Balancing sound strength and reverberation time in small concert halls by means of variable acoustics

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Sound strength G is a measure of the physical sound level in a concert hall and is closely related to the subjective sensation of loudness. It has been measured in six small concert halls in Cambridge, UK, in combination with measurements of reverberation time. The aim is to investigate the relationship between sound strength and reverberation time in small halls and to study the effect of variable acoustics in these halls. Large ensembles in small halls are often too loud and it is desirable to reduce the sound level. This can be done by introducing acoustically absorbent material but the reverberation time is also decreased. Reverberation time cannot be decreased by an arbitrary amount as it is closely related to sound quality. Therefore, reverberation time and strength have to be carefully balanced in order to maintain sufficient reverberance whilst at the same time avoiding excessive loudness. The study also compares measured strength levels with values derived from traditional and revised theories for strength calculations [1]. Measured strength levels were consistently lower than theoretical predictions and possible reasons for this are discussed with reference to design features of the halls and objective acoustics parameters.

1. INTRODUCTION

Many small concert halls are being built in music departments in schools and universities and these have to cater for a wide variety of musical ensembles ranging from orchestras to solo performers. Such diverse musical forces require different acoustic conditions in terms of reverberation time and loudness and so variable acoustics are frequently provided, usually in the form of moveable acoustically absorbing drapes or panels [2]. However, introducing absorption decreases both reverberation time and sound strength so that a careful balance needs to be struck between controlling loudness and maintaining sufficient reverberation.

To determine the range of reverberation times and sound strengths in small concert halls, including changes due to variable absorption, measurements were carried out in six halls in Cambridge, UK. The halls accommodate a range of sizes of musical ensembles from quartets to orchestras. Details of the halls are given in Table 1.

2. MEASUREMENT METHODOLOGY

All measurements have been carried out by following the principles described in "ISO 3382, Acoustics – Measurement of the reverberation time of rooms with reference to other acoustical parameters" [3]. All strength levels and reverberation times have been measured in octave bands. Additionally, mid-frequency parameters have been calculated as the mean of the 500 Hz and 1 kHz octave band levels. The

Table 1. Data for the measured concert halls

Hall	Volume m^3	Seats	Volume/Seat m^3	$RT_{mid, unocc}$ sec
1) Fitzwilliam College Auditorium	2047	250	8.2	1.3 - 1.5
2) Faculty of Music Auditorium	4100	496	8.3	1.7
3) Faculty of Music Recital Room	990	0*	-	0.8 - 1.4
4) Queen's Building Auditorium	1200	130	9.2	1.1
5) Perse Music School Auditorium	1165	90*	12.9	1.0 - 1.8
6) Leys Music School Auditorium	850	48*	17.7	1.1 - 1.5

* indicates halls with loose seating, the given number corresponds to the number of seats set up for the measurements

measurement results for each receiver position were averaged over two or three measurements.

All halls were measured unoccupied with the dodecahedron loudspeaker set up at the centre of the stage area. For each hall a representative sample of 4 to 5 receiver positions was chosen covering the typical range of distances between audience and performers in the considered halls. Halls 1, 3, 5 and 6 were measured for both extreme settings of the variable acoustics supplied in these halls in order to assess the whole range in which reverberation time and sound strength can be adjusted. Halls 2 and 4 were only measured in one condition.

Further details of the measurement methodology are given in the appendix at the end of the paper.

3. MEASUREMENT RESULTS

3.1 FITZWILLIAM COLLEGE AUDITORIUM, CAMBRIDGE

Brief Description of the Concert Hall

The Fitzwilliam College Auditorium (see Figure 1), built in 2004, has a seating capacity of 250 seats and has been designed for a wide range of purposes including musical concerts, drama productions, dance performances, conferences and exhibitions. In order to account for the different acoustic requirements, acoustically absorbing panels can be flipped out on the upper side walls of the auditorium to reduce reverberation time. Another feature of the hall is that the medium upholstery seating is mounted on a raked bleacher system and can be retracted when a flat floor is required. The geometry of the hall is based on a simple rectangular 'shoebox'. The inner surfaces are predominantly hard and reflective, such as concrete and brickwork, in order to provide sufficient reverberation throughout the sound spectrum.

Figure 1. Fitzwilliam College auditorium

Measurement Results

As can be seen in Figure 2 (a) a drop of about *0.2* sec in reverberation time can be achieved for mid and high frequency bands by flipping open the absorption panels. Due to the limited thickness of the absorbing material the panels do not considerably affect the reverberation times in the *63* Hz and *125* Hz octave bands. The unoccupied mid-frequency reverberation time in the auditorium can be adjusted in a range between *1.3* and *1.5* sec, which is appropriate for the various uses of the hall ranging from speech to chamber music performances. The strength measurements in Figure 2 (a) show similar results. Low frequency strength is hardly affected by the panels, whereas mid and high frequency strength goes down by

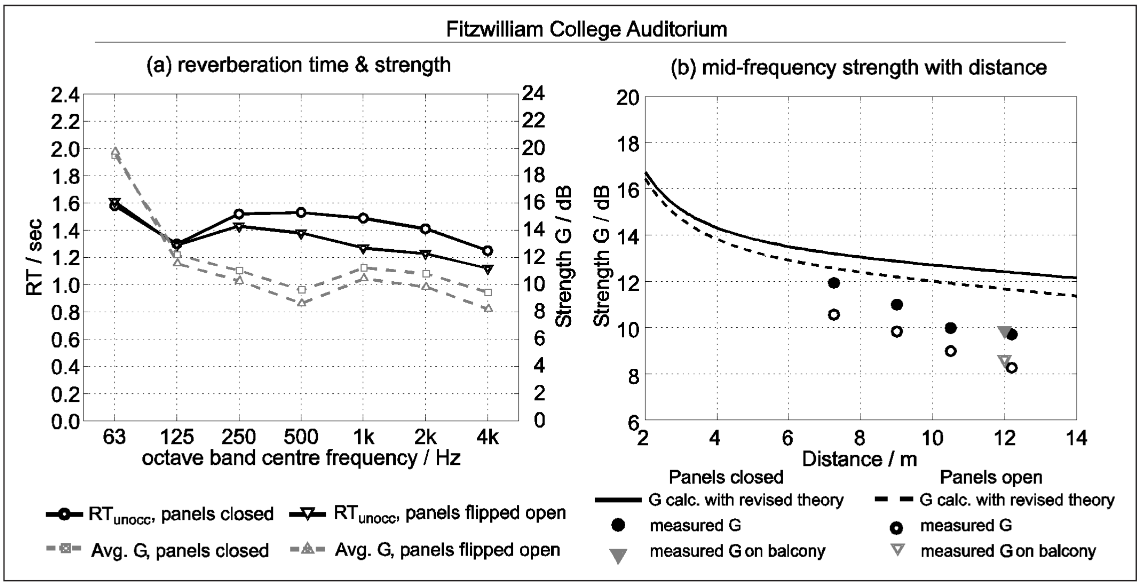

Figure 2. Fitzwilliam College auditorium:
(a) Average unoccupied octave band RT and strength for open and closed panels
(b) Comparison of calculated and measured mid-frequency strength

approximately 1 dB with panels flipped out.

