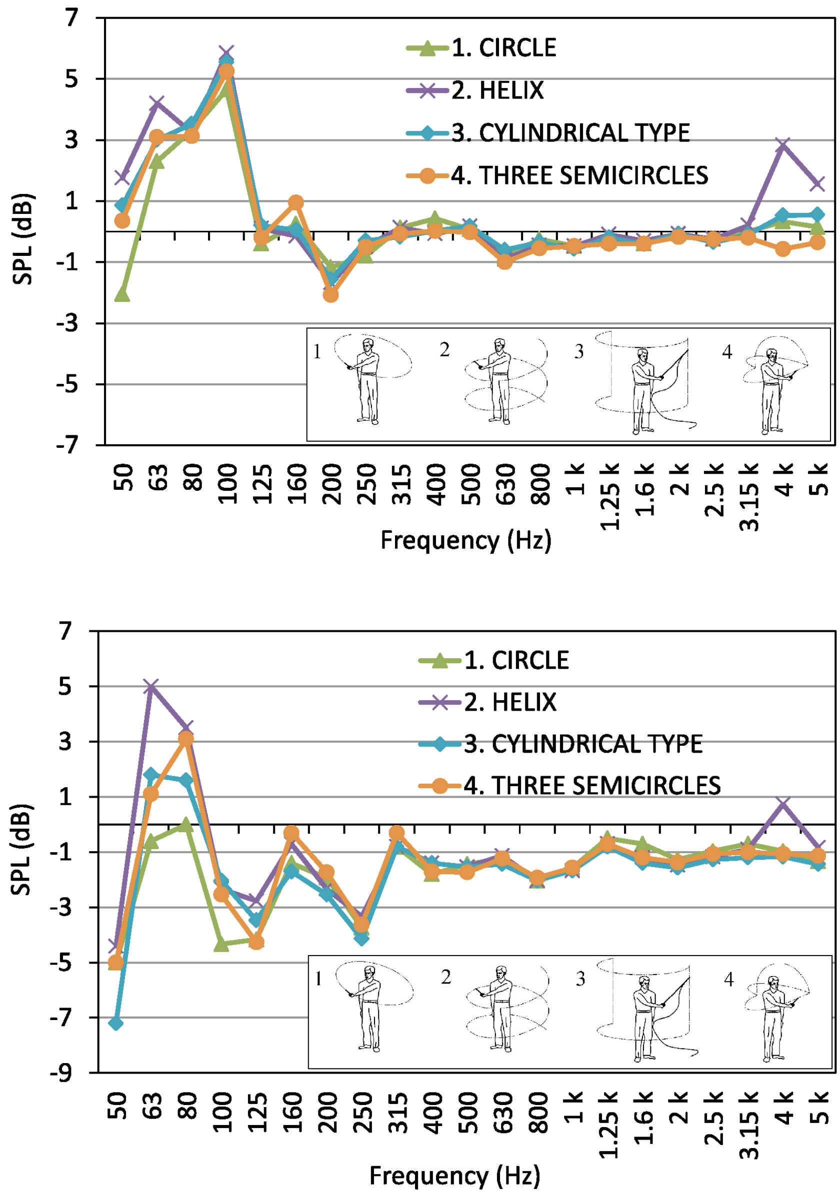


Figure 4. *Differences between the SPL measured through manual scanned microphone according to the paths reported in ISO 16283-1, and the average of values in fixed positions according to ISO 140-5, room 1 (above) and room 2 (below).*

values in fixed positions were higher than the SPLs obtained with the scanning method.

Other studies have hence been done to evaluate the SPL in rooms [5,20]. According to these, the SPL in the corners of the rooms are found higher values than in the center as consequence of the local reflections. Moreover, the measurement of the SPL in the corners of the room is prescribed in the standard for the measurement of the SPL from service equipment [21] and in draft standard ISO 16283-1[19].

The SPL was measured in the four corners of each room at a height of 1.5 and 2.5 m above the floor, and at a distance of 0.3 m from the two lateral sides. The previous heights were chosen as they correspond to that of the head when the body is sitting or lying, that of the ISO 140-5 and that where the highest SPL in the room are expected respectively. Fig. 5 shows the results of the measurements for the two rooms. As expected, SPL values at 2.5 m resulted in higher values. Looking at results in the bands of 50, 63 and 80 Hz, the SPL average in the center of the room were 10.7, 9.9 and 11.9 dB lower than those obtained in the corners at the height of 2.5 m above the floor in room 1, and 5.3, 5.0 and 7.2 dB in room 2 respectively.

