HIGH-PERFORMANCE STUDIO ROOMS FOR SIMPLE DOMESTIC CONSTRUCTION

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1 INTRODUCTION

The Covid-19 pandemic forced many people to think about building personal, professional-standard sound recording and mixing facilities in or near their own homes. These studios were mainly for people who needed to work professionally, but who could not continue working in, or travelling to, their previously-usual studios. The uncertainty about the future also drove many people to consider working in their domestic premises in order to avoid the risk of committing themselves to expensive long-term rents or leases, because nobody knew if the forthcoming years would provide them with the wherewithal to support such monthly or yearly bills.

However, given the more ‘private’ nature of these new facilities, the often (literally) ‘in house’ studios have tended, primarily, to be functional. That is to say, they need to be made to work to very high technical standards, but without having to impress any attending clients with their visual splendour or ancillary features. This being the case, the ability to concentrate the available budgets on the acoustics has not only greatly reduced the cost of construction, but has also facilitated the achievement of perhaps ‘higher than expected’ acoustic quality in such rooms.

What is more, once freed from undue decorative compromises, the acoustic performance of the rooms can often be achieved with resort to little more than ‘standard’ building material, and the construction techniques fall within the capabilities of any person(s) who can reasonably competently use a hammer, a screwdriver, a crowbar, and a few saws. So, this paper will explore the performance goals to be met in such rooms, the basic acoustical concepts underpinning them, and their practical realisation in a robust manner. In addition, it will also discuss the computer-modelling difficulties which have led many people to, erroneously, doubt the viability of these techniques.

2 THE GOALS TO BE MET

2.1 General discussion

In most domestic or small-scale-studio circumstances, the rooms are usually too small to allow the development of any elaborate room-acoustics. Small rooms tend not to have ‘good sounds’ of their own, so whether a room be for use as a control-room or a performing room (such as for dialogue, music, or Foley purposes), the object is usually to create an acoustic environment that is not only comfortable to work in, but also barely noticeable in its effect on a recording – or on the monitoring of a recording. Some people may consider these requirements to be mutually exclusive, yet experience has shown that clean and reliable recordings can be made in conditions which offer not only comfort and high fidelity, but also offer the widest range of flexibility in terms of post-processing options. That is to say, the recorded sounds, captured in the rooms, are generally those of the sources, with only a little of the ‘room sounds’, and the monitoring in a such a control room will give a good representation of the timbre of the actual recorded signals (be they of acoustic or electronic origin).

In the performing rooms, the requirement is usually for a space that is free of noticeable resonances. Individual reflexions tend to be less of a problem, however, because the appropriate choices of microphone(s) and the relative position with the source(s) can usually minimise the intrusion of any undesirable reflexions. Nevertheless, the reflexions from non-parallel surfaces, such as a hard floor and/or the window(s), can often be used to introduce some acoustic life into the rooms for the benefit of the people working inside them, yet in a manner which is easily avoidable for the recordings. In any case, floor reflexions tend to be generally innocuous, and can usually be perceived as being quite 'natural', because we live most of our lives on solid floors. (Their collection by microphones and their direct perception by the ears can be very different.)

If the rooms are to be used for the general recording of a range of sources, such as for musical instruments or sound effects, there may be no particular preferred orientation for the room, but in the case of a room which is principally used for a single purpose, such as for dialogue recording, the room acoustics can be optimised for a fixed microphone position and a small dedicated area for the artistes to perform in. This technique can make rooms workable in spaces that would be too small to control adequately for more general use.

Somewhat similarly to the latter case, the loudspeaker and mixing positions in a control room are usually fixed, so the room-acoustics can be optimised for the achievement of the sonic neutrality of the sound-transmission in a specific direction, yet can more lively in another direction. For example, as the persons working in the room will usually be facing the principal loudspeakers, the 'life' to be heard from their own actions and voices can be supplied from surfaces that the loudspeakers cannot 'see'. The consequence of this is that one direction of the room can be acoustically optimised for the accurate transmission of sound from the loudspeakers to the ears, whilst the other direction can be optimised for alleviating any undesirable 'deadness' for general conversation.

2.2 Modal-decay thresholds, and reflexion issues

Regarding the room resonances, Fazenda, Stephenson and Goldberg published details in a JASA paper in 2015, outlining the thresholds of perception for room-resonances with different types of sounds [1]. Figure 1 is taken from that paper.