Figure 2 (b) shows the measured and calculated distance-dependency of mid-frequency strength levels in the hall. Estimated strength curves are calculated using Barron's revised theory. A detailed discussion of the results presented in this figure as well as in the corresponding figures for the other measured halls will be given in section 5.

3.2 FACULTY OF MUSIC AUDITORIUM, WEST ROAD CONCERT HALL, CAMBRIDGE

Brief Description of the Concert Hall

The Cambridge University Faculty of Music Auditorium has a capacity of 496 seats and hosts a wide variety of events, encompassing classical music, opera, world music, jazz and more. The form of the concert hall is basically rectangular in plan with a raked, medium upholstered seating area and additional 'boxes' in stepped side galleries. A heavy curtain on the back wall of the stage can be used for slight adjustments of reverberation time in the auditorium. With a volume of 4100 m^3 the auditorium was the biggest to be measured in this study. Most of the inner surfaces in the auditorium are brickwork to maintain sufficient reverberation in the hall. In order to maximize internal volume for acoustic purposes lighting and ventilation ducting are contained within the ceiling space of the hall. A grill shaped structure made of plywood is used to obscure the ducts and technical equipment in the ceiling (see Figure 3).

Figure 3. Faculty of Music Auditorium, West Road Concert Hall

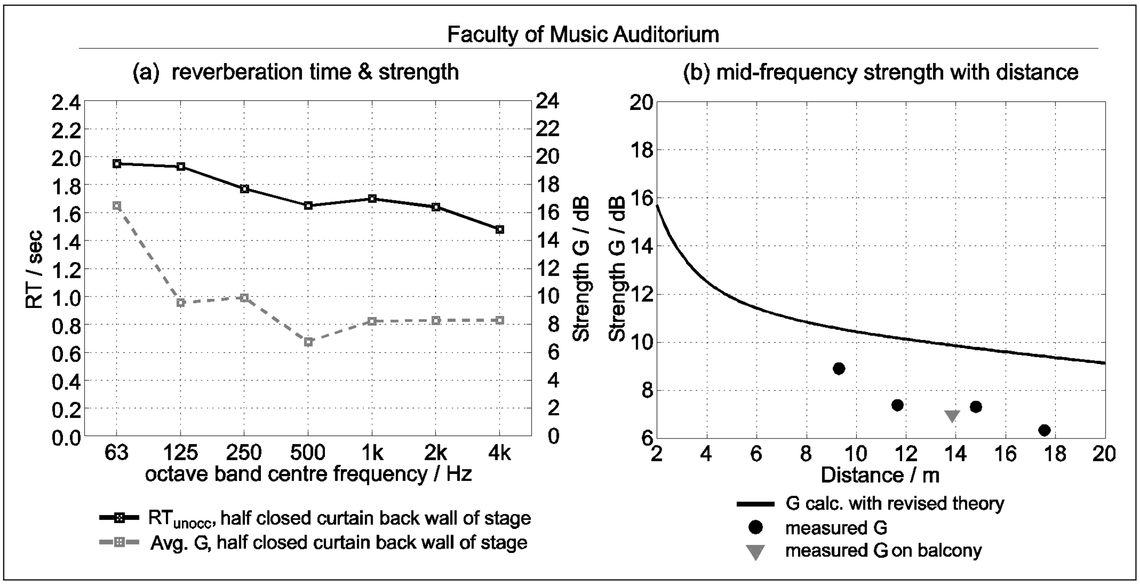

Figure 4: Faculty of Music Auditorium:
(a) Average unoccupied octave band RT and strength
(b) Comparison of calculated and measured mid-frequency strength

Measurement Results

Measurements have been carried out with a half closed curtain at the back wall of the stage. The measured average reverberation times and strength levels in octave bands are shown in Figure 4 (a). With an unoccupied reverberation time for the mid frequencies of about 1.7 seconds, the Auditorium has a longer reverberation time compared to other concert halls of similar size. The measured relation between strength and distance in Figure 4 (b) reveals that the first measurement position in the 5th row is still influenced by the direct sound from the stage and thus strength is about 2 dB higher than for the other measurement positions. The measured strength on the balcony position shows a slightly decreased level compared to the results obtained in the main seating area, which is believed to be due to a reduced number of reflections reaching the receiver on the balcony position.

3.3 FACULTY OF MUSIC RECITAL ROOM, WEST ROAD, CAMBRIDGE

Brief description of the concert hall

The recital room of the Cambridge Faculty of Music is a versatile space seating up to approximately 100 people. The room is flat floored with a rectangular floorplan. Acoustic curtains all around the side walls can be used to adjust reverberation in a wide range thus making the space suitable for smaller concerts and recitals, as well as for workshops or rehearsals. Slightly curved wooden panels hang from the pitched ceiling in order to enhance diffusion in the space. In addition three wooden diffusing screens of about 6 m^2 are mounted on the side walls of the hall in order to provide diffusion in the vertical dimension. Furthermore the bunched curtains can be hidden behind the screens to minimize the absorptive surface in the space (see Figure 5). Although the Recital Room is very close to the Concert Hall it is acoustically isolated from the Concert Hall and it is therefore possible for events to occur in both simultaneously.

Measurement results

During the measurements the seating was stacked up on a rack at the side of the room. Besides the seating rack only a grand piano and some tables were present. The source position was chosen to be a likely position for musicians in a

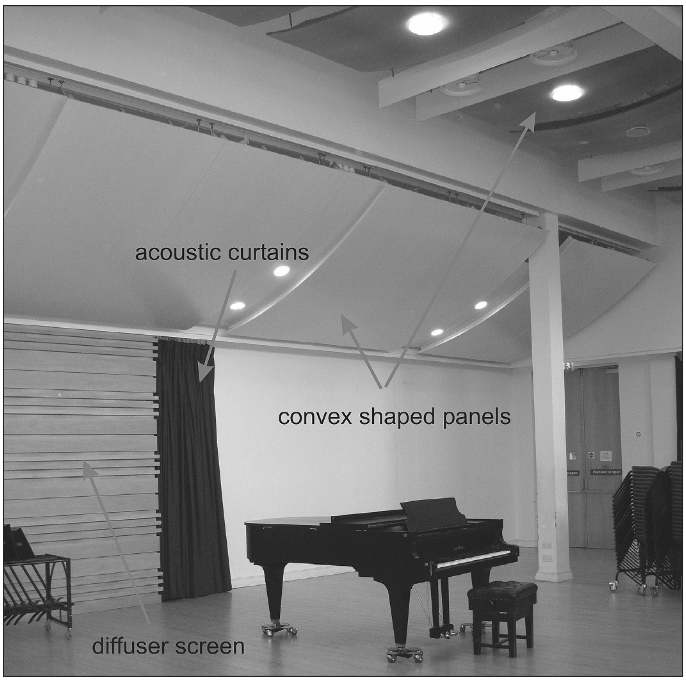

Figure 5. Faculty of Music Recital Room

concert situation and the receiver positions were chosen to cover the typical distance range for an audience in this auditorium.