Comparing the results at higher

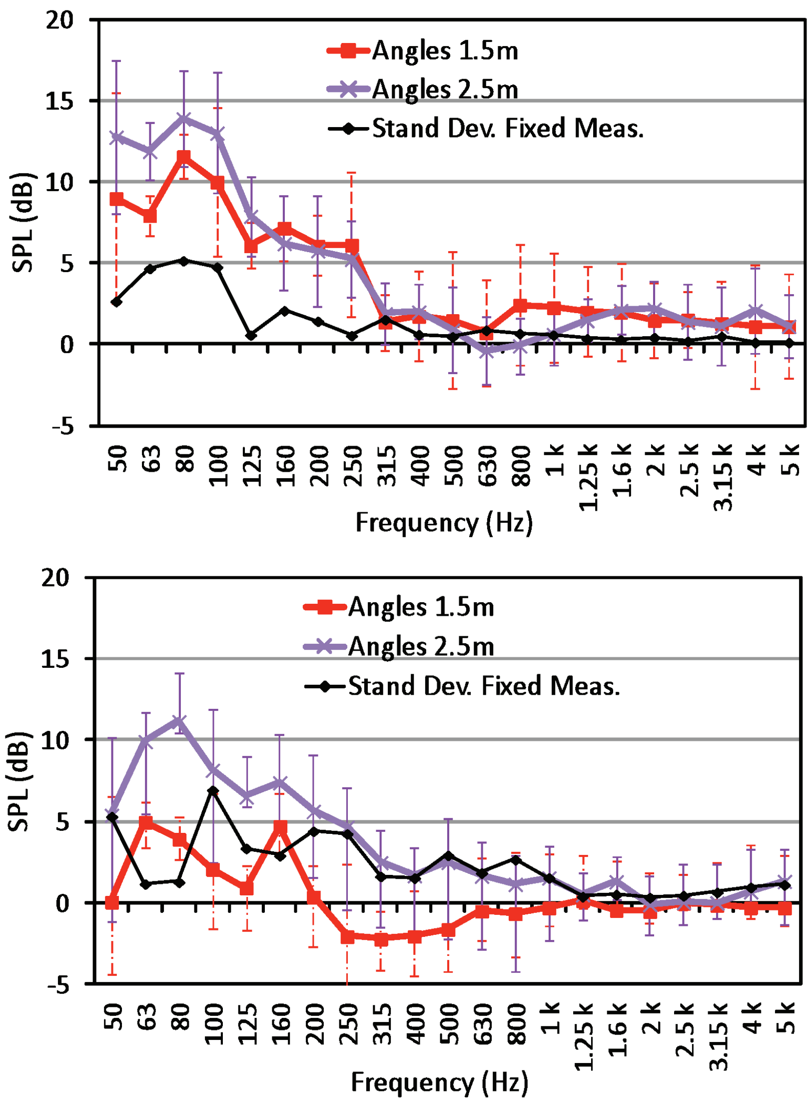


Figure 5. Differences between the SPL in the corners at different heights (standard deviations refer to measurements in the four corners of the room) and average values in the center of room 1 (above) and room 2 (below).

frequencies, similar values were found between the measurement positions. In fact, the differences between corner and center room values were below 1 dB above 1 kHz in both rooms. Fig. 5 also reports the standard deviations among measurements in four corners : these were particularly high at low frequency.

Finally, the high values measured at 2.5 m state that the measurement below the ceiling, which is required in the draft version of the ISO 16283-1, gives unrepresentative values respect to the values in the center of the room. On the contrary, the measurement of the SPL in the corners at the height of 1.5 m seems more relevant also because sleeping and seating positions are often near room corners.

3.3 THE MEASUREMENT OF THE REVERBERATION TIME

The normalized measurement of the sound insulation of a façade requires the determination of the RT in the room behind the façade. Considering that both rooms in Fig. 2 have a rectangular plan and that they are empty and without furniture, strong low frequency resonances may appear. In fact, the Schroeder frequencies for the rooms were 355 and 476 Hz for room 1 and 2 respectively.

