A survey of reverberation times in 50 European venues presenting pop & rock concerts

Niels W. Adelman-Larsen
Flex Acoustics, Scion DTU, Diplomvej 377, Kgs. Lyngby, Denmark

Jens Jørgen Dammerud
Department of Sound Production, Nordic Institute for Stage and Studio, Oslo, Norway.

Summary

In the fall of 2010 more than 50 halls around Europe were measured in order to determine their reverberation times as a function of frequency as well as other objective acoustic parameters. Many of the measured halls had a capacity of more than 2000 audiences and this paper is primarily an attempt as to look into what is actually achievable and what may through future subjective studies turn out to be recommendable in terms of i.e. T_{30} in this type of larger venues at pop and rock concerts. Also possibly acceptable spectral tolerances around recommendable T_{30} are investigated. Often pop and rock concerts take place in multipurpose venues that also host classical music or even sports games. This paper furthermore introduces an affordable variable and mobile absorption product that also absorbs the important low frequency sound energy.

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1. Introduction

Many of today's musical geniuses are performing within pop, rock and related genres. From the point of view of the musicians, live concerts are becoming increasingly important because of declining sales of recorded music. Both for the sake of musicians as well as to serve the vast masses of audiences attending their concerts, more focus on suitable acoustics for pop & rock appears relevant.

The major aim for this paper is to document the acoustic behaviour of a range of different venues for pop & rock music. A total of 55 venues around Europe have been investigated in terms of what acoustic conditions are achievable and significant differences between the venues. The 55 venues varied from small clubs to large arenas with volumes up to 600,000 m^3. For pop & rock venues with a volume above 7,000 m^3 there are not found any scientific investigations of suitable reverberation times. 31 of the 55 surveyed halls are larger than 7,000 m^3.

Real acoustic conditions using the venues' sound system have not been investigated, since the aim has been to isolate the acoustic responses of the rooms which in some cases alone lead to challenging conditions for musicians and sound engineers. A set of objective measures are used to describe the acoustic qualities of the venues. The selection of measures are based on results from [1] and on considerations of what characteristics appear relevant and sufficiently valid compared to real acoustic conditions. The objective characteristics are not compared extensively to subjective characteristics, but a study of three new and Danish mid-sized venues with good reputation is used as a reference and to see if optimal ranges of the objective measures may exist.

Several classical as well as pop & rock concerts are held in multipurpose venues in arts performing centres, recital halls etc. In order to try to adapt the acoustics to these different needs of different type of genres, variable acoustic systems – passive as well as active – are rightfully often employed in such halls. Though questionable, even some of the surveyed large multipurpose arenas having impressively low measured reverberation times probably suitable for pop & rock music were reported to have a lack of vivacity during sports games. A new inexpensive on/off absorption system that alters the reverberation time of a hall at mid-low to low frequencies is briefly presented at the end of this paper.

2. Measurement procedures

Room acoustic impulse response were measured using Dirac software installed on a laptop employing a linear sinus sweep of either 5 or 21 s length and a GRAS omnidirectional microphone. The small venues were measured with a Norsonic dodecahedron and a subwoofer, while the larger halls were measured with a d&b PA system consisting of two mid/high frequency speakers (50° vertical and 80° horizontal coverage angle) and two subs, all connected to the same dedicated d&b amp.

Impulse responses of between 5 and 10 relevant microphone positions were recorded in all venues using one constant loudspeaker position approximately at the centre of the stage area. All venues were measured without audience but some had temporary chairs set up on the floor area (affecting measured T at the highest frequencies). In some of the large arenas there was no stage set up on the date of the measurement. None of the room responses covered in this paper was measured on stage. Although the above is not fully in compliance with the ISO standard ISO 3382-1:2009 it is believed that the results are indeed trustworthy. All measured responses were checked during the measuring procedures.

3. Relevant objective measures to study

The priority for this study was to investigate objective measures which assess the acoustic conditions imposed by the room itself, not including a sound system. Such measures can evidently be a background for selection of sound system or the consideration of improving the venue's acoustics. Venues that are acoustically challenging at mid-hi frequencies can result in acceptable conditions if a suitable PA system design and precise installation is applied. The following geometric measures were obtained: volume and length, width and height of the venues, denoted as V, L, W and H. Additionally the maximum distance from the position of the main sound system to a listener within the audience was measured, denoted in this paper as $r_{\max}$. The ratio $H/r_{\max}$ was also found, since low venues with listeners close to respectively far from the sound system often results in poor conditions.