The comparison of the measurements in Figure 6 (a) with open and closed curtains shows the wide range in which reverberation time and strength can be adjusted in this space. The reverberation time curve shows a broad maximum for the 1 kHz, 2 kHz and the 4 kHz octave bands when the curtains are hidden behind the diffuser panels. Although this may be heard as brilliant tone in the unoccupied hall, this maximum will be attenuated when the lightly upholstered seating is set up and occupied. The measured strength levels with distance in Figure 6 (b) show good agreement with the predicted levels according to revised theory, especially when the absorbing curtains are bunched and hidden behind the diffusing panels.

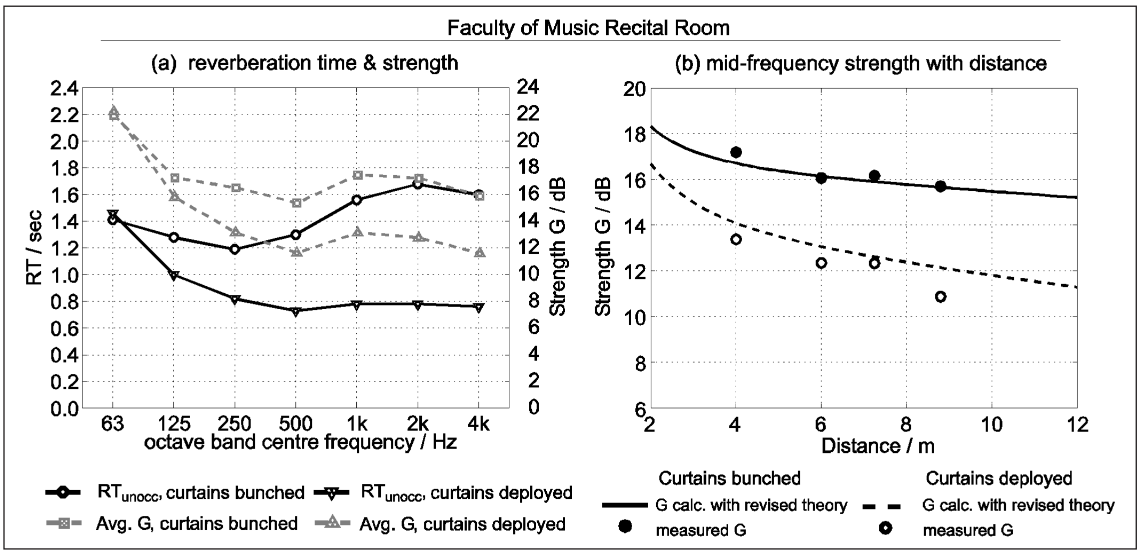

Figure 6. Faculty of Music Recital Room:

(a) Average unocc. octave band RT and strength for bunched and deployed curtains

(b) Comparison of calculated and measured mid-frequency strength

Figure 7. Queen's Building Auditorium with cylindrical stage wall and acoustic curtains

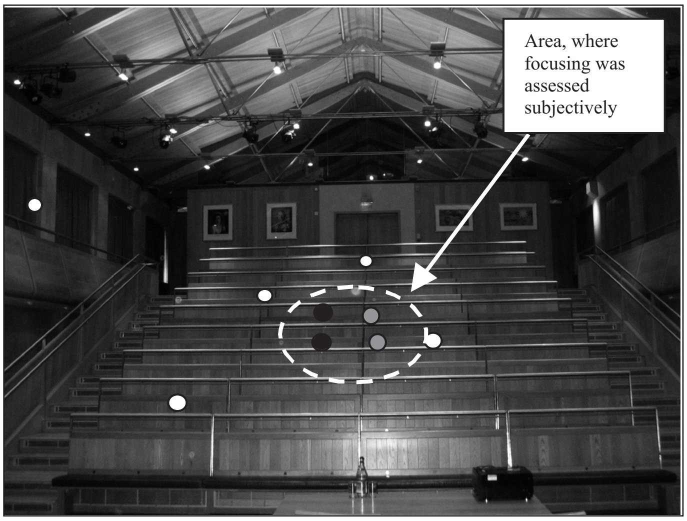

Figure 8. Receiver Positions in the Queen's Building. Black spots indicate where strong focusing was measured and grey spots indicate light focusing. The white dots show measurement positions where no significant focusing was measured

3.4 QUEEN'S BUILDING EMMANUEL COLLEGE, CAMBRIDGE

Brief description of the concert hall

The recital hall in the Queen's Building in Cambridge has a capacity of 108 seats on a raked seating area plus about 20 additional seats on a gallery which runs all around the concert hall. The floorplan of the hall is basically a rectangle with an adjacent half circle, which forms the stage area. The geometry of the roof above the curved stage area is therefore a half cone which transforms into a double pitched roof above the seating area. Around the curved back of the stage moveable acoustic curtains hang at one metre distance from the hard and reflective back wall of the stage. For acoustic reasons all windows on the balcony can be obscured with heavy curtains. The seating in the auditorium consists of wooden benches with leather covered padded seats (see Figure 8) which provide minimal acoustic absorption. A moderate unoccupied reverberation time was expected due to the large window surfaces covered with heavy curtains on the balcony and the curtains at the back of the stage. Taking into account the curved stage wall and the ceiling above the stage, noticeable focusing effects were expected in the seating area.

Measurement Results

The measurements in the Queen's Building Auditorium were carried out with a configuration of the curtains as seen in Figure 7. All the windows on the balconies were covered with curtains and the curtains at the back of the stage were also partly closed. Special attention was given to the possible focusing effect in the hall. A subjective assessment of the focusing effect using a pink noise source on stage showed that a considerable rise in subjective loudness could be heard across the centre seats of the raked seating area. This area is also marked in Figure 8. Additional strength measurements were carried out in this area to get a quantitative measure of the effect.

Despite the leather-upholstered benches in the auditorium, the measured mid-frequency reverberation time of 1.1 sec is rather low due to the large area of absorbing curtains. The reverberation time characteristic with