The RT in both of the two rooms investigated was determined according to the ISO 3382-1 from 50 Hz to 5 kHz [22]. At frequencies as low as 50 Hz, the frequency response of the omnidirectional sound source is generally quite poor unless an additional sub-woofer is used. Consequently, the equipment was carefully checked before any measurement. Moreover, great attention was given to move the microphone considering both the positions given by the Matlab routine (to be sure those random positions were selected) and the necessity to avoid room modes. In fact, measurements often revealed the presence of modes which prevented to determine the slope decays of the sound energy.

The time histories of the room response showed the typical pulsating behavior that characterizes normal modes throughout the whole low frequency range, making the selection of a decay slope to determine the RT more difficult (Fig. 6). Further evidence of this was the high standard deviation among measurements at low frequencies (0.6 s in room 1 and 0.8 s in room 2 at 50 Hz), whereas at high frequencies, the results obtained in the several measurement points had a standard deviation of less than 0.1 s. A decay of only 10 or 20 dB was hence used to calculate the RT at low frequencies.

Fig. 6 reports the results of the RT measurements in both rooms, together with the standard deviation among measurement positions. Although the volumes of the rooms were small, long RTs resulted especially at frequencies below 100 Hz, given their emptiness and low absorption.

3.4 THE MEASUREMENT IN CORNER ROOMS

An interesting research case for the sound insulation of building façades is the measurement of sound insulation in irregular shape rooms or in rooms in the corner of a building. In particular, this section describes this last case. These rooms have more than one façade and often, more than one window. Windows can also be on different sides of the room, and of the building.

Current standards do not clarify how to measure the sound insulation of the façades in these cases or where to position the external loudspeaker. In fact, during the measurement, we can put the loudspeaker in a way that it faces one side only or both. The sound entering the room would be different in the two cases, and hence, the measurement of the sound insulation would differ. The problem of corner rooms is similar to every case in which the sound can enter the room behind the façade from several directions and boundaries.

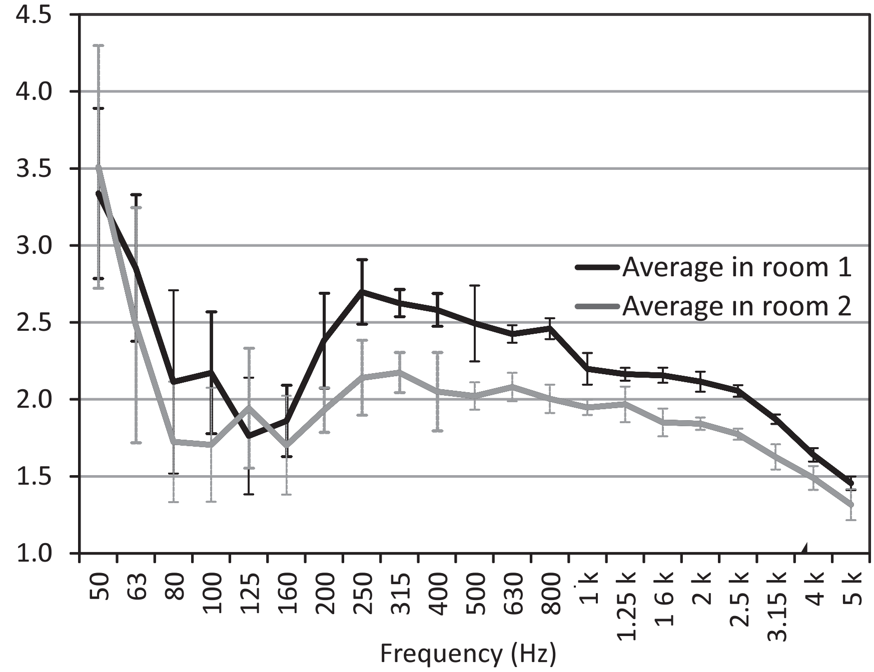


Figure 6. *Reverberation time in the two rooms with standard deviations among measurement points, and time history of the decays at 50, 63 and 80 Hz in room 2.*

For example, room 1 in Fig. 2 has a window on the main façade and a door-window on the loggia. When measuring the sound insulation of this façade, it is possible to place the sound source on the left or the right respect to the perpendicular to the façade (source S1 or S2 in Fig. 2). Obviously, given the different insulation performances of the windows and walls, the sound energy which enters in the room is different in the two cases. Measurements were hence performed with the loudspeaker on the two sides in order to estimate this difference. Single values of the sound insulation with the source in S1 or in S2 differed by 2 dB (higher if the loudspeaker was in S2).