The following acoustic measures were obtained (125–2000 Hz): Reverberation time T, early decay time EDT, bass ratio BR ($T_{30,125\text{Hz}}/T_{30,500–1000\text{Hz}}$), EDT/T_{30}, $D_c/r_{\max}$, G_{late} (G_l) and $G_{\text{d,min}} - G_{\text{late}}$. D_c is the critical distance and was estimated using equation 1. G_{late} is the late part of the acoustic measure G (Strength) and represents the level of reverberant sound arriving after 80 ms relative to the direct sound. G_{late} was estimated using equation 2 based on Barron's Revised Theory [3] and a source-receiver distance, r, of 15 m. As seen below G_{late} is affected by T and V. This measure has been found relevant for classical concert hall stages [4]. $G_{\text{d,min}}$ is the free-field direct sound level from a point source at the distance $r_{\max}$.

$$D_c = 0.057\sqrt{V/T} \ , \qquad (1)$$

$$G_l = 10 \cdot \log_{10}\left(\frac{31200 \cdot T}{V} \cdot e^{-0.04r/T} \cdot e^{-1.11/T} \right), \qquad (2)$$

$D_c/r_{\max}$ and $G_{\text{d,min}} - G_{\text{late}}$ are proposed for studying to what degree the reverberant sound may take dominance over the direct sound or on the contrary be inaudible. These measures are ignoring early reflections, but could provide indications of challenging conditions.

4. A study of three Danish halls with good reputation

As a supplement to the subjective results from [1], three mid-sized Danish venues with good reputation were investigated. All these three venues are overall identified as good venues among musicians, sound engineers as well as the owners. Objective measures obtained from these three venues may provide an indication of acceptable tolerances around the recommendable T_{30}. The volumes of the three venues are: 2,300 m^3, 2,700 m^3 and 4,000 m^3 for Fermaten, Magasinet and Skråen respectively.

With regard to subjective judgments of these three venues, one of the loudest Danish bands found it pleasant that in Magasinet they were able to hear the audience so well. Sound engineers of very loud amplified performances may judge Magasinet a little too live although there are no reports of this at the present time. A well-known Danish performer unlike other bands commented after playing with an amplified acoustic guitar duo in Skråen that the acoustics were 'too dead'.

The results for T_{30} within 1/3 octave bands for the three Danish halls are shown in Figure 1. Suitable values of T_{30} for the three volumes are according to [1] 0,8 s for the two smallest volumes and 0,9 s for the bigger volume, with T_{30} averaged over the 63–2k Hz octave bands as suggested in [1]. The actual measured T_{30} for the three halls when employing this average is 0.62, 1.12 and 0.99 s for Fermaten, Magasinet and Skråen respectively. The corresponding deviations from the recommended values are –23, +40 and +10 %.

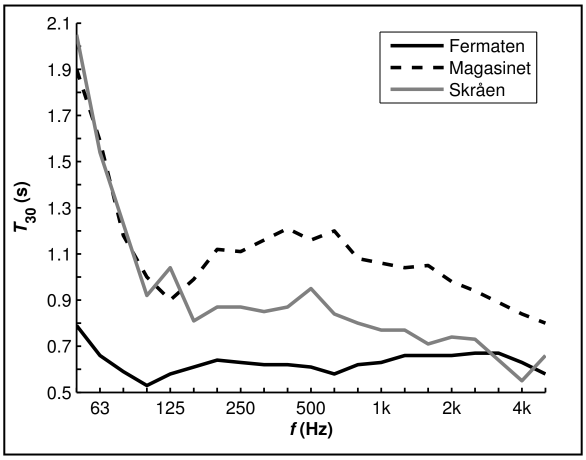

Figure 1: Measured T_{30} for the three Danish venues.

Magasinet contains no mid/high frequency absorption at all apart from upholstered chairs. The sensation of too dead acoustics at Skråen is probably because of the very low reverberation at high frequencies due to a wall-to-wall carpet and upholstered seats that the hall owner decided to install without notice after the completion of the hall. A reason why Fermaten has not been judged 'too dead' is partly that the stage was designed with many reflective surfaces directed towards the musicians. This design was chosen since it was believed that such a balance of early to late support as pointed out by Gade in [5] for classical music may cause a higher comfort for the musicians even for amplified music concerts.