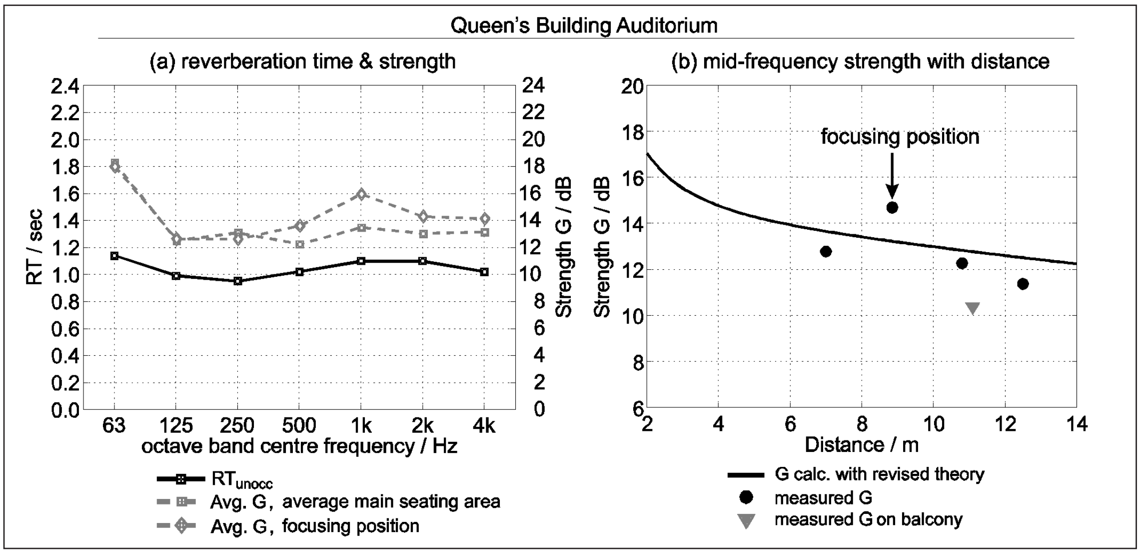

Figure 9. Queen's Building Auditorium:
(a) Average unocc. octave band RT, strength and strength in focusing position
(b) Comparison of calculated and measured mid-frequency strength

frequency is given in Figure 9(a), which also shows the strength characteristic for the main seating area (excluding the focusing position) and in the focusing position. Strong focusing was observed in the measurement positions in the centre of the seating area which corresponds well with the subjectively observed focusing area. Measurements in positions only a few seats around positions with strong focusing did not show a significant rise in strength compared to the other measurement positions, which were clearly outside the focusing area. This indicates that the focusing appears to be very sharp and that the exact position of the focusing is strongly dependent on the source position. This is undesirable considering a group of several musicians playing on the stage. The different instruments would focus to different positions in the audience, thus giving a different hearing sensation of the ensemble depending on the seat position in the audience. Figure 9(a) shows that focusing is mainly observed in the mid-frequencies. The results in Figure 9(b) also point out the special characteristics of the focusing position.

3.5 THE PERSE MUSIC SCHOOL AUDITORIUM, CAMBRIDGE

Brief description of the concert hall

The Perse Music School Auditorium is a typical shoebox-shaped recital hall with a pitched roof and a flat floor. Taking into account that the hall is a school facility which has to serve multiple musical purposes ranging from rehearsals and concerts of very differently sized ensembles, the hall has been designed to supply variable acoustics and seating, which is lightly upholstered. As can be seen in Figure 10 heavy acoustic curtains can be deployed all along the sidewalls to decrease reverberation if desired. Large scale wooden diffusers are mounted on the sidewalls to increase the diffusion of the sound field.

Measurement Results

A rectangular seating area of 90 seats was set up for the measurements. Besides the seating, a considerable number of musical instruments such as a grand piano, several kettle- and bass-drums as well as some xylophones were present during the measurements. As can be seen in Figure 11 (a) a

Figure 10. The Perse Music School Auditorium

considerable decrease in reverberation time of about 0.7 sec can be achieved by closing all the curtains in the hall, which is mainly due to the large surface area of the curtains covering almost the entire side wall surfaces of the space. The strong rise of reverberation time in the lower frequencies and the steady decreasing slope at the higher frequencies are believed to encourage a warm tone in the auditorium. The analysis of the strength measurements also shows the big influence of the curtains on the sound level in the auditorium. The average strength level can be attenuated by 2.5 to 3 dB throughout the spectrum. In contrast to the acoustic drapes in the Faculty of Music Recital Room and the absorbing panels in the Fitzwilliam College Auditorium, an attenuation of strength is also achieved for the low frequency bands, due to the comparatively thicker curtains.

3.6 THE LEYS MUSIC SCHOOL AUDITORIUM, CAMBRIDGE

Brief description of the concert hall

The Leys Music School Auditorium was built between 2004 and 2005 and serves as the main recital and rehearsal hall of the Leys Music School in Cambridge.

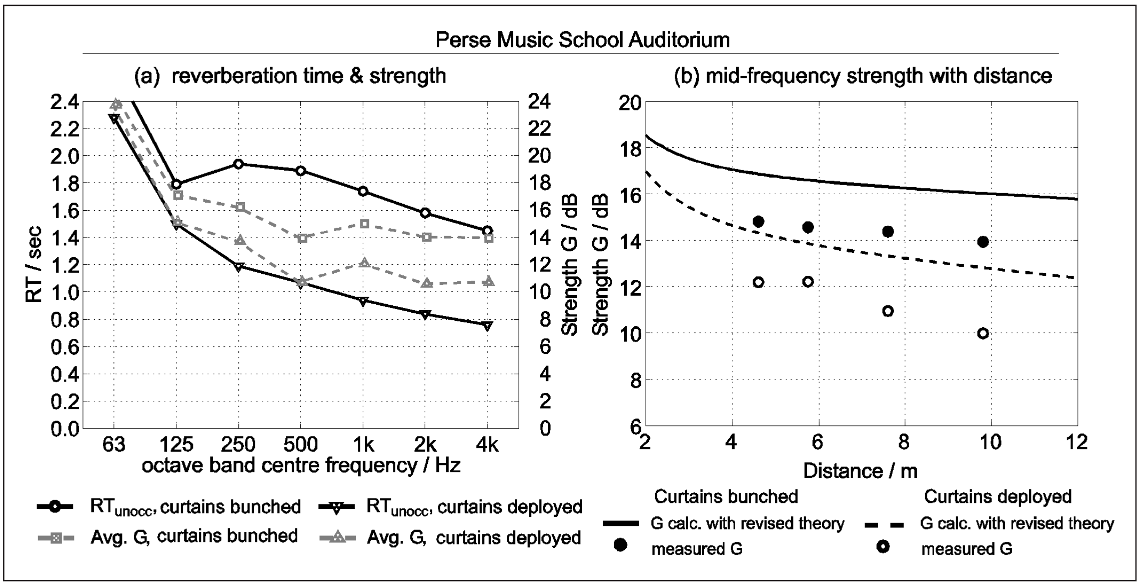

Figure 11. Perse School Auditorium:
(a) Average unocc. octave band RT and strength for bunched and deployed curtains
(b) Comparison of calculated and measured mid-frequency strength

Figure 12. The Leys Music School Auditorium

The room is flat floored with a rectangular floorplan and a pitched roof. On the stage side of the hall, an approximately 1 m deep bay with a glazed façade of about 12 m^2 provides natural lighting (see Figure 12). On the opposite side of this glazed façade a small balcony stretches along the back wall of the auditorium. All around the sidewalls and in front of the glazed façade acoustic drapes can be deployed to adjust reverberation time and strength in the hall. In order to enhance diffusion in the space when the curtains are bunched the side walls have been designed in a gentle zigzag shape. Due to its use as both a concert and rehearsal space, the hall has loose, lightly upholstered seating . It should also be mentioned that the position of the performing area in the hall might also vary according to different preferences of the musicians.