Another singular configuration, which is similar to the corner rooms, is that of rooms over pilotis. This architectural typology originated from the Swiss architects Le Corbusier represented a common design in the 20th century. In this case, the measurement of the sound insulation of the façade at the first floor can be influenced by the sound that enters in the room from the floor too. Similarly, in cases of attics or apartments on the top floor, the sound enters the room both from the façade and the roof. None of the standards explain the configuration of measuring sound insulation in previous cases, leaving freedom in the choice of different configurations. This problem can partially be solved by establishing which performance is to be measured. If the scope of the measurement is the assessment of the effect over occupants in the room, then the position of the equipment should be selected in order to measure the maximum SPL inside the room and hence, by choosing the position of the equipment which minimizes the sound insulation of the façade. However, none of the existing standard helps with this issue.

4. PROPOSALS FOR THE MEASUREMENT METHOD AND CONCLUSIONS

The results shown in the previous section allowed the discussion of several problematic aspects of measurements of sound insulation of building façade. Limits described in section 3 should be resolved in future standards if the measurement has to be extended to low frequencies, where limits are more significant.

As said, the paper aims to compare different standards for the measurement of the sound insulation of building façades. In particular, the results of the investigation suggest:

- averaging the external SPL measurements among different positions in order to reduce the effects of interference in front of the façade. A possible solution for the average is represented by the prescription already contained in the American standard ASTM E 966 which is based on the average among measurements in five points both in the global and element method, while placing the loudspeaker in different angles in front of the façade;
- reducing the interference effects at low frequencies by considering the measurement in octave band (63 Hz) instead of one-third octave bands (50, 63 and 80 Hz) to limit the drops of interference;
- averaging the internal SPL by considering the values in the center of the room and in corner positions. A tentative choice for this average is the procedure for low-frequency measurements reported in the prISO 16283-1. This requires considering a weighted average of the measurements in the center and the corners of the room. In the standard for the airborne sound insulation, the weighting ratio of the average between values in the center and in the corners is 2:1. Before adopting the same ratio also for the measurement of the sound insulation of building façades, this ratio has to be validated. However, the measurements in the corners have shown to be relatively complex, and could be preferable to perform them on the edges of the room;
- establishing unique procedures for the measurement of the reverberation time (RT) at low frequency. In particular, the measurement method should help to generate a consistent sound field in the room in order to help selecting the energy sound decay at low frequencies;
- in all cases in which the sound could enter in the building from several surfaces, doubts about the position of the source exist. A solution to this problem has been given in the paper in which the source has been positioned where the sound insulation resulted the lowest. This position of the source would give an estimation more similar to the disturbance of the occupants of the room.

Further research should consider the low-frequency measurements in the corners to map the effect of different position of the instruments. Moreover a study has to be done about the weighting factors between measurements in the corners and in the center of the room. Finally, measurements with road, rail and air traffic noises are necessary as, no data exists about corner measurements inside the rooms with these sources.

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MORE TIGHTENING

Ocean City (MD) is strengthening its noise regulations. In the case of rented commercial property, if the tenant is seeking a noise permit, the address of the owner and/or an emergency contact must be provided. This should help address the issue of legal liability in the event of a noise offence as well as making it simpler for the authorities to have the landlord pressure tenants into responsible behaviour. Second, the fine for noise offences will go up from $400 to $1000, the City arguing that $400 doesn't cover its costs if the matter goes to court.

'WRONG KIND OF WIND' BLAMED FOR HEATHROW NOISE

A dramatic increase in noise pollution is being caused by the wrong type of wind according to BAA. The entirety of South West London has been affected by the increase in noise pollution with complaints about aircraft noise rocketing to more than 900%. London Councillors initially believed that the increase of complaints was due to an on-going trial which allows BAA to use Heathrow's two runways simultaneously under certain conditions. BAA's Director of Airside, Tim Hardy, said: "The significant increase in noise complaints is probably due to the unusual weather we've had recently which has seen 90% of wind coming from the west between July and September."