In [1] suitable reverberation times for small to mid-sized pop & rock venues up to approximately 7,000 m^3 were determined. It was also found that what distinguishes the best from the less appropriate halls is a significantly lower value of *T* in the 125 Hz octave band, as well as in the 63 Hz band. The results suggested that a too high value of *T* in 125 Hz octave band alone can ruin the acoustics for pop and rock concerts. The reason for this is probably the high (perceived) sound level in that band, in conjunction with the low degree of absorption that the audience provides at low frequencies as well as the loudspeakers being close to omnidirectional. Furthermore the bass levels have even been reported to increase the latest years with the introduction of sound level limits at live concerts throughout Europe. Another important finding in [1] was that *T* must not be too low. For venues with very short reverberation time, musicians reported a sensation of lacking contact with the audience.

Magasinet and Skråen show significantly higher values of T_{30} in the 63 Hz octave band. The frequency-range of recommended T_{30} in [1] includes the 63 Hz octave band. For a more precise recommendation for T_{30} (for at least small and midsized pop & rock venues), in this light it appears beneficial to incorporate a separate tolerance for the 63 Hz octave band of approximately a factor of +1,8 compared to the suitable T_{30} within 125–2000 Hz for a specific volume. This factor is probably only acceptable if the T_{30} curve rises steeply towards the 50 Hz third octave band. As a matter of fact there has not been found an upper limit yet, since in [1] the halls with high values of T_{30} at 63 Hz also had high values of T_{30} at 125 Hz. It is therefore not possible to tell if both or just one of the octave bands is to blame. In many situations, the available absorption leading to an acceptable reverberation time at the 125 Hz octave band will also lead to a reverberation time at the 63 Hz octave band of reasonable values. On the other hand, a reduction of T_{30} from 125 to 63 Hz is not something to strive for since it will take more power to provide an adequate sound level. A factor within 1 to 1.8 for T_{30} at the 63 Hz compared to the 125 Hz octave band therefore appears to be an optimum range.

The average values of G_{late} within 125–2000 Hz are –2.3, 4.0 and –0.9 dB for Fermaten, Magasinet and Skråen respectively. For the 63 Hz octave band corresponding values of G_{late} are –1.5, 7.5 and 6.1 dB. The extreme values of BR, EDT/T_{30}, $D_c/r_{\max}$, $G_{\mathrm{dmin}} - G_{\mathrm{late}}$ and $H/r_{\max}$ for these three venues are presented along with the results for the 55 venues, see Section 5.1.

5. The 55 venues within Europe

The smaller halls in this survey are all dedicated pop & rock, while the larger venues are multi-functional and present famous musical acts as well as musicals, sports games, exhibitions etc. All halls were chosen from the same criterion: a large number of pop and rock concerts were being held there during the fall of 2010. 24 (44 %) of the 55 venues are regarded as small with a hall volume within 7,000 m^3, while 31 (56 %) are regarded as large with the largest volume being 600,000 m^3.

5.1. Results

Figure 2 shows the results for T_{30} versus hall volume for the small and large venues respectively. In Figure 2a) the results for the three Danish venues are indicated with shaded diamonds, as well as the extreme values of estimated G_{late} (G_l) within 125–2000 Hz for these venues. 54 % of the small venues are within the range of estimated G_{late} for the three Danish venues. For the large venues, estimated values of G_{late} are below –3 dB for 55 % of the venues.