Measurement results

48 seats were set up in five slightly curved rows facing the bay with the glazed façade. The source position was chosen about 3 metres in front of the glazed façade. The curtains in front of the glazed façade were kept closed all the time to cancel very early reflections that could cause comb filtering effects.

The results in Figure 13 (a) show a mid-frequency reverberation time for unoccupied seating ranging from 1.5 sec for open curtains to 1.1 sec for closed curtains and a drop of about 2 dB in strength between the two configurations. Looking at strength as a function of source-receiver-distance it can be seen that the 4th measurement position (shown arrowed in Figure 13 (b)), which was in the last row close to the balcony at the rear of the hall, seems to slightly stick out of the measurement results both for open and closed curtains. The increased strength levels in this position are considered to be due to reflections from the under side of the balcony at the rear of the hall.

4. COMPARISON OF REVERBERATION TIME CHARACTERISTICS

Taking into account that most of the measured halls have variable acoustics which allows their characteristics to be changed considerably, the discussion of the reverberation times for the measured halls has to be done separately

[1]Since most of the wall surfaces in hall 2 are hard and reflective, results for hall 2 are plotted in Figure 14 (a). Results for hall 4 are plotted in Figure 14(b) due to the large areas that were covered with acoustic curtains during the measurement.

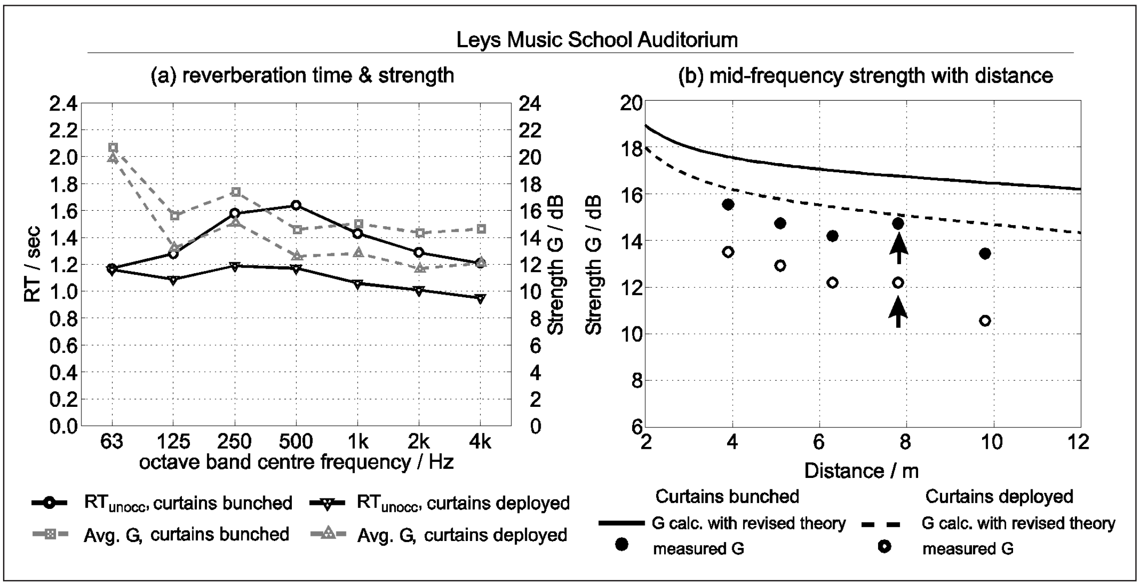

Figure 13. Leys Music School Auditorium:
(a) Average unocc. octave band RT and strength for bunched and deployed curtains
(b) Comparison of calculated and measured mid-frequency strength

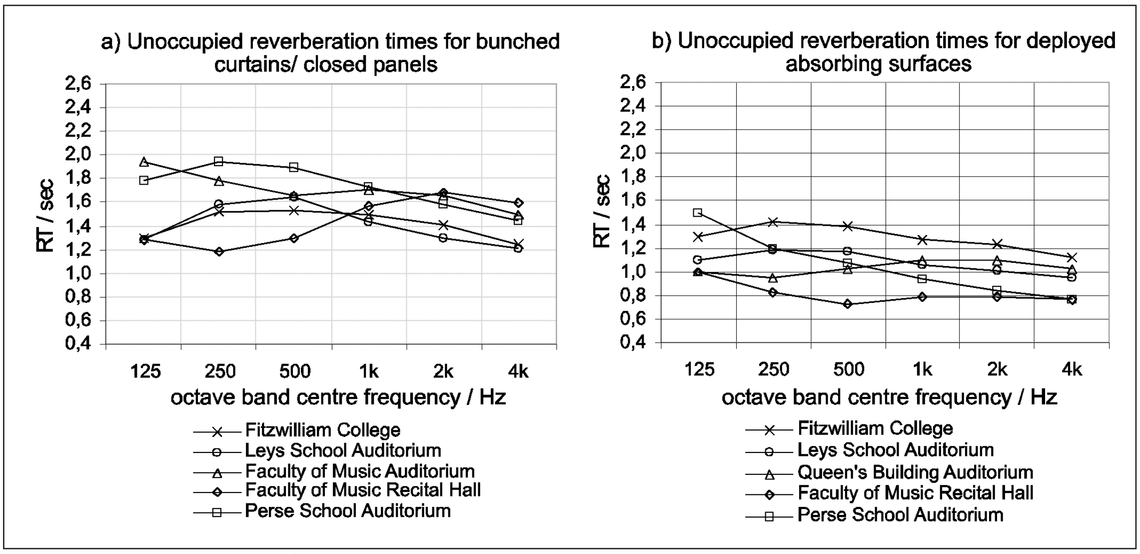

Figure 14: Comparison of the RT characteristics with frequency for unoccupied conditions

for open and closed acoustic curtains/panels. Figure 14 (a) shows a comparison of the measurement results for unoccupied seating obtained for bunched curtains/ closed panels, whereas Figure 14 (b) shows the results obtained with deployed absorbing surfaces (1). Since the measured auditoria can be roughly classified as chamber music halls, their reverberation time characteristics have to be interpreted on the basis of the acoustic requirements of these spaces.

With mid-frequency reverberation times for unoccupied conditions in a range from 0.8 to 1.7 seconds, the reverberant conditions vary considerably between the measured halls and curtain configurations. Figure 15 shows calculated reverberation times for occupied conditions. The calculations were carried out using average absorption and seating surface data which was taken from a large database containing absorption data for occupied and unoccupied seating. The occupied reverberation times can be compared to the recommended occupied values given by Barron [4], which are