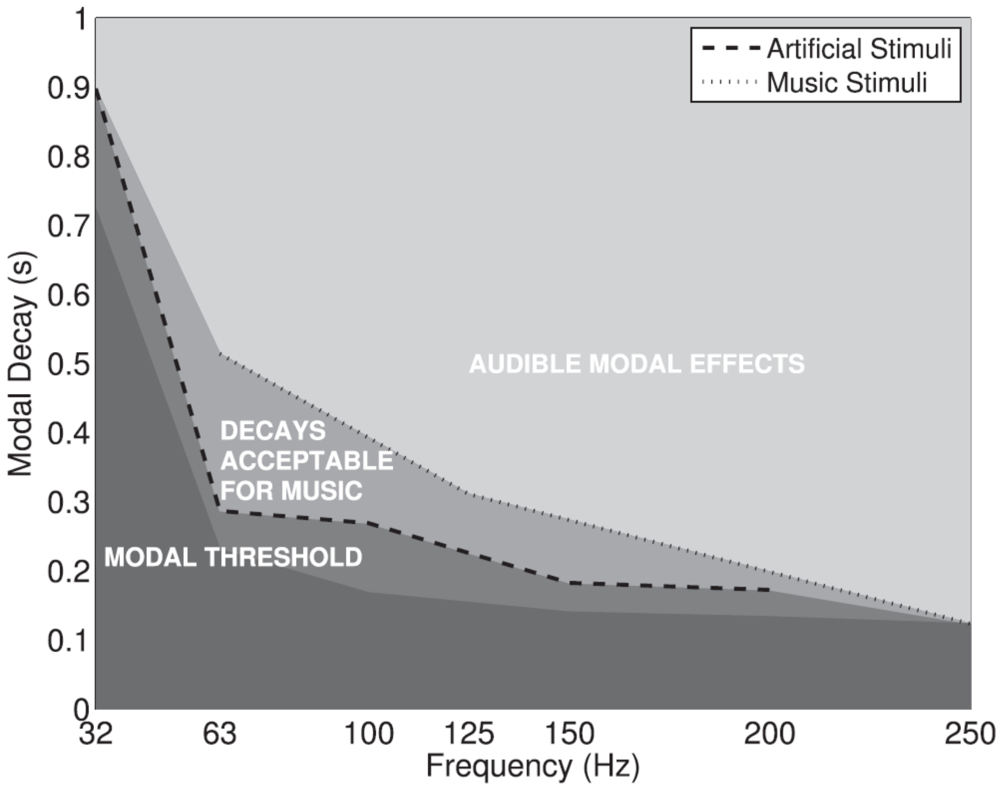

Figure 1 The perception thresholds for resonance-detection in rooms

The paper stated that, below the 'modal threshold' shown in Figure 1, it is unlikely that modal problems will be detected – in which case any control-methods employed to correct them would be likely to be perceptually meaningless. Above this region lies a range of acceptable decays where the reproduction of music signals is not significantly *impaired* by modal problems, so this range would probably be viable for music mastering, where finished mixes are being assessed in more 'domestic' acoustics. The paper suggested that the application of further modal-control in this region would, indeed, be likely to be perceived as a decrease in modal activity, but perhaps revealed only in the presence of carefully selected stimuli, and under instantaneous comparison between the 'before and after' conditions. In fact, for many purposes, resonances below this threshold would also be acceptable for most monitoring purposes. However, at modal decays well above the thresholds measured with music stimuli (the 'Audible Modal Effects' range), it is highly likely that their perceptual effects would be obvious, and as such, these could *not* be considered to be conditions appropriate for accurate monitoring or 'clean' recording, free of room sounds.

In fact, the modal thresholds defined in [1] correspond closely with not only the current tendencies for precision music-recording control-rooms, but also with the decay times of modern dubbing theatres for cinema-soundtrack mixing. Especially when working in any form on 'immersive' or surround sound, all the required ambience is in the multi-channel mixes, so an acoustically 'clean' room helps in the assessments of the 'drier' ambiences in the mixes. This is now very relevant for mixing in formats such as *Dolby Atmos for Music*, although there was already a trend towards lowering the mid-band and high-frequency decays for surround rooms in the 1990s [2]. However, the low frequency (LF) extension of the low decay-times (as noted by Fazenda *et al*) also correspond very closely with that shown in Figure 2, taken from Toyashima's 1986 AES conference paper on music-studio control-room design [3], published at a time when the transient responses and phase-accuracy of digital recordings had exposed the LF inadequacies of most of the then-current rooms, because 'tight' bass is difficult to monitor in resonant rooms.