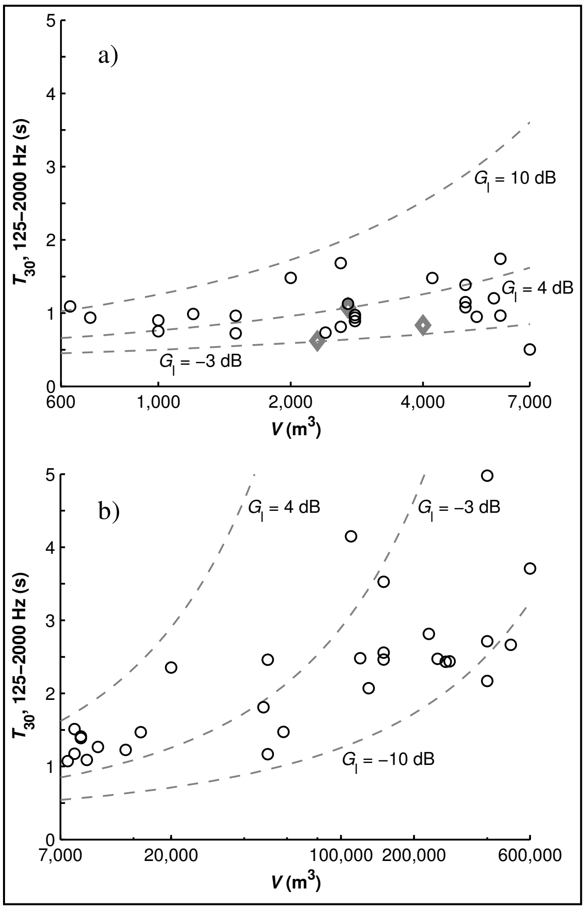

Figure 2: Calculated reverberation time (T_{30}) as a function of volume (V) of a) small and b) large venues.

Figure 3 shows the results for calculated bass ratio *BR*. The results for the small and large venues are given as circles and squares respectively. The range of *BR* for the three Danish venues is given as dashed lines in Figures 3–7. From Figure 3 we see that a significant portion (47 %) of the venues has higher values of *BR* compared to the three Danish venues. There is no dominance of either small or large venues for high values of *BR*. Four venues show low values of *BR*. These are all small venues.

Figure 4 shows the results for EDT/T_{30}. The resulting values are generally below 1 but there is no clear difference in the results for the small and large venues. The results for the three Danish venues are among the lowest values.

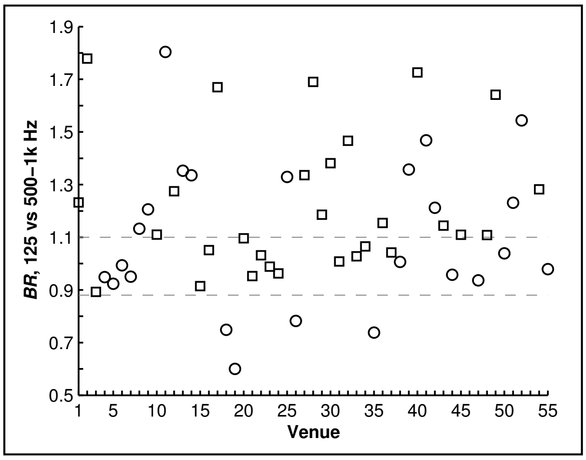

Figure 3: Calculated *BR* for the 55 venues.

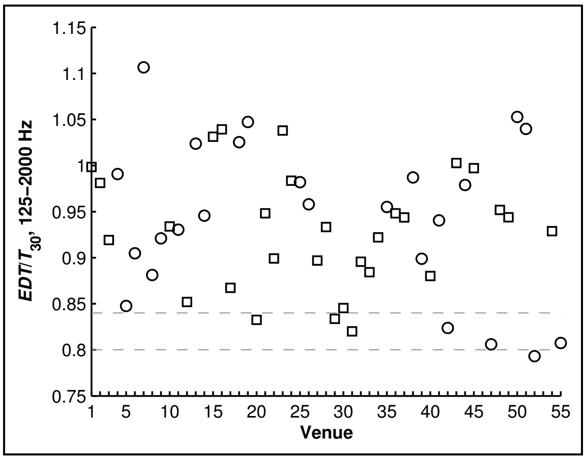

Figure 4: Calculated EDT/T_{30} for the 55 venues.

Figures 5 and 6 show the results for D_c/r_{max} and $G_{d,min} - G_{late}$ respectively. The results are similar for these two measures, but for D_c/r_{max} fewer venues have values below and more venues with values above the range for the three Danish venues. Low values of these two measures will indicate dominance of late reverberant sound within a larger portion of the audience area. Again there is no clear difference between small and large venues, except the small venues show the highest values for $G_{d,min} - G_{late}$.

Figure 7 shows the results for H/r_{max}. 27 (49 %) venues show results within the range of the three Danish venues. The lowest values are dominated by small venues.

Regarding correlations between the objective measures, measured T_{30} is highly correlated with the geometrical measures V, W, L and H (r = 0.75–0.77) and EDT (r = 0.99). $G_{\mathrm{d,min}} - G_{\mathrm{late}}$ is not highly correlated with any of the other objective measures apart from T_{30} and EDT (r = –0.47 to –0.49. G_{l} and $G_{\mathrm{d,min}} - G_{\mathrm{late}}$ is not highly correlated (r = –0.35), while D_c/r_{max} and $G_{\mathrm{d,min}} - G_{\mathrm{late}}$ are moderately correlated (r = 0,68). H/r_{max} is not highly correlated with any of the acoustic measures apart from H (r = 0.60). All correlations were significant at the 1 % level.