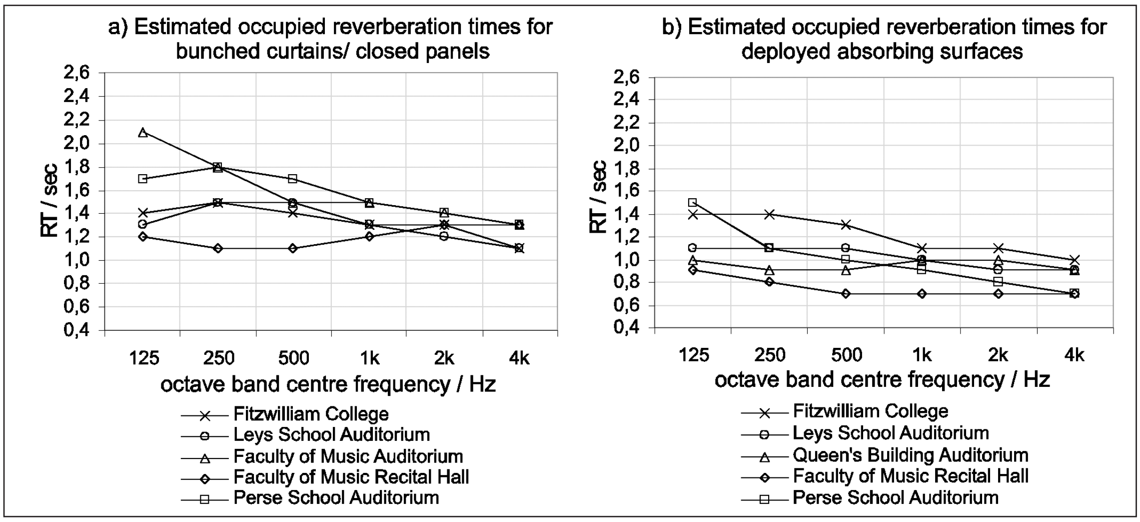

Figure 15. Comparison of the estimated RT characteristics with frequency for occupied conditions

presented in Table 2. It can be seen, that appropriate mid-frequency reverberation times for chamber music can be obtained in most of the halls when the acoustic curtains/panels are not deployed. Reverberation times measured with deployed absorbing surfaces appear appropriate for drama theatre or speech. However, excessive loudness may become a critical issue in small recital halls when the acoustic surfaces are not deployed. Considering for example a rehearsal of an orchestra in such a hall, it is not possible to reduce the sound strength in the hall whilst at the same time maintaining high reverberation. Although this problem can obviously be solved with larger volumes, these measures are often considered unpopular due to cost. Therefore the reverberation time in small halls has to be balanced against the total sound level depending on the size and the instrumentation of the orchestra. In small halls it might not always be possible to meet Barron's recommendations for chamber music whilst at the same time avoiding excessive loudness. Consequently, sound strength, which is closely related to the subjective sensation of loudness, has to be considered as an important design factor for small concert halls.

On the basis of the spectral characteristics of reverberation time, the acoustics of the measured halls can be roughly classified into two different categories according to Hidaka and Nishihara [5] (2). Firstly the 'traditional' category with a strong rise in reverberation time towards the lower frequencies and a steady decreasing slope at the higher frequencies and secondly the 'modern' category with a well balanced RT over a large frequency range which extends well into the higher frequency range. In contrast to the recommendations regarding frequency variation of the reverberation time for larger music halls, which correspond to the 'traditional' category, the rather flat frequency characteristic in the bass is regarded a desirable feature for contemporary chamber music halls by some designers. According to Meyer [6] the flat frequency characteristic in the bass helps to enhance intimacy and inclusion, by supporting a more direct sound in the lowest range of the cello and double bass.

Except for halls 2 and 5 which show rather 'traditional' frequency characteristics, the measured halls show

[2]In their paper of 2004 Hidaka and Nishihara compared the reverberation time characteristics of modern Japanese and traditional European chamber music halls and found that the modern Japanese halls only have a very small rise in reverberation time towards the lower frequencies, whereas most of the traditional European halls have a rather strong rise towards the lower frequencies.

mostly a 'modern' characteristic with a well balanced reverberation time over a wide frequency range. Although a subjective assessment of the sound quality of the halls has not been conducted, the 'traditional' characteristic is considered to encourage a warm and enveloping sound, due to the bass enhancement, whereas the 'modern' characteristic is believed to provide improved intimacy with a more brilliant tone.

Table 2. Recommended occupied mid-frequency reverberation times in seconds by Barron [4]

Organ music	>2.5
Romantic classical music	1.8 – 2.2
Early classical music	1.6 – 1.8
Opera	1.3 – 1.8
Chamber music	1.4 – 1.7
Drama theatre	0.7 – 1.0

5. LOUDNESS AND SOUND STRENGTH IN THE MEASURED HALLS

In the past thirty years a substantial number of publications have dealt with subjective loudness and total sound level in large concert halls. A review of this work can be found in [8]. While many of these contributions deal with the problem of supplying sufficiently high sound levels to the back seats and balconies of large halls, the present study investigates possible issues of excessive loudness in small concert halls. Since perceived loudness was found to be strongly correlated to sound strength by Lehmann and Wilkens [9] and also by Barron [1], we will relate to the physical measure of sound strength when investigating aspects related to loudness in the measured halls, although this can obviously not cover all relevant aspects.

Since sound strength is considered an important design factor in the very early stages of concert hall design a reliable prediction formula is needed to estimate sound strength as a function of other fundamental design parameters. The revised theory on sound strength calculations presented by Barron and Lee in 1988 [1], which has now been widely accepted, provides such a formula and determines sound strength as a function of reverberation time, volume and source-receiver distance. However, observed differences for measured and predicted strength levels in the discussed halls (see Figures in section 3) indicate that additional design features also have a significant impact on sound strength in these spaces. A very difficult but interesting task therefore consists in specifying suitable measured acoustic quantities which can be related to the differences between measured and predicted strength levels.

5.1 REVISED THEORY ON SOUND STRENGTH CALCULATIONS

Before taking a closer look at the measured strength levels and the observed differences between measurement and prediction, a brief review of revised theory on sound strength and its limitations will be given.

According to traditional theory [(3)] it is assumed that the energy of the reflected sound is equally distributed throughout the space. However, as was shown by extensive measurements by Barron and Lee [1] total reflected sound energy does significantly fall off with increasing source-receiver distance. This is due to the fact that listeners closer to the source not only receive a higher level of direct sound but also higher levels of early reflections because they have travelled shorter distances. In their paper of 1988 Barron and Lee therefore propose their "revised theory of sound decay in concert spaces", which accounts for these facts. The corresponding formula is given as

[3]The traditional sound strength formula is given by $G_{trad} = 10 \cdot \log_{10}(100/r^2 + 31200 \cdot RT/V)$

follows:

$$G = 10 \cdot \log_{10}(100/r^2 + 31200 \cdot RT/V \cdot \exp(-0.04 \cdot r/RT)), \quad (3)$$

where r is the source receiver distance, RT the reverberation time and V the volume of the space. The exponential term accounts for the fact that the linearly decaying reflected sound, which is assumed to have a uniform instantaneous level at late time, cannot start before the arrival time of the direct sound .

Although applying revised theory to concert halls markedly improves the prediction quality compared to traditional theory, the theory still has obvious limitations that have been widely discussed by Barron [10], [8] and other authors, for example [11]. Firstly there has been some discussion about the appropriate starting time t_0 of the diffuse sound decay. In his paper of 1995 Vorländer [11] suggests that the integration should not start at the arrival time of the direct sound but at the arrival time of the first order reflections. A reasonable assumption for the starting time of the integration is therefore the direct sound delay plus the delay of the first order reflections (known by Beranek [12] as the initial time delay gap "ITDG"). Barron [8] acknowledges that considering the ITDG might be beneficial, but points out that this would require a consideration of the shape and geometry of the hall and the exact source and receiver position. In addition he makes clear that irrespective of the choice of t_0 precise agreement from a theory like this can generally not be expected since using continuous integration of the energy fractions of the reflected sound can obviously not account for the discrete character of the early reflections.

