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AUDIBILITY OF ROOM RESPONSE SMOOTHING WITH RESPECT TO REFLECTION NUMBER

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1. INTRODUCTION

Computation of room impulse responses requires several factors, such as knowledge of the frequency-dependent reflection coefficient for each surface in a given room, specification of source and receiver positions along with source directivity, and sufficiently accurate modeling of diffractive and scattering properties. This paper deals with the reflection coefficient. In particular, energy values of measured wall reflection responses are averaged over various bandwidths (octave or third-octave), "smoothed" using cubic-spline interpolation, and inverse Fourier-transformed to create a corresponding set of "smoothed" wall impulse responses. Two series of *room* impulse responses are then constructed from the two separate reflection libraries. One series is produced from just the library of smoothed reflection responses; the other, from only the library of original ones. The two series of room impulse responses are finally convolved with anechoic signals (music and speech) and tested for audible differences as a function of reflection number.

Previous work by Mommertz [1] delved significantly into this area. He first experimented with measured reflection coefficients by giving them different phase types (e.g., zero phase, minimum phase) and by also varying the size of the frequency bands over which they were averaged. He then used these modified reflections to construct longer impulse responses and conducted listening tests of whether the modifications were audible. He found that basically any of the phase functions could be used without creating audible changes, reaffirming previous studies by Kuttruff [2]; the audibility of modifications depended more upon the frequency bandwidths used for averaging the *magnitude*. The approximations ranged from step-wise octave-band averaging through cubic-splined third-octave band averaging, for which audible differences finally disappeared. Impulse responses and listening tests, furthermore, were constructed to present "worst case scenarios". Giron [3] also studied essentially similar methods (ETBA,"energetic third-octave band averaging") in his analyses and auralizations. He found that ETBA functioned well for cases in which the source was small compared to the wavelengths of interest; for instance, it could not successfully be applied to a grand piano.

This investigation follows Mommertz's approach but focuses further on how audibility of narrow band averaging ("smoothing") is related to reflection *number* and *density*, both of which, for a given impulse response length, are related to room size and source/receiver positions. This study also proposes when octave-band, splined averaging may be acceptable, depending on the sound source and the absorption characteristics of the surfaces. This preliminary study postpones consideration of certain factors. For example, the surface reflection coefficient (which implicitly assumes an infinite surface) is of limited use; the influence of source/receiver positions along with scattering due to surface roughness and edge diffraction must eventually be included. Walls undergoing low-frequency vibration, for instance, also cannot be described by a simple reflection coefficient.

Listening tests are finally performed on a newly developed "test station" which allows the simple yet effective construction of various types of evaluation [4], as further discussed below.

2. THE REFLECTION LIBRARIES

Measurements of reflection coefficients are taken at an auditorium with a variety of surface types: painted brick walls, heavy hanging draperies, among others. The library of measured reflections is obtained by using Mommertz's "subtraction technique" [5], in which the complex reflection coefficient may be obtained *in-situ* for perpendicular and oblique incidence. "Subtraction" refers to the process of canceling the direct sound (i.e., the pseudo-free field response of the loudspeaker) to calculate the reflection coefficient. (See Ref. 5 for more details.) A measurement from a heavy hanging drapery in front of a brick wall is shown in Fig. 1. The horizontal axis is logarithmically-plotted frequency, and the vertical axis has units of decibels.

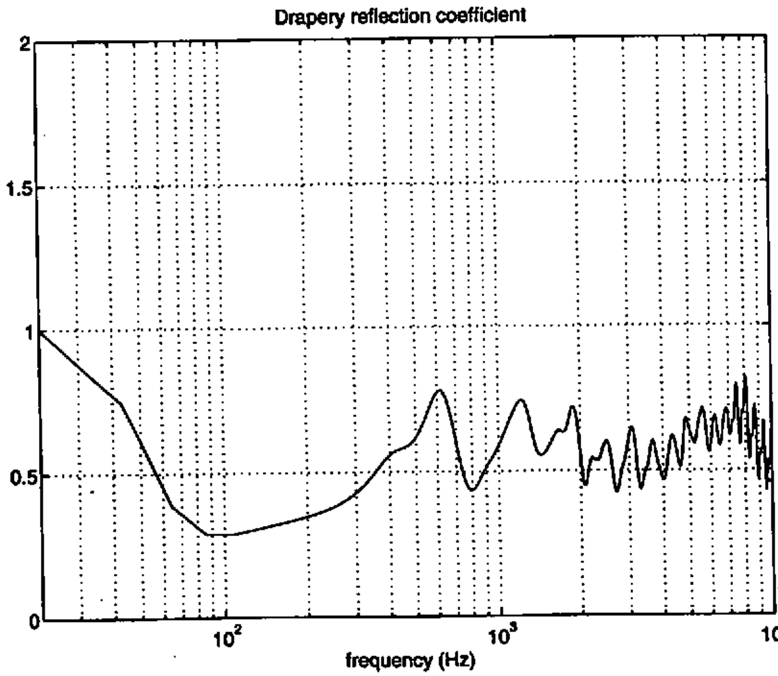

Figure 1: Magnitude of the reflection coefficient for a heavy hanging drapery.

These measurements comprise the collection of first-order reflection impulse responses. Second-order reflections are created by convolving the appropriate first order responses; for example, a second-order reflection from the drapery to the painted brick wall (or vice-versa) is obtained by convolving the two first-order responses corresponding to these surfaces. Strictly speaking, one recognizes that this convolution is rigorously valid only for plane wave propagation; likewise, Mommertz's technique is strictly valid for plane-wave reflection. The aim of this study, however, is to examine effects of *smoothing*. Thus, one may define nearly any type of reflection as a "reference" reflection, even if it does not exactly represent the surface to which it corresponds.

At this point, one has a library of first- and second-order *reference* reflections. (For this initial study, third- and higher-order reflections were neglected. Higher-order reflections and diffraction will increase the reflection density and, hence, the difficulty in identifying audible changes in the impulse response.) The magnitude of the energy for each reflection in this reference library is then subjected to narrow-band averaging and cubic-spline interpolation to create a corresponding library of *smoothed* reflections. Figure 2 shows different degrees of smoothing, i.e., octave band and third-octave band averaging, and it is clear that the latter conforms more closely to the original curve at higher frequencies.

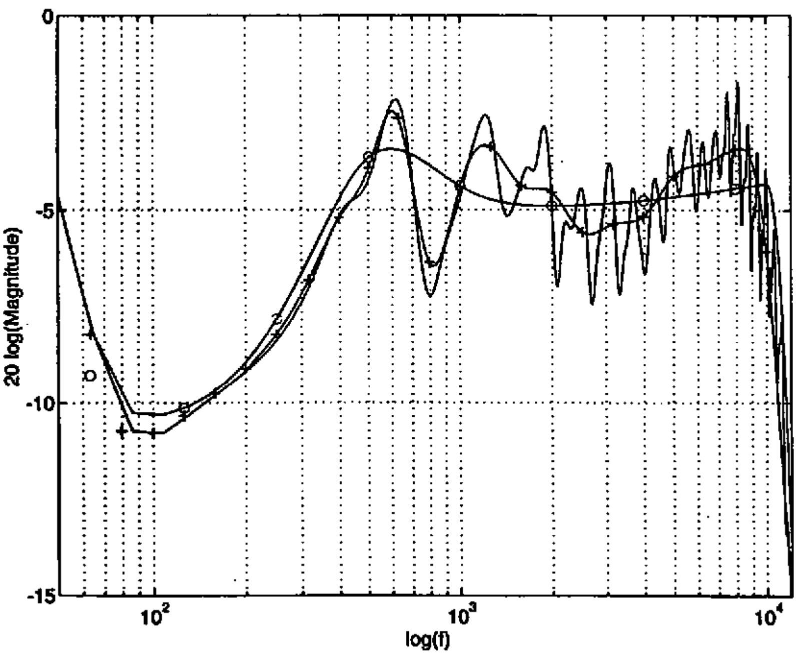

Figure 2: Reference response, octave-band smoothed (circles), third-octave band (+)

3. CONSTRUCTION OF THE IMPULSE RESPONSES

The fictitious room has a generic "shoebox" form with dimensions 8 m x 10 m x 24 m (volume 1920 m^3). Five of the surfaces were assigned "hard brick wall" reflection coefficients; the sixth, an absorptive "heavy drapery" reflection coefficient, corresponding to the floor/audience area. To compute the room impulse response for a given pair of source/receiver positions, an image source model is used to determine the sequence and time-delays of each reflection; distance attenuation from spherical spreading included as well. The main interest is how the early reflections are affected by the smoothing process; thus, all first- and second-order reflections which arrive in the first 200 ms are included in the computed impulse response.

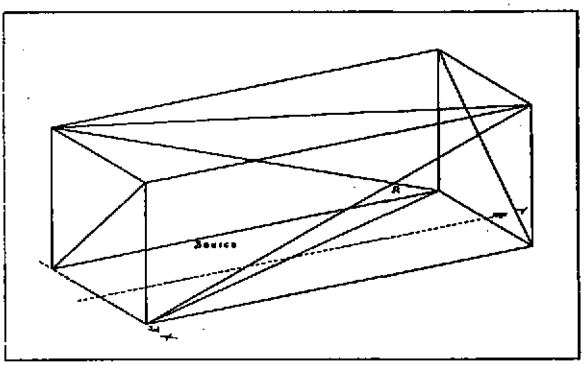

Figure 3: Sketch of room and source/receiver positions.

In summary, the procedure for constructing the impulse responses is as follows:

(1) Construct reflection libraries: one containing "reference"reflections, the other containing "smoothed"versions, both having first- and second-order reflections.

(2) Create minimum phase functions for both the reference and smoothed reflections (so that only their magnitudes differ). See also Ref. 1 and Ref. 2.

(3) Assign sequence and relative strengths of the reflections according to the image source method. Having assigned minimum phase functions to the reflections, one shall thus ignore any excess phase shifts introduced by the surfaces.

(4) Now, one has two impulse responses of length 200 ms:
  (a) "reference" reflections = reference impulse response
  (b) "smoothed" reflections = comparison impulse response

(5) The final pair of room impulse responses, using progressively greater number of reflections (e.g., 1, 5, 10, 15, 20), are compared by convolving with anechoic recordings: a clarinet, male speech, and set drums.

4. LISTENING TESTS

A special "test station" has been developed in tandem with this project at the department by Helén Molander [4]. Extremely easy to use for both the test-leader and the test-taker, this tool offers five different types of tests typically used in psychoacoustic evaluations, among them pair comparisons, multiple-case comparisons with ranking of importance, and AB-x comparisons. The latter, AB-x, is used in this study and allows the test taker to choose whether sound "A" or "B" is the same as "x"; neither the test-taker nor the test-leader know the correct answers until after the evaluation. Results and information on the test-taker are automatically compiled, and the test station handbook makes it simple for the test-leader to statistically evaluate results and to define guidelines for selecting listeners.

The tests are done first in mono, i.e., without any binaural, head-related transfer functions (HRTFs); this leaves the frequency content uncolored. Binaural tests using directivity filters are later to be conducted to allow more realistic sounding comparisons.

5. CURRENT RESULTS AND CONCLUSIONS

Third-octave band, spline-interpolated smoothing is sufficiently precise for purposes of auralization (i.e., convolution with musical/speech signals), regardless of how few reflections are included. This agrees with Mommertz's and Giron's findings.

If one uses, however, coarser smoothing (e.g., octave band interpolations), there is apparently no simple, direct correlation between audibility of smoothing with respect to reflection number; it is, not unexpectedly, a multi-dimensional relationship. Although many listeners can recognize the difference with just one reflection and very few can recognize the difference with all reflections within the first 200 ms, there are exceptions to the trend that audibility decreases with increasing reflection number. For certain impulse response lengths, the audible difference increases. This happens particularly when a strong reflection comes much later than a cluster of previous ones. The resulting "comb filter" can presumably affect the spectrum significantly in the absence of additional, higher density reflections, although its exact relation to the entire response is quite complicated. These effects may disappear under binaural listening conditions.

The relation of the time and frequency characteristics of the *source* (type of instrument or type of voice) to the frequency absorption properties of the *surfaces* is likewise important. For example, reflection coefficients with several sharp dips are not precisely approximated with octave-band averaging. For these imprecise approximations to be heard, the sound source must have significant, unmasked frequency content exactly within those octave bands. "Unmasked" requires that the time characteristics of the source not be excessively reverberant, which often occurs when a recording microphone is positioned close to acoustic instruments such as the cello or the acoustic guitar.

The demands on the listeners also have significant influence. For many listeners with no special ear training, the octave band smoothing seemed sufficiently good to simulate the original. And in general, even the most sensitive listeners had to be able to psychoacoustically "search" for different aspects of the input signal that indicated the smoothing. An important consideration learned from constructing these tests is to avoid placing obvious comparisons before subtle ones; the subtle shades of difference can become entirely insignificant to the "mind's ear". Finally, one should try to keep the listener from growing fatigued, as this also dulls evaluation; the test should thus be as efficient as short as possible within statistical requirements.

The significant, concentrated effort required of all the listeners indicates that there is, nevertheless, a *general* tendency that smoothing is less audible with higher number and density of reflections. As discussed above, exceptions can arise when (1) there is a relatively high peak (e.g., two reflections arrive simultaneously), or (2) there is a particularly long gap between reflections; both have comb-filter effects. And it seems reasonable to surmise that audible differences from octave-band, splined smoothing will become even more subtle (and perhaps insignificant) with the addition of diffusion, higher-order reflections, and reverberation.

6. FUTURE INVESTIGATIONS

Binaural comparisons will also be performed. Future considerations should include the effect of varying reflection coefficients depending upon incidence angle, the influence of higher order reflections, and the audibility of multiple-order diffraction. And when acceptably accurate models for finite impedance surfaces are developed, absorptive qualities can also be taken into account.

7. ACKNOWLEDGMENT

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DESIGN AND PERFORMANCE OF THE STRAVINSKY AUDITORIUM IN MONTREUX

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1. INTRODUCTION

In the late 1980s, the local town council of Montreux, in the French speaking part of Switzerland, were contemplating incorporating a large-volume hall for concerts, conferences and exhibitions within the framework of the extension to their Exhibition and Congress Centre. One of their concerns was to hold the internationally renowned Vevey-Montreux Music Festival which did not have at that stage a concert hall worthy of the name. Since it was founded in 1945, the Festival had always taken place in under-equipped venues with unsuitable acoustics. The Auditorium was planned as the ideal location for the Music Festival.

The Montreux Town Council stated in its requirements that the Auditorium must primarily be a symphonic hall and that its acoustics should be designed accordingly. The second requirement was that conferences and congresses should be held there, requiring excellent speech intelligibility without any modification of the natural acoustics, i.e. any changes in the volume, or walls and ceiling absorption. On the other hand, it should be possible to reduce the number of seats according to the audience size and make the floor flat (terraced seating taken down). The third requirement was that large exhibitions (e.g. TV Symposium 93, 95 & 97) could be held there with a flat floor (stage and terraced seating taken down) and with all the seats removed, except those on the balcony.

These three requirements were very challenging ones and posed many difficult problems. Furthermore, the town council's proposals were put into question and were the subject of a referendum, mainly for reasons related to cost: it should be pointed out that for a small town such as Montreux or Vevey, that also participated in the project, this represented a substantial financial undertaking even with the Cantonal and Federal aid, with the result that local taxes would have to be raised. Despite this, the population of Montreux followed the recommendation of the town council and voted for the project on the condition that the Auditorium would also be able to house regional and local cultural events. The architects of the Auditorium were Mr. J.-M. Jenny and Mr. P. Steiner (Vevey and Montreux) and the acoustic consultants were B. Gandet (Bächli AG, Baden) and the undersigned with his work colleagues. The Auditorium was built between 1990 and 1992. The opening concert was held on the 28th of April 1993. The last four Music Festivals have been held in the Stravinsky Auditorium. A large cultural programme including all kinds of music is also held in the Auditorium. Roughly speaking, three main complementary axes can be distinguished within the overall aim of offering eclectic programming: classical music world-wide music and Pop music.

Just when the building was completed, a requirement was made for the Auditorium to host the Montreux Jazz Festival. It was too late to design variable acoustics - this was totally excluded at an early stage of the project. With this is mind, it was decided to shorten the reverberation time, of course only temporarily during the Montreux Jazz Festival, using therefore removable devices.

2. CAPACITY, VOLUME AND SHAPE

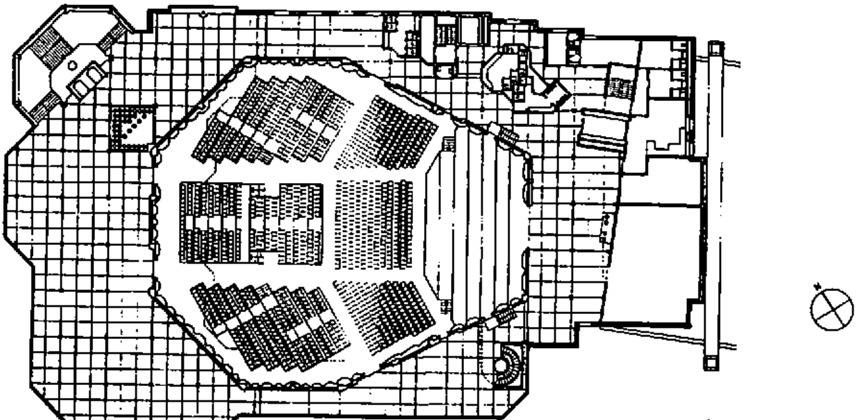
The capacity was originally fixed at 2000 people. Because the Auditorium had to be adjacent to the Congress Centre, the available space was strictly limited to the North by a main road, to the South by the Lake Geneva and to the West by a classified park and Hotel. This virtually set the available volume and proportions of the hall, also taking into account the areas required for large exhibitions.

The volume of the Auditorium was initially fixed at 10'000 m3 due to an easement (view on the lake from a prestigious hotel) restricting the height. This volume was considerably too low, particularly for symphonic music and the town council managed to get this easement lifted and the volume was increased to V=18'000 m3. The shape of the Auditorium desired by the architects was the result of various considerations. The stalls are an irregular octagon that is symmetrical in relation to its centreline (see Figure 1). The front is fan-shaped, the greater part of which is taken up with the stage. The back is approximately half of a regular octagon. Their is no stage frame as such, except for certain pop concerts. There is no stage-house. The stage can be lowered in independent sections (possibility of setting up the stage with tiers) and is made flat for exhibitions. The 1285 stalls seats are removable. They are grouped in 6 blocks, the three rear blocks of which are on tiers which can be taken down independently. The balcony is set back, in such a way that the overhang is reduced and only the last three rows are situated underneath it. It has tiered seating with 523 fixed seats in all. It has a lateral part on the lake side only (about 60 seats). In total there is therefore N=1808 seats, that is to say a ratio V/N of 10 m3 per person. For pop concerts and for the Montreux Jazz Festival, the capacity is raised to 2223 seats by increasing the number of seats in the stalls. The Montreux Jazz Festival plans to organize certain concerts with a standing audience of up to 3000 people in the stalls. Table 1 summarises the main geometrical characteristics of the hall according to the notations used by Beranek [1].

$V = 18{,}063\ m^3$ (637,890 ft^3)	$S_a = 860\ m^2$ (9,260 ft^3)
$S_A = 1{,}000\ m^2$ (10,765 ft^2)	$S_0 = 175\ m^2$ (1,885 ft^2)
$S_T = 1{,}175\ m^2$ (12,650 ft^2)	$N = 1808$
$H = 11.5$ m (37.7 ft)	$W = 30$ m (98 ft)
$L = 51$ m (167 ft)	$D = 38$ m (125 ft)
$V/S_T = 15.4$ m (50 ft)	$V/S_A = 18.1$ m (59 ft)
$V/N = 10\ m^3$ (353 ft^3)	$S_A/N = 0.56\ m^2$ (6 ft^2)
$H/W = 0.38$	$L/W = 1.70$

Table 1 - Technical details

The Auditorium is equipped with control rooms for both sound and light (incorporated in the rear wall of the balcony) and simultaneous translation booths.



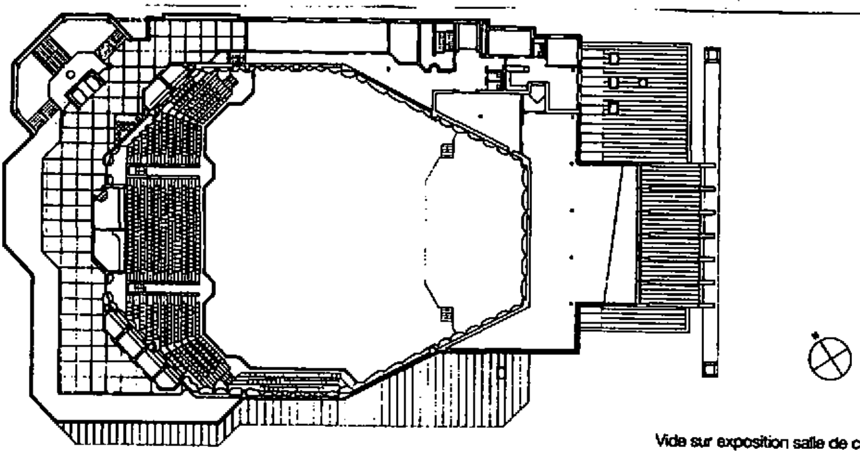


Figure 1 — Plans of stalls and balcony (scale roughly 1:736)

3. ACOUSTIC DESIGN AND ARCHITECTURAL DETAILS

The walls are covered with heat-formed "waves" of wood, shaped according to 6 different profile and manufacturing types. The basic material is multi-layered fibreboard of varying thickness with veneered cherrywood. The axis of the waves is vertical, and over the height of the hall several waves are set on top of each other with negative joints. Certain waves have horizontal enclosures. Mineral wool, of varying density and thickness is placed at the back of part of the waves. These waves play an absorption role in the 80-200 Hz frequency range (their resonance frequencies are spread out between 100 and 160 Hz) and a diffusion role above this frequency range. The optimization of the waves from the absorption point of view was carried out in a reverberation room: prototypes were built and measured until the required properties were obtained, in particular a suitable spread of resonance frequencies and an adequate value for the absorption coefficients. Helmholtz resonators were fitted in between the waves in such a way as to create complementary low-frequency absorption. Finally, the front wall of the sound and lighting control rooms is treated with a Quadrillo type of perforated wood, that is very absorbent across the entire range of bass to treble frequencies. It goes without saying that the glass partitions of these control rooms are suitably angled to avoid any unwanted reflections.

The floor is a robust wooden balata parquet on sub-layers of pinewood, able to support heavy loads during exhibitions.The ceiling is also made of waves of wood, but the large empty space above for technical infrastructure means that the absorption is only significant for the very low frequencies. A small part of the ceiling, above the aisles between blocks of seats is treated with a wood/mineral wool sandwich in such a way as to obtain a complementary absorption between 160 and 250 Hz.

In view of the fact that certain elements, for example the tiered seating, could not be characterized in a reverberation room, their contribution to the absorption could only be estimated. Furthermore, the question arose of the seats, which had to be removable and stackable in sets of ten in view of them having to be stored in the modest storage area available. This excluded classical padded seats and the problem was to design a low-cost seat with the required qualities regarding in particular suitable absorption, coupled with good audience comfort. The following method was successfully carried thorough. A supplier was selected on the basis an expert appraisal carried out on several chair models found on the market taking into account their acoustic performance and the possibility of increasing their absorption in a simple way without adding too much to the cost.

After the hall itself was completed, the reverberation time was carefully measured. The comparison with the reverberation time sought led to the acoustic specification of the chairs. In close collaboration with the supplier, the design of a suitable chair was carried out on the basis of a standard chair (chair seat modified and perforated to form a Helmholtz resonator, padded with absorbent material, nature of the upholstery, etc.). Measurements in the reverberation room of series of chairs (either occupied or empty) enabled the requirements to be met. For these measurements, the reverberation room was set to match the Auditorium in the following way: the reverberation time of the Auditorium was measured a first time without any seats and a second time with 1500 identical seats from the Congress Centre (standard chairs with a seat and backrest covered on one side with a fine layer of absorbent material): the absorption of the chairs can be deducted from this (the Auditorium is used in this case as a reverberation hall!). A series of the same chairs was then measured in the reverberation room which enabled the required matching to be achieved.

The study of the shape to give to the waves on the walls and ceiling was carried out on a reduced model (one twentieth). The TDS method was implemented with a frequency transposition at emission and reception using a digital recorder that was specially designed. The transducer for the emission was a piezoelectric hydrophone with a frequency response compensation between 2 and 80 kHz carried out by a weighting filter (the radiation was virtually omnidirectional in the horizontal plane). The transducers for the reception were 1/4" et 1/8" electrostatic microphones. The echograms obtained enabled the wave-shapes to be determined in relation to their diffusion.

The wall and ceiling waves are convex and the available moulding press allowed their profile to be defined by three arcs of a circle, the radii of which can vary to quite a large degree (from 30 cm to 200 cm). Figure 2 shows the most extreme profiles that the mould could handle for the ceiling elements. The width of the wall waves ranges from 100 to 185 cm, right up to 3 m for one of the types. They are made up of one or several parts according to the radius size.

DESIGN AND PERFORMANCE OF THE STRAVINSKY AUDITORIUM

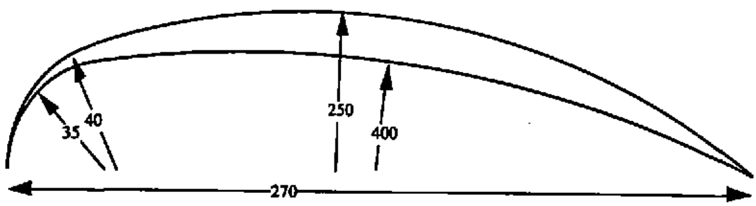


Figure 2

In view of the shape chosen for the hall, the side walls just in front of the stage (fan-shaped part) required a carefully designed wave profile in order to avoid strong late reflections for the audience seated opposite, whilst on the other hand favouring early reflections on the same side. After defining the profile of these waves on the model, a real-size trial carried out in the hall confirmed the conditions forecast: strong lateral reflections were observed due to these elements.

The great width of the auditorium excluded strong side reflections arriving earlier enough in the central part of the auditorium. It was for this reason that it was decided to suspend suitably curved wooden panels from the ceiling positioned in such a way as to produce good reflections in the area concerned. Note that only part of the stalls required this treatment. The design of these sound reflectors was carried using the scale model. The aim was to install as few as possible and to limit the surface area as much as possible. There are in fact only eight and their total surface area only represents a small proportion of the ceiling area (we are well below the 0.5 ratio often mentioned in the literature). The initial time gap everywhere is smaller than or equal to 30 ms.

The free space above the stage had to be quite large for various technical reasons and because the stage itself is quite large, both in width and depth, there was a concern that the acoustic conditions for the musicians and conductor would not be ideal, in particular for a soloist or singer during a recital placed very much to one side of the stage along its axis. The decision was made to suspend a semi-circular shaped sound reflector, that was in fact made up by a fan-shaped array of 5 curved trapezial wooden panels. This element was also studied using the scale model. Figure 3 exhibits a longitudinal cross-section of the Auditorium in which it is possible to see the stage sound reflectors.

In order to meet the requirement of the Montreux Jazz Festival mentioned in paragraph 1, 1000 m2 of absorbent panels made up of wooden frames 5/3.8/2.6 m over 2.15 m filled with mineral wool of 10 cm thickness and covered at the back and front sides with a black cloth were suspended vertically in the hall in several rows (additional load of about 10 tons). The entire set of panels was suspended out of the light and high enough to go unnoticed by an uninformed spectator. Curtains were also suspended from the side walls, mainly to reduce the reflections.

The second requirement - to be able to host conferences and congresses - was fulfilled by installing a sound system, achieving good intelligibility and listening comfort. Six loudspeaker clusters were necessary to correctly cover all audience areas. They are arranged in two rows of three and are hung from the ceiling. They can be removed, for example when a classical concert takes place. The clusters, that are not used (unoccupied areas) are muted in order not to increase unnecessarily the reverberant field. The design of the sound system was made according tospecific criteria, the most important of which was speech intelligibility. To allow basic designs by several companies, speech quality was specified by two different criteria, corresponding to specific criteria, the most important of which was speech intelligibility. To allow basic designs

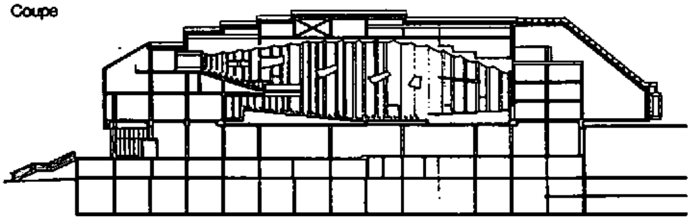


Figure 3 — Longitudinal Cross-section of the Auditorium

by several companies, speech quality was specified by two different criteria, corresponding to quasi-equivalent speech intelligibility: a speech transmission index STI greater than or at least equal to 0.5 and Lochner-Burger signal to noise ratio at least 4 dB (without audience). The required equivalent sound level anywhere in the listeners' area has to be between 60 to 75 dB(A) for an untrained speaker, with at least an 8 dB margin of stability. To ensure proper localization of the speaker, delay lines are used in the sound system. Comb filtering is reduced to a minimum by proper time alignments and directivities of the clusters. Details can be found in [2].

4. PERFORMANCE

Figure 4 shows the measured reverberation time in third octave bands without any audience compared to that computed with 1'200 and 1'800 people, where in both cases there were 1'808 seats (1'285 in the stalls and 523 on the balcony). The values computed are based on the absorption differences measured with occupied or empty seats in the reverberation room. after matching the room with the Auditorium as described earlier in paragraph 3. A suitable reverberation time is observed for symphonic music which does not vary too much between a full house et 2/3 full house.

Figure 5 shows the averaged clarity C_{80} for the empty hall (measured) and with a full house (computed).The three band average C_{80} (3) is 1.7 dB with the hall empty and 2,7 dB with the hall occupied. These values are relatively high in view of the also relatively high values of reverberation: we are in the opposite situation to the usual one where a high degree of clarity goes hand in hand with low reverberation. The subjective appreciation of experts is a high degree of transparency and intimacy of the music without losing the sense of surrounding spaciousness and reverberation.

Figure 6 shows the averaged measured reverberation time in third octave bands without any audience and no seats in the stalls (tiered seating taken down) after setting up the absorbent panels for the Montreux Jazz Festival, compared to that with 1808 empty seats and a full house. The objective of achieving a reverberation time below 1 second is respected below 400 Hz. For the very low frequencies the reverberation time is still below 1.5 ms.

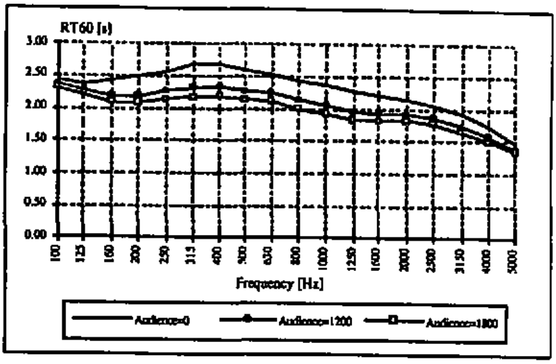


Figure 4

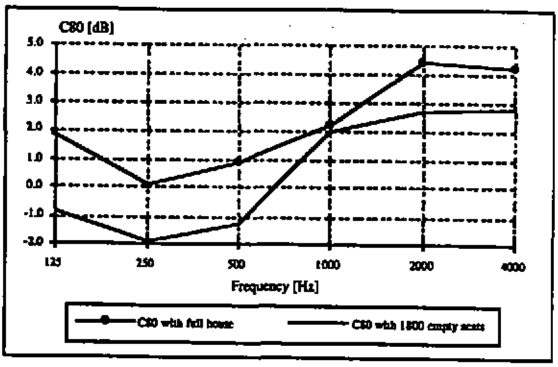


Figure 5

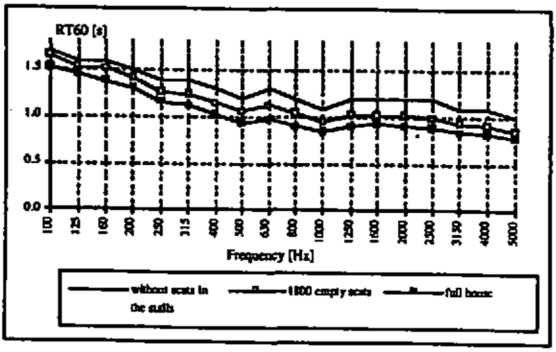


Figure 6

In what concerns the public address system for speech, Figure 7 shows the measured RASTI in the stalls without any audience and with only the first row of clusters on. Figure 8 corresponds to all clusters on. The detrimental role of the reverberant field is clearly seen. No measurement has been made with an audience, but the subjective quality of speech is very good. The first Congress was held in December 1992, just after the completion of the Auditorium (30.11.92): it was the General Meeting of a large multinational with an audience of 500 people sitting only in the stalls and everything worked very satisfactorily.

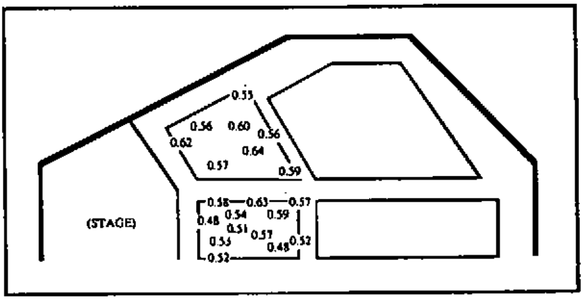


Figure 7

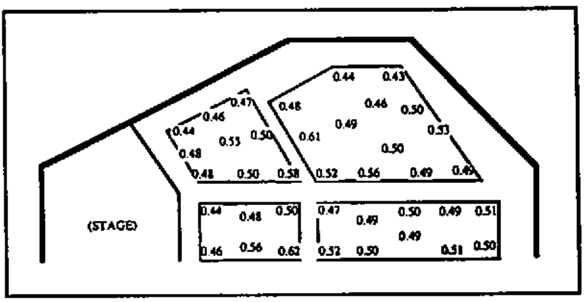


Figure 8

After 4 years of activities in the Auditorium, the time would seem to be appropriate to carry out a study to evaluate the musicians' and audience appraisal of the Auditorium according to the criteria proposed in [1]. We hope to obtain the necessary financial support to carry out this work within the next year.

5. REFERENCES

[1] L BERANEK, 'Concert and Opera Halls - How they sound'. Acoustical Society of America, Woodbury, NY (1996).

[2]. O. MEYLAN, PA CORTHÉSY, & M ROSSI. 'The Sound System of the Auditorium Stravinsky in Montreux. 94th AES Convention, Berlin, March 16-19 Preprint 3612 (1993).

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THE REVOLVING ACOUSTICS OF THE EDINBURGH INTERNATIONAL CONFERENCE CENTRE

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1. INTRODUCTION

The Edinburgh International Conference Centre (EICC) forms the cornerstone of a new financial and business district, The Exchange, and has been operating successfully since its opening in September 1995. It is the first building in UK which makes use of 'Turntable Divisible Auditoria' to convert a large auditorium into smaller auditoria. The sub-division takes place within minutes by revolving two seating areas to create either two or three separate self-contained raked auditoria. When subdivided into three the auditoria seat 600 and 2 X 300 delegates.

The concept provides the acoustic consultant with interesting sound insulation and acoustic challenges, and provides the operators of such a venue with flexibility far beyond that which can be found in traditional auditoria.

The key acoustic issues are sound insulation against external noise and between auditoria, speech intelligibility, background noise from the air conditioning systems and other mechanical services, reverberation times of auditoria in the various configurations, and the avoidance of echoes bearing in mind that the spaces are circular.

This paper sets out the findings of measurements carried out to quantify the acoustic performance of the revolving auditoria and provides more general information about other areas of the conference centre.

2. BACKGROUND

The conference and exhibition industry continues to expand worldwide as cities compete for delegates and the tourist trade that follows. The traditional illustrated address is often giving way to new concepts of 'meet and eat' and 'industrial theatre' for product launches.

The platform often becomes a stage with sophisticated lighting, stage machinery and projection systems. Simultaneous interpretation, voting and interactive delegate systems are frequently needed.

The requirement for the City of Edinburgh to successfully compete in the conference centre market, in the face of increasing competition from UK and overseas venues, was recognised some years ago, and a decision was taken to provide the city with a conference centre, the equal of any in the world.

The objectives were to secure and develop Edinburgh's position in the International and National conference market, to promote Edinburgh and Scotland as a visitor venue and to enhance Scotland's image.

3. FLEXIBILITY

The design of the EICC had to take account of the conference market, and site and budget considerations. As well as the larger conferences with their associated exhibitions, there is also a demand for smaller meetings catering for the needs of disciplines such as medicine, science and technology. To take advantage of these opportunities it was essential to develop a design that maximised the flexibility of the main auditorium and the breakout spaces. The EICC comprises four principal elements.

(a) A main auditorium which seats 1200 delegates and which is capable of sub-division into three separate auditoria.

(b) Breakout rooms seating 600 people and capable of subdivision into a number of separate configurations.

(c) Committee rooms providing seating from 50 – 150 delegates.

(d) An Exhibition Hall capable of supporting conference related events; this hall is also capable of adaptation to provide a major Banqueting Suite.

These facilities are linked by generous foyer, entrance and reception spaces. They have been designed so that the four principal facilities can be operated equally well together for a major international event, or entirely independently providing access, service and security for a wide variety of separate functions.

4. ENVIRONMENTAL NOISE AND VIBRATION

Site surveys indicated that the main noise sources affecting the conference centre was traffic. The results of these measurements were used to formulate sound insulation proposals for the building envelope. The auditorium and other noise sensitive areas were planned so that they were generally shielded from external noise by buffer zones such as foyers and other ancillary spaces.

The roof of the auditorium and the stage, as well as the rear wall of the stage, are subjected to external sources of noise, although the roof is shielded to some extent from traffic noise. The roof is also exposed to noise from roof mounted plant, including the chillers. It comprises a concrete slab with an inner imperforate plasterboard ceiling, and the stage wall is made up of dense concrete blockwork with stone cladding and an inner wall of plasterboard on studwork.

The main line railway running between Waverley and Haymarket is a potential source of both noise and vibration although it is some distance from the conference centre. The results of our vibration survey indicated that vibration would not pose a problem. Therefore, no vibration isolation measures were included in the design. The results of our commissioning measurements confirmed that the control of vibration from the railway was unnecessary.

5. SOUND INSULATION

5.1 Turntable Divisible Auditoria

The relative expense in time and labour inherent in dividing an auditorium by movable partitions is well known. A solution that has been used in North America for some time, and more recently in Europe, is based on 'Turntable Divisible Auditoria' (TDA). In the EICC two such auditoria are used within a main auditorium which seats 1200 delegates, as shown in Figure 1. The main auditorium can be converted in moments into three separate self-contained auditoria for 600 and 2 x 300 delegates, or into two auditoria, seating 900 and 300 delegates.

Each TDA consists of raked seating located on a revolving turntable, which has an integral back and sidewalls to provide sound attenuation together with its own control and projection suite. In the 'open' position the seats face towards the main stage. On rotating the turntable through 180° the seats face into a smaller hall. The back wall having turned with the seats becomes the sound barrier between the main auditorium and the one formed by the rotation of the turntable.

5.2 TDA ceilings

Two ways of constructing the ceiling over each TDA were considered.

(a) Attaching it to the back and sidewalls and cantilevering it over the open front part of the auditorium so that it turned with the turntable beneath.

(b) Keeping it fixed and supporting it from the overhead structure, the back wall rotating within deep slots in the ceiling itself.

The latter of the two was favoured and adopted by the design team for three main reasons. The weight of each revolve would be lower, the complications of having to deal with movable mechanical services would be avoided, and the cost of fixed ceilings would be less.

5.3 TDA walls

The construction details of the rotating walls and the details at the top of and base of walls are shown in Figures 2,3, and 4. The walls are high performance separated stud plasterboard constructions and are built on the revolving platform. The head of the wall is free to revolve within an acoustically lined channel or labyrinth. The sound path from one auditorium to the next is narrow, tortuous and acoustically lined, and provides high levels of sound attenuation. A similar labyrinth detail is provided at the base of the wall.

Before arriving at proposals for the construction of the walls we visited two TDA installations in Europe. These were the auditorium of the Conservatoire Nationale du Région in Nantes, France, where the ceiling and mechanical services rotated, and the main auditorium of Vrije University in Brussels where the ceiling and services were fixed. We carried out subjective assessments of the sound insulation at both sites and measurements at Vrije. Our main concern was to ensure that the acoustic weakness at the EICC presented by gaps between the fixed and the moving elements of the auditoria should be minimised.

As well as construction tolerances the labyrinths also had to take into account relatively large deflections which we were advised by the structural engineers would take place as a consequence of the considerable point loads imposed on the building by the revolving auditoria at the top of the building.

The results of our sound insulation measurements at Vrije and Edinburgh are shown in Figure 5. At Vrije the sound insulation was comparatively good at mid and high frequencies but not so good at low frequencies. Our aim for the EICC was to achieve better results, and comparable measurements at EICC showed that we succeeded in doing so. The results of intermediate measurements taken during the snagging period were poor in relation to the final performance and caused us some concern. However after investigations on site we established that the reason for this was the omission of a small area of acoustic absorption in one of the labyrinths. Once this defect was rectified the performance of the wall and labyrinth achieved our expectations. This observation highlights the importance of paying attention to the detail of acoustically critical constructions during the building phase of the project.

The operators of the EICC are very happy with the sound insulation that has been achieved. It allows for simultaneous use of the adjoining spaces as long as limitations are placed on extremes. For example, the use of loud amplified 'pop' music in one auditorium would not permit satisfactory use of an adjacent auditorium requiring low background noise levels. This was brought to the attention of the client early on in the design process and was accepted, as such extremes were not expected to arise in practice.

6 ACOUSTICS

The brief listed a variety of possible uses for the auditoria. The primary use noted was conferences and associated functions such as product launches. The brief also stated that the EICC will occasionally be used for theatre, choral and orchestral performances. The acoustic design had to deliver good speech intelligibility, and unintrusive background noise from the mechanical ventilation system and from other external sources. For the majority of events it was envisaged that the sound system would be used.

The design aim for the mid-frequency RT of the auditorium as a whole was 1.0 to 1.2 Seconds. In arriving at this figure we took account of its 1200 seating capacity, and the range of uses. For the smaller auditoria RTs were not specified, but our intention was to achieve similar or lower values.

An electro-acoustic enhancement system was considered for the few occasions when the conference centre was to be used for musical events but cost considerations and the infrequency of such events ruled this out.

The background noise level from air conditioning system was specified as NR25.

Early discussions within the design team lead to decisions about ceiling profiles, auditorium volumes, and zones for acoustic finishes. The primary objective during these discussions was to put in place the fundamental parameters that would enable the performance criteria for the various spaces to be achieved.

As regards the selection and design of finishes, we had to bear in mind that some of these would play a part in the acoustics of more than one auditorium. A major concern was to ensure that finishes would complement each other and that auditoria would have good acoustics either when merged, or when operated individually.

In general the ceilings were GRG and profiled to conceal lighting bridges and provide reflected sound energy to the rear of the seating areas. The floor was carpeted and the seats upholstered.

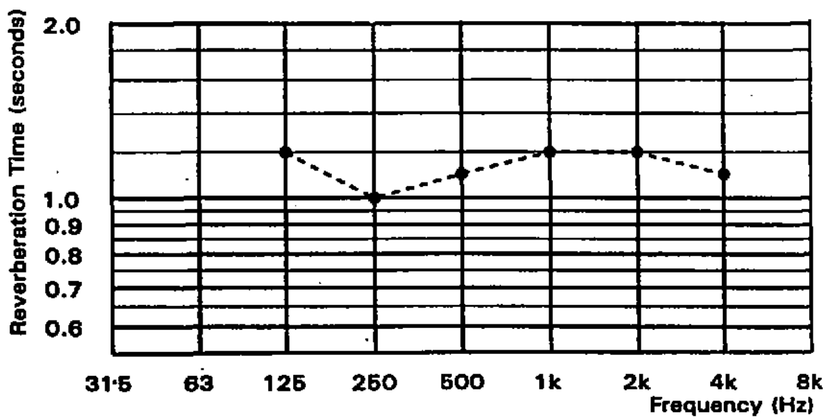
For the auditorium as a whole the side walls at low level were American cherry veneered timber panelling to provide low frequency absorption and reflected sound to seating areas. The panelling near the front of the main auditorium is arranged in a sawtooth format. The side walls at mid level and the rear walls were treated in a similar manner, but with a concealed slot detail, backed by mineral wool, to provide acoustic absorption. The upper levels of the side and rear walls were painted GRG panels, with a similar concealed slot detail.

Exposed areas at the rear of the auditoria that were likely to give rise to echoes or strong focussing effects were made acoustically absorbent.

The unoccupied mid frequency RTs measured were as follows:

In individual revolves – 300 seats	0.8 seconds
600 seat configuration	1.1 seconds
900 seat configuration	1.1 seconds
1200 seat configuration	1.1 seconds

More detailed results for the 1200 seat configuration are:



The vast majority of RASTIs measured placed subjective speech intelligibility in the 'good' or 'excellent' categories with a few falling in the 'fair' category. In general RASTIs in the 300 seat auditoria were better than those measured in the larger configurations as would be expected.

7 CONCLUSIONS

The sound insulation achieved between the revolving auditoria of the Edinburgh International Conference Centre, is higher than that provided by similar auditoria visited by Sandy Brown Associates in Brussels and Nantes.

The full potential of sound insulating constructions is dependant on attention to detail at the implementation stage, and this has been demonstrated during the snagging and commissioning stages of this project.

The acoustic separation provided between the auditoria enables the operators of the Edinburgh International Centre to make simultaneous use of the subdivided spaces, and provides them with the flexibility they were seeking to achieve at the outset.

The objectives for the Edinburgh International Conference Centre of flexibility, speech intelligibility, a sufficiently low background noise and an appropriate acoustic for speech have been fully realised.

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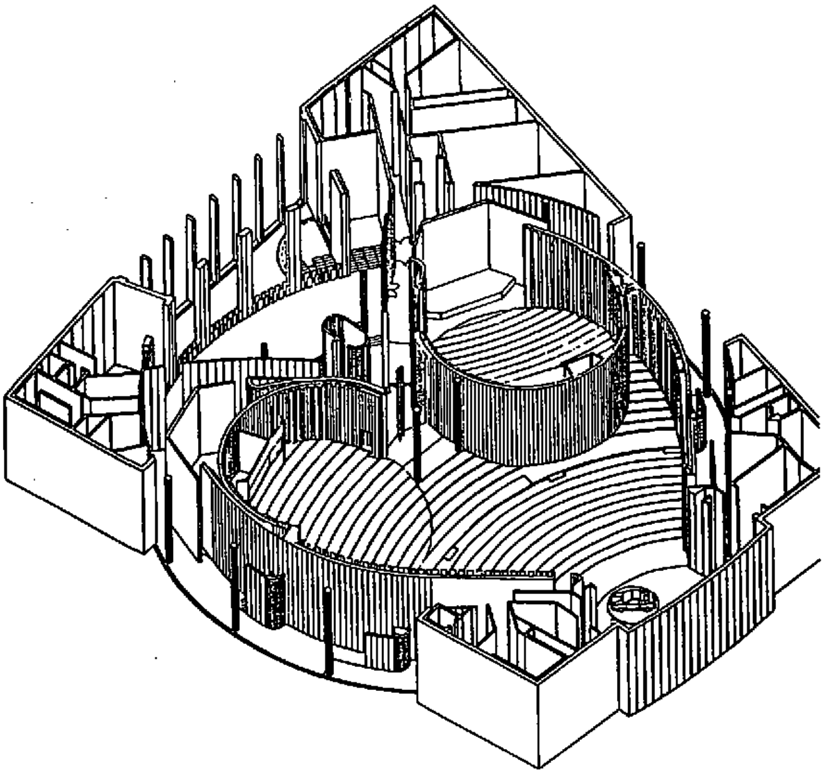

FIG 1 TURNTABLE DIVISIBLE AUDITORIA

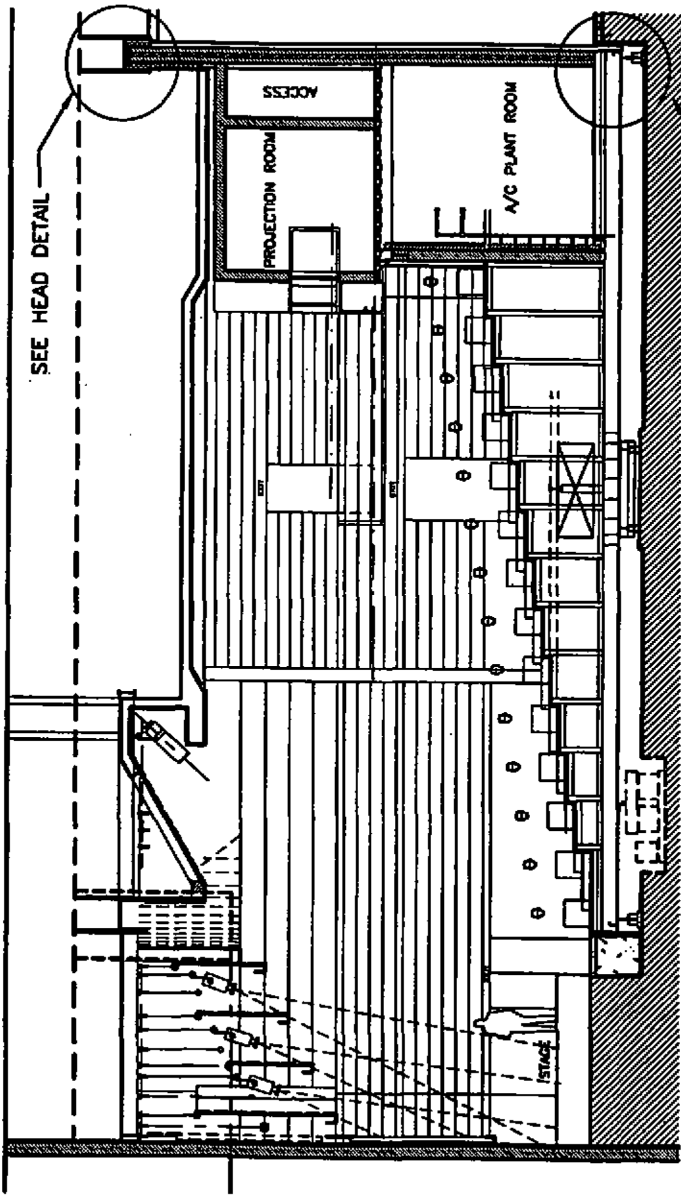

FIG 2 SECTION THROUGH REVOLVE

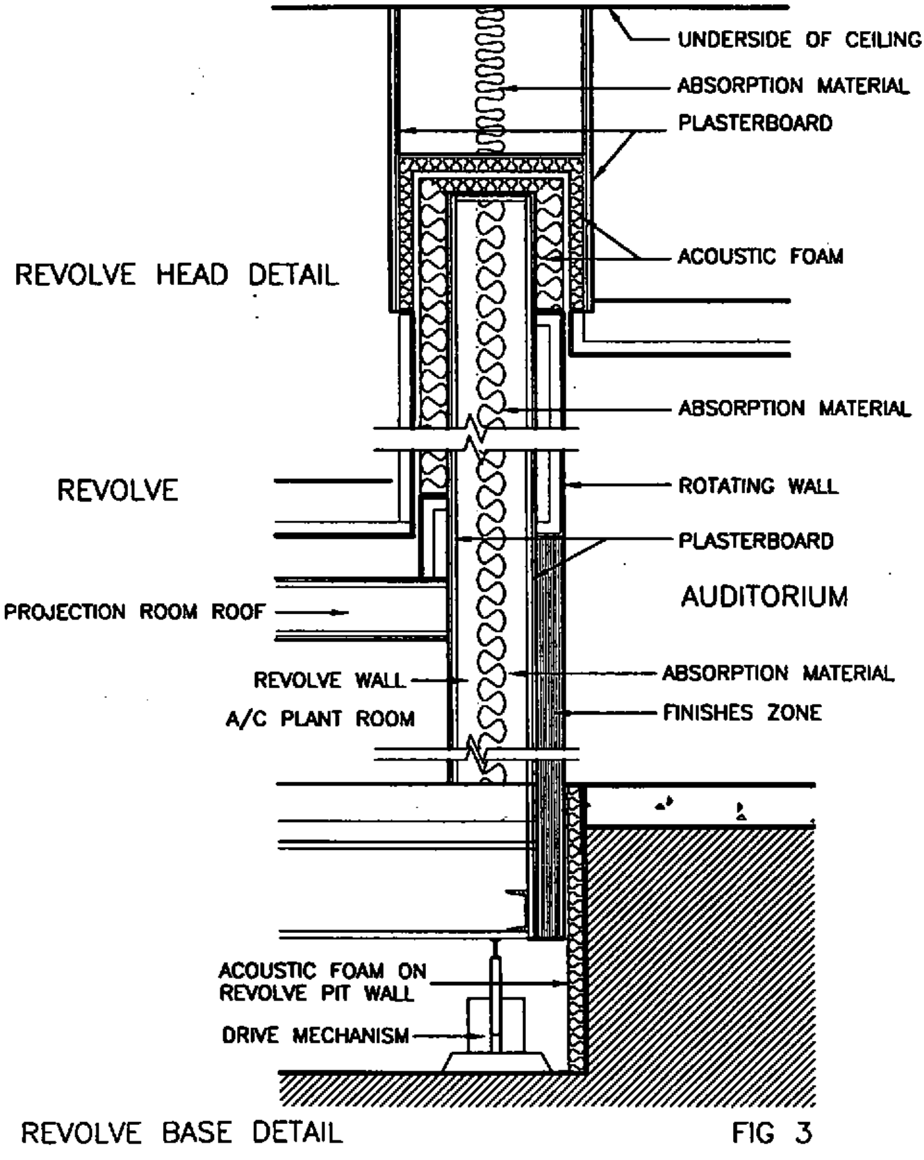
UNDERSIDE OF CEILING
ABSORPTION MATERIAL
PLASTERBOARD
ACOUSTIC FOAM
REVOLVE HEAD DETAIL
ABSORPTION MATERIAL
REVOLVE
ROTATING WALL
PLASTERBOARD
AUDITORIUM
PROJECTION ROOM ROOF
REVOLVE WALL
A/C PLANT ROOM
ABSORPTION MATERIAL
FINISHES ZONE
ACOUSTIC FOAM ON
REVOLVE PIT WALL
DRIVE MECHANISM
REVOLVE BASE DETAIL

FIG 3

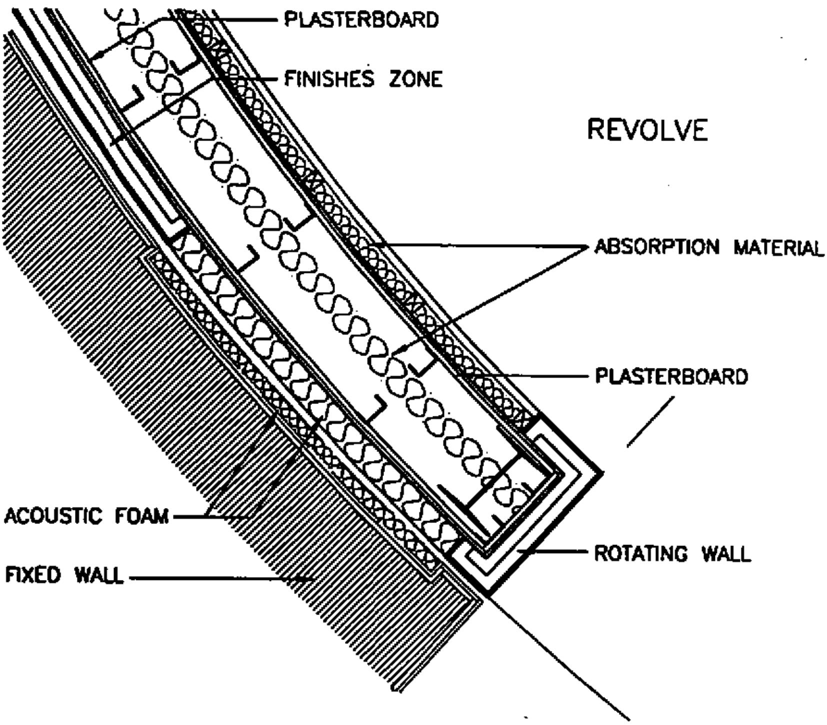

FIG 4 WALL DETAILS

EDINBURGH INTERNATIONAL CONFERENCE CENTRE