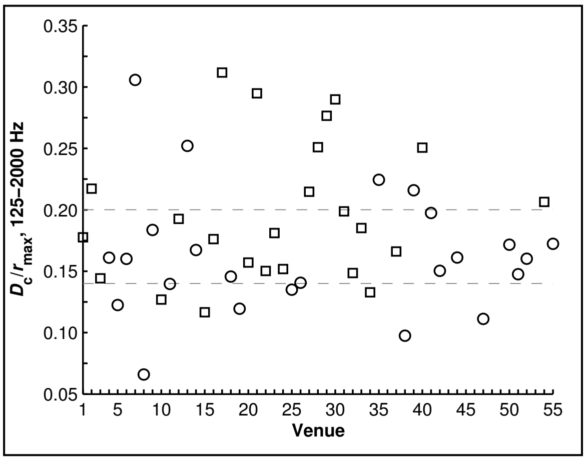

Figure 5: Estimated D_c/r_{max} for the 55 venues.

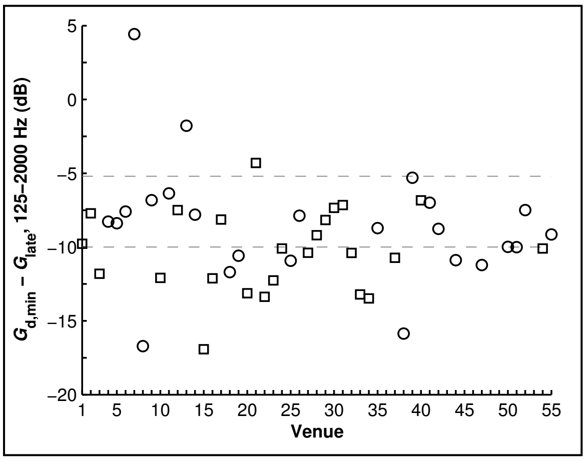

Figure 6: Estimated $G_{\mathrm{d,min}} - G_{\mathrm{late}}$ for the 55 venues.

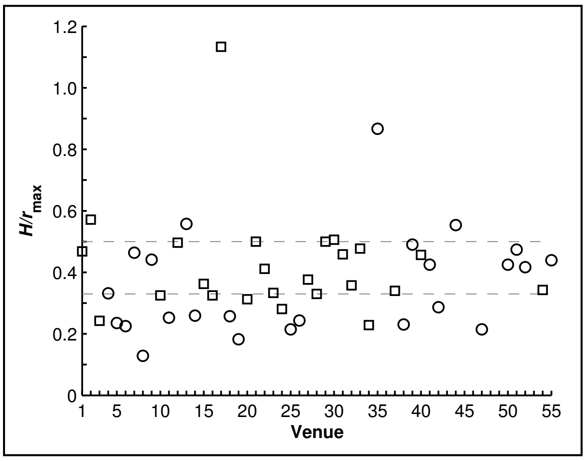

Figure 7: Calculated H/r_{max} for the 55 venues.

5.2. Discussion and conclusions

For all the objective measures there are significant variations for the venues studied. The variations within the three Danish venues are clearly smaller compared to the 55 venues. This observation may suggest that the objective measures studied can be used to discriminate between venues that are likely to suitable and less suitable for pop & rock concerts. The low correlations between the acoustic measures suggest that none of them are clearly redundant, though $G_{\mathrm{d,min}} - G_{\mathrm{late}}$ and D_c/r_{max} show similar but not highly correlated results.

A significant portion of the large venues show low values of G_{late}, but this may need to be seen in relation to direct sound levels assessed by D_c/r_{max} and $G_{\mathrm{d,min}} - G_{\mathrm{late}}$. Even a low level of G_{late} is likely to result in unsuitable conditions if the direct sound levels are low (for the large venues).