Other possible reasons for observed differences between measured and predicted strength levels relate to the state of diffusion in a concert hall. Revised theory assumes a sound decay with a constant decay rate from time t_0 which is given as a function of RT. The assumption of a uniform linear decay is generally based on the prerequisites of a regular shape and geometry of a space as well as fairly equally distributed absorption. As Barron [10] has shown, measurement results in concert auditoria partly show considerable variations from this behaviour especially for the early decay curve, which results in differences between measured EDT and RT values. Among possible reasons for this the most striking is that auditoria are generally not diffuse spaces with equally distributed absorption. The absorbing material in auditoria is mostly concentrated in the seat area at least when additional/variable absorption is not deployed. Cremer and Müller [13] as well as Kuttruff and Strassen [14] have found that this can lead to so called "sagging" (concave) reverberation curves if the side walls do not provide sufficient diffusion in the vertical dimension.

5.2 DISCUSSION OF MEASURED STRENGTH LEVELS AND CORRELATION WITH OTHER PARAMETERS

As can be seen in Table 3 average strength levels in the measured halls vary in a wide range between 7 and 15 dB. For most of these halls adjustments of the strength levels in a range from 1 to 3 dB can be achieved by the use of variable absorption. This seems particularly useful for these halls considering their multipurpose use ranging from solo and small ensemble performances where high strength levels are desirable to medium and large orchestral rehearsals and even concerts where the total sound level needs to be attenuated to an acceptable level. However, as was already mentioned before, the attenuation of sound

Table 3. Comparison of measured and calculated mid-frequency strength levels for average source-receiver distances in dB. Hall numbers refer to Table 1
$\bar{r}$ indicates typical source-receiver distance in the main seating area of each hall.
r_H is reverberation radius and is the average strength level measured in the main seating area.
(* focusing position was omitted when calculating average measured strength)

Hall	variable acoustics	r_H m	$\bar{r}$ m	RT_{unocc} sec	$\bar{G}_{meas}$ dB	$G_{trad}(\bar{r})$ dB	$G_{rev}(\bar{r})$ dB
1)	panels open	2.2	10.6	1.3	9.0	13.2	11.8
1)	panels closed	2.1	10.6	1.5	10.2	13.8	12.6
2)	–	2.8	14.7	1.7	7.0	11.3	9.8
3)	curtains deployed	2.0	7.4	0.8	11.8	14.3	12.8
3)	curtains bunched	1.4	7.4	1.4	16.0	16.6	15.7
4)	–	1.9	10.1	1.1	12.1*	14.7	13.2
5)	curtains deployed	1.9	7.7	1.0	11.1	14.5	13.3
5)	curtains bunched	1.5	7.7	1.8	14.3	17.0	16.3
6)	curtains deployed	1.6	6.4	1.1	12.4	16.3	15.4
6)	curtains bunched	1.4	6.4	1.5	14.6	17.6	16.9

strength is generally achieved at the cost of a decreased reverberation time.

As can be seen from the previous equations both traditional and revised theory on strength calculations predict strong correlation between sound strength in a concert hall and the ratio of its reverberation time and volume. Figure 16 shows averaged measured and predicted mid-frequency strength levels in the main seating area of each hall for the different settings of variable absorption and corrected for direct sound [4] as a function of RT/V. The regression line shown in Figure 16 is based on the least squares approximation of the following simple model:

$$G_{reflected} = 10 \cdot \log_{10}((31200RT/V) \cdot \mathrm{b}) = 10 \cdot \log_{10}(31200RT/\mathbf{V}) + \hat{b} \qquad (5)$$

A generally good agreement is found between the regression model and the actually measured average levels for the halls with a correlation coefficient equal to r = 0.94, $\hat{b}$ = –3.3 dB and a standard deviation of the error of 1.1 dB. It is interesting to note that we would expect $\hat{b}$ to equal 0 dB for traditional theory to apply and $\hat{b} \approx -1.25$ dB for revised theory, respectively. This is also indicated by the additional curves in Figure 16 which show total reflected sound according to traditional and revised theory.

Concluding the results from Figure 16 and Table 3 it can be observed that traditional theory overpredicts the average measured levels by about 3.3 dB, mainly due to the fact that the decrease of the reflected sound energy with increasing distance is not considered. Considering that doubling the size of an orchestra results in a level change like that, this cannot be seen as satisfactory. While revised theory improves the prediction accuracy for the measured halls and generally captures the decreasing tendency of sound strength with increasing source receiver distance very well, see Figures in section 3, an average overprediction of about 2 dB for the total sound levels remains for the measured halls [5].

[4] $G_{reflected}$ is calculated from the strength levels as $G_{reflected} = 10 \cdot \log_{10}(10^{(\bar{G}_{meas}/10)} - \frac{100}{\bar{r}2})$.
$\bar{G}_{meas}$ refers to average measured strength levels calculated from the receiver positions in the main seating area of each hall. Receiver positions close to the source (within two times of the reverberation radius) as well as balcony positions and positions at the very back of a hall are omitted.

[5] For discussion of possible bias of the measurement results see appendix

Possible reasons for observed differences between measured and predicted levels by revised theory can be interpreted on the basis of the limitations of the theory presented in section 5.1. Firstly the measurement results indicate that consideration of a refined integration limit for the total reflected sound, which accounts for an average ITDG as a function of the basic room geometry, might lead to improved prediction accuracy. Irrespective of a refinement of the starting time of the diffuse sound decay, the spread of the measurement results with respect to the calculated regression line clearly shows, that further parameters also influence measured strength levels.

It is striking that only for the Faculty of Music Recital Room very good agreement was found between measured and predicted strength levels, particularly with a configuration of minimum absorption on the side walls, see Figure 6. Bearing in mind the large diffusing panels on the side walls and the ceiling of the hall and that no seating was set up during the measurements suggests that good prediction quality can be expected in highly diffuse spaces. This was also stated by Vorländer [11] who found that agreement between sound strength measurement in reverberation chambers and predictions derived from revised theory are within 0.5 dB.