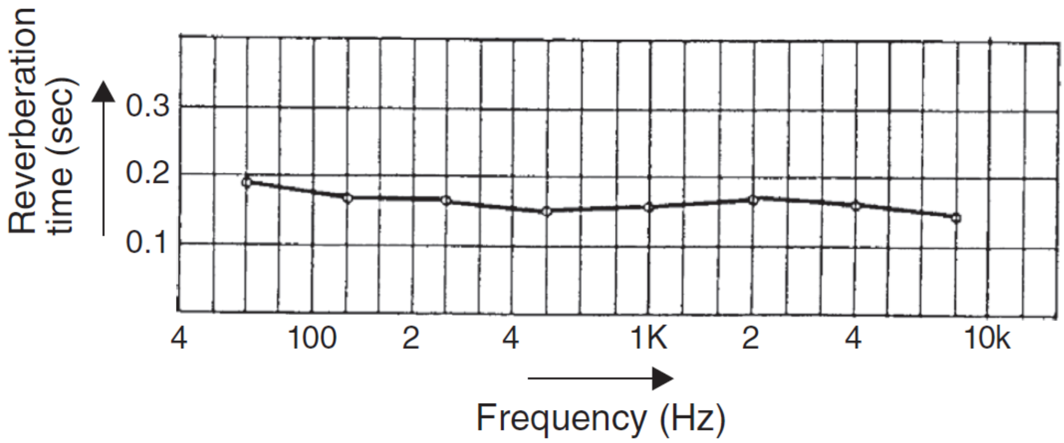

Figure 2 Suggested decay time for music control-rooms for reliable and accurate monitoring (from Toyashima [3])

With decay-times of around 200 ms or less, the monitoring range and the quality of reproduction in a control room is essentially that which is determined by the loudspeakers themselves. Consequently, if the loudspeakers are appropriately chosen and positioned, the sizes and shapes of the rooms have relatively little effect on the room-to-room consistency of the monitoring – provided that the reflexions are carefully controlled. To some degree, this latter point sets a minimum distance to the nearest lateral boundaries, but excellent results have been achieved in control-rooms as small as 12 m^2 if a minimum height (to a rigid ceiling) of about 2.6 m is available (although more is better). Nevertheless, sizes in this range are clearly suitable for application in many 'domestic' (albeit still professional) studio environments.

Furthermore, in the *performing* rooms, floor areas as small as 6 m^2 can often be viable because, as previously mentioned, directional microphones can be used to circumvent most of the likely reflexion problems. Again, this is very convenient for small 'home' studios of high quality, but the requirement for a control room of significantly greater floor area is likely to be because, when listening, the ears need more room to 'breathe' than microphones need to *capture* a sound. This is because two ears and a brain are far more aware of their surroundings. (More on these subjects can be found in the References [4, 5]).

3 PRACTICAL REALISATION

3.1 General outline

The description of a practical way to reliably achieve the aforementioned goals will now be outlined, although it does presume that high degrees of sound-isolation are not a major, concurrent issue. This method will nevertheless tend to provide an isolation of about 20 dB at the lower frequencies, and about 40 dB at the higher frequencies, but the primary intention of the technique is to construct a shell to control the internal acoustics of any space in a typical domestic structure. However, if higher isolation is required, separate isolation treatment would need to be installed before the internal structure was built, because strengthening the inner shell, itself, could reduce the LF absorption (due to the isolation constraining more of the sound within the space).

Using this technique, the whole of the side walls, the rear wall, and the ceiling are used for wide-band absorption, including at quite low frequencies. The reflective surfaces are confined to the floor, the front wall (and/or window), and the surfaces of any equipment installed within the rooms. A cross-section of such an acoustic shell is shown in Figure 3, and a finished room in Figure 4.

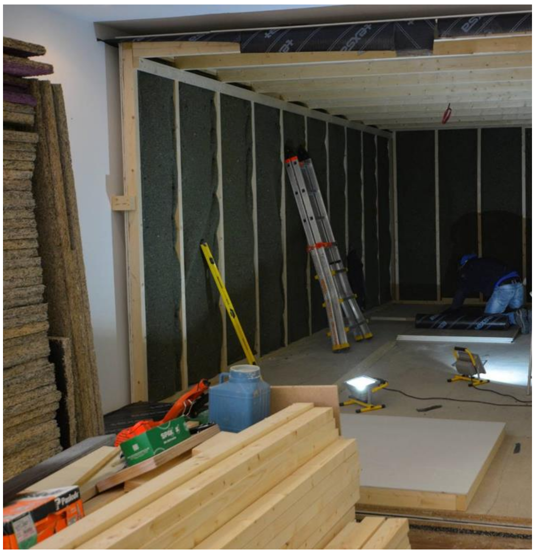

Figure 3 The view of a room-section during construction, showing the sandwich floor, the walls, and the ceiling.

Figure 4 The interior of a finished room in Lisbon, lined with Celenit AB

3.2 The floors

The floors of the rooms should be hard, rigid and non-resonant. A floor of stone or concrete is a good starting base, upon which can be laid a wooden, linoleum, or vinyl surface. However, the upper layer should ideally be stuck to the base in a way that prevents any noisy 'vibrating', in sympathy with the low frequencies of the sources. In cases where the basic floors of the buildings are resonant, such as if made from floorboards over joists, a non-resonant sandwich structure may need to be laid on top, of a construction similar to that which can be seen in Figure 3. Such as sandwich would typically consist of alternating layers of 12.5 mm plasterboard and 'deadsheet' (two of each), with two cross-lapped layers of chipboard on top, glued and screwed together. The result is a highly-damped (non-resonant) floor of great rigidity.

['*Deadsheet*' refers to any heavy, limp, damping material – which could be either bitumen-based, mass-loaded vinyl, or anything similar – of around 3 to 5 kg/m^2. Roofing-felt of a similar weight is another option, although its acoustic characteristics may not be as predictable as those of a specially-fabricated product. (Nevertheless, in the vast majority of cases, plain roofing-felt will function adequately well.)]

If sound-isolation to a lower floor would also be useful, the first layer on top of the floorboards could be two or three centimetres of reconstituted open-cell polyurethane foam (sponge), with a density of at least 100 kg/m^3, but if the extra isolation not be necessary, a layer of a suitable damping material (deadsheet) should be laid on the existing wooden floor.

3.3 The walls

The walls are typically constructed on wooden frames of nominally 5 cm x 5 cm or 7.5 cm x 5 cm timber. The outsides of the frame (facing the structural walls) are covered with a sandwich of two sheets of 12,5 mm plasterboard with a 3.5 kg/m^2 deadsheet in between. The weight of this damping layer is not critical, but 3 to 3.5 kg/m^2 provides a good degree of low-frequency absorption. Heavier damping-layers will give improved sound-isolation, but potentially at the expense of less LF absorption.

The wooden (vertical) studs of the frame should be spaced on 60 cm centres where possible, to facilitate the mounting of boards with typically 60 cm or 120 cm widths, and in the spaces between the studs should be inserted 4 to 5 cm of a porous material of about 40 to 60 kg/m^3. This can be a mineral wool, a glass wool, sheep's wool, or a cotton-waste felt, etc. There is little difference in their acoustic performances in these circumstances, but the organic ones are by far the most comfortable to work with, and many varieties are pre-treated to be either flame retardant or virtually incombustible.

The inner surfaces of the walls are covered with 25 mm to 50 mm of a wood-wool/Portland-cement/air material, such as Savolit, Celenit, Hereklith, Troldtekt, etc. (An old brand in the UK was called *Woodcemair*, because it consisted of *wood*-shavings, *cem*ent and *air*.) These materials give excellent wide-band absorption down to relatively low frequencies when placed over a fibre-filled frame, and the plasterboard sandwich on the outside extends the low-frequency absorption still lower. (The wood-wool/cement materials are also quite environmentally friendly, as well as being resistant to attack by moisture, insects, or fire.) A thickness of 35 mm is usually used on the walls, although 25 mm is often employed on the ceilings if the weight needs to be reduced.

3.4 The ceiling

The construction of the ceilings is usually similar in principle to that of the walls, other than that the timber frames will be mounted horizontally, and therefore will need to be of a depth which will adequately support the weight of the boards without significant bending. For spans of up to three metres, timbers of around nominally 15 cm x 5 cm are usually adequate, although 20 cm x 5 cm may be needed for a four-metres span. However, if the ceiling height does not allow this extra depth, shallower timber 'beams' can be used, reinforced with 25 mm plywood on one or both sides, which greatly increases their strength and rigidity. Nevertheless, if using the deeper timber ceiling-beams (say 20 cm x 5 cm), the greater depth of the frame, as well as the space above the ceiling, will be useful in augmenting the low-frequency absorption. This is beneficial because the ceiling faces a hard and rigid floor, which will consequently be highly reflective. (And the greater depth in a ceiling frame also helps to compensate for the loss in absorption if using wood-wool boards of only 25 mm, instead of 35 mm.)

3.5 Positioning

In many cases, acoustic shells such as these will be made to treat entire rooms, already chosen to be of adequate size. In these situations, the ‘acoustic walls’ will be positioned with the outer plasterboard at least 5 cm from the structural boundaries (to achieve sufficient LF absorption), but the ceiling frames will usually be mounted with their frame-tops at a height which will leave a space of at least 15 to 20 cm below the structural ceiling. The extra space not only helps to augment the low-