One 50,000 m^3 hall with a T_{30} of only 1.3 s was by sound engineers reported acoustically too dead, a lack of feeling of being enveloped in sound. All surfaces except floor are absorptive. In some very large arenas of 2–500,000 m^3 impressively low T_{30} around 2 s have been reached though higher at 125 Hz. Apparently the reverberation time can be too short for both small and large venues, but due to high values of r_{max} very low values of T_{30} may very well be preferable for the volumes above some 100,000 m^3. Even more precise speaker coverage is then necessary since there will be little reflected sound in non-direct sound areas. For volumes below approximately 100,000 m^3 and audience capacity below approximately 10,000 listeners, it appears appropriate with a somewhat airy and lively sound. In large arenas a colossal amount of chairs are permanently installed. If these seats are not upholstered the presence of an audience has an enormous impact on the reverberation time. Therefore, recommendations of acoustical measures for that type of venues could be with an occupied audience area.

The results for BR suggest that several venues have high values of T_{30} at 125 Hz that could represent a problem. A significant amount of the venues may also suffer from a too low ceiling compared to the maximum distance to a listener. Regarding EDT/T_{30} a majority of the venues have a value below 1. This can indicate that early reflections are not directed towards the listeners. This may be beneficial to avoid strong early reflections from the sound system.

As mentioned in Section 2, the reputation of how a venue sounds is not only dependent on beneficial acoustic conditions but also a sound system that suits the geometry and acoustics of the venue. Examples of critical aspects will here be point source versus line array, direct sound interference, directivity and delay zones. Some European arenas taking part in this survey consistently and independently reported how certain acts were sound-wise poor while other excellent partly because they set up their own PA systems.

We acousticians will never be in a position to ensure perfect PA coverage at every concert since that, as mentioned above, is not even in the hands of the arenas. But we can look further for substantial subjective data to find out if a venue can become acoustically not only too lively, but also too dead at mid and higher frequencies even in large halls and arenas. Acceptable range of T_{30} should in any case be used by the acoustician to achieve what acoustical environment is aimed for primarily by the hall owner who is in charge of the musical programme of the venue, or to support the architects in their design ideas for the venue.

6. New transportable, on/off low-frequency absorption product

From the basic idea presented in [2] two variable absorption products have been developed. Here is focused on the so called AqTube™ which enables an inexpensive way to achieve enough absorption variability when installed in the ceiling to make it possible to present both symphonic and rock concerts in the same venue. The product is extremely thin and light and can thus be installed for certain occasions or permanently for ON/OFF use.

The system builds upon the membrane absorption technique and consists of inflatable soft membranes. Table I shows measured absorption coefficient α when inflated. In the deflated state α is found to be close to 0 in all octave bands. The absorption coefficients were measured in the reverberation chamber at the Technical University of Denmark and by the Fraunhofer Institute in Stuttgart. From our knowledge that a low T_{30} at low frequencies is required for amplified music attaining a high alpha over a broad spectrum at lower frequencies has been one aim in the development of this embodiment of the absorber. The product can be custom made to fulfil certain absorption requirements. The one embodiment that was measured for this purpose was less than 1 mm thick, weighed less than 0.8 kg/m^2 and had a diameter when inflated of 80 cm and thus is 126 cm wide in its empty state. When active the air pressure of the system is constantly surveyed by a Programmable Logic Controller (PLC) to ensure maximum absorption at all times.

If single tubes are mounted side by side in the ceiling in a building of i.e. $30 \cdot 20 \cdot 10$ m with a T_{30} of 2 s then the 600 m^2 of the product will lead to a T_{30} at 125 Hz of 1 s when active with an absorption coefficient as shown of 0.8. The high frequencies are diffused by the convex shape of the cylindrical product and with i.e. a woollen curtain drawn on the rear wall opposite the stage suitable conditions for pop and rock concerts and rehearsals are obtained. A lowered acoustically transparent ceiling can be mounted underneath the absorbers. This of course may include attachment of lighting, ventilation, fire sprinklers etc. The material is flame retardant and maybe other safety precautions must be taken before incorporating the system. It is the hope that the product will be used in favour of amplified as well as classical music in many applications from music schools, recital halls, arts performance centres, multi-purpose halls etc. The technology is patented.

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Table I: Measured absorption coefficients for AqTube™ in the “ON” and “OFF” positions respectively.

f [Hz]	63	125	250	500	1k	2k	4k		f [Hz]	63	125	250	500	1k	2k	4k
α ON	0.2	0.8	0.8	0.9	0.6	0.3	0.3		α OFF	0.0	0.0	0.1	0.1	0.2	0.2	0.2