However, auditoria with seating are generally not diffuse spaces, as was already discussed in section 5.1. Besides the fact that absorbing material in auditoria is mostly concentrated in the seat area, Barron [8] points out that absorbing material located around the stage [(6)] can be given as a further reason for low measured strength levels compared to revised theory. While it is generally difficult to evaluate all relevant influencing factors that relate

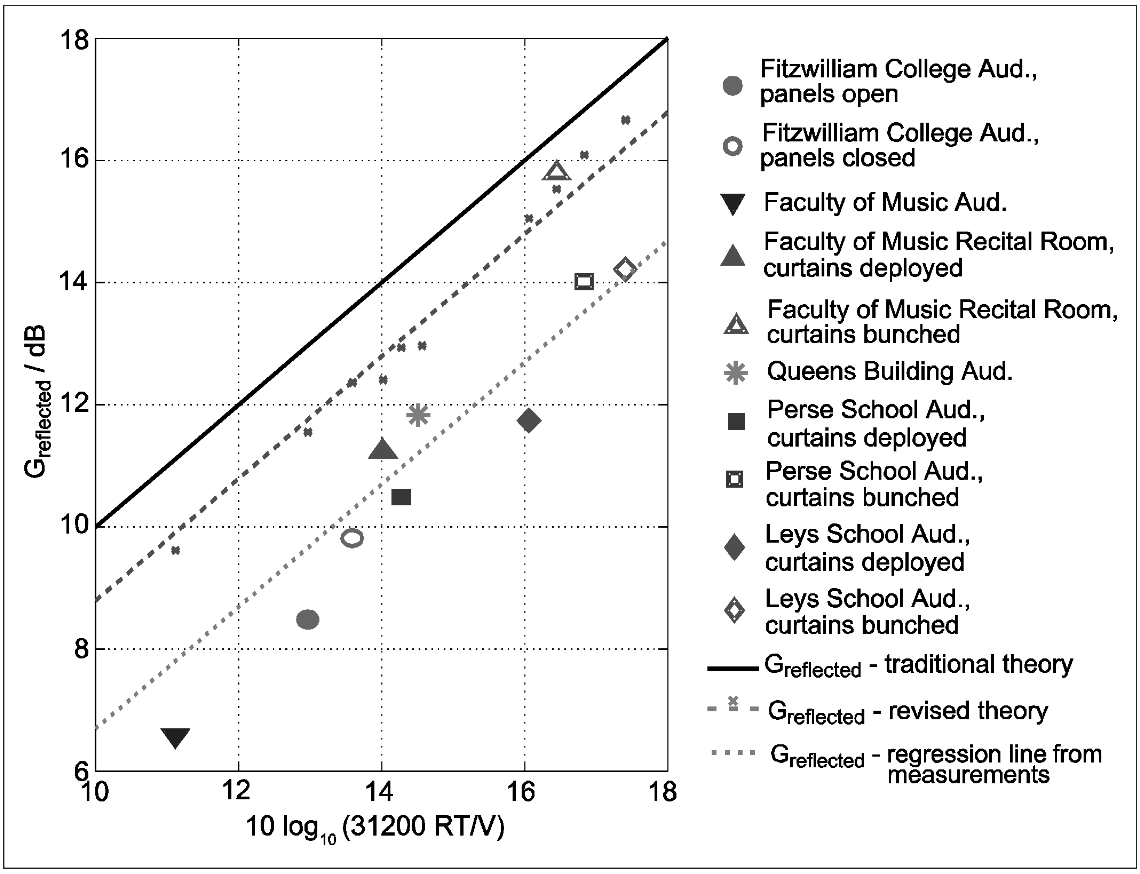

Figure 16. Average mid-frequency strength as a function of RT/V for five of the measured halls

[6] e.g. the heavy curtain on the stage wall in the Faculty of Music Auditorium or the curtain in front of the glazed façade in the Leys School Auditorium

to the state of diffusion in a concert hall, a comparison of the predicted and measured decay traces and particularly the measured *EDT/RT* ratio can possibly serve as an indicator here [10].

6. CONCLUSIONS

In the course of this study strength and reverberation time have been measured in six small concert halls in Cambridge, UK. The measurement results clearly point out the correlation between sound strength and reverberation time in the measured halls as is expected from traditional and revised sound strength theory. Furthermore conventional features for applying variable acoustics like acoustic curtains or absorbing panels were found to provide appropriate means to adjust sound strength and reverberation time in a wide range. Appropriate mid-frequency reverberation times for purposes ranging from speech to chamber music performances were measured depending on the settings of the variable acoustics. Although these acoustical features cannot provide an independent adjustment of strength and reverberation time, since the increase of absorbing surfaces in the hall reduces both reverberation time and strength, the results presented have shown that additional design parameters besides reverberation time and volume can have a considerable influence on the total sound level in a hall. As indicated by Barron the location and distribution of absorbing material and features for the enhancement of diffusion are promising contenders here. Moreover the slight but consistent discrepancy between measured and predicted strength levels with revised theory indicates that consideration of the ITDG in addition to the travel time of the direct sound might lead to improved prediction accuracy.

7. APPENDIX

According to ISO 3382 [3] strength measurements can be conducted by using an impulse response based approach or by using a steady state broad band noise approach. In the course of this study all strength measurements were carried out using both methods. The aim of the measurements was therefore to also check the agreement of these two different approaches and to double check the measurement results. Throughout the whole series of measurements good agreement was found between the two measurement techniques. Deviations were mostly found to be in an acceptable range of about *0.5* to *1.0* dB. In order to check our calibration measurements for possible bias we compared our measured strength levels for the Faculty of Music Auditorium with those obtained by Barron [4] and good agreement was found for the measured strength levels with differences in a range of less than 1 dB. However, considering that calibration measurements were conducted in a rather small anechoic chamber, a minor bias resulting in slightly too high calibration levels and thus low measured strength levels cannot be excluded. The strength levels presented in section 3 give the average results obtained from both measurement techniques.

An extended version of this paper with more technical detail was published in:

Aretz, M., Orlowski, R., *Sound strength and reverberation time in small concert halls*, Applied Acoustics, 70 (8), pp. 1099-1110, 2009

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NOISE RULING WORRIES NY NIGHTCLUBS

A court decision in favor of a West Side co-op building is causing concern through New York's nightclub and restaurant industry. In ruling that a roof-deck bar at the Empire Hotel exceeded a city ordinance for noise level and interfered with the residents' "right to use and enjoy their respective apartments," the New York appellate court on Aug. 24 reversed a lower court's decision and sent it back to that court to recommend a remedy. Operated by restaurateur Jeffrey Chodorow, the popular bar in recent months has hosted numerous gatherings, including events for the U.S. Tennis Association, New York's Internet Week conference and the launch of a new cigar line from Bill Paley, son of William and Babe Paley. Attorneys familiar with the case say the roof deck will probably have to close earlier than it currently does, sometimes as late as 4 a.m. on weekends. The co-op's lawyer said he doesn't want to close the bar, but will push to prohibit anyone from going on the roof deck. "We just want them to comply with the law," says Steven Sladkus, the attorney for the co-op building at 61 W 62nd St. Bruce Bronster, an attorney for Mr Chodorow's company, China Grill Management, said he would appeal the decision. "We don't believe that we have created excessive noise," he said. While the bar's neighbours have been the ones complaining about late-night noise, this ruling may end up causing the city's nightclub owners to lose sleep. Battles between bar owners and their neighbours have raged for years at community boards and before the New York State Liquor Authority, but not too many cases make it to court. This marks a rare instance of a building prevailing in court against a bar that is already operating, and it could set a precedent, encouraging other buildings to use the courts to settle such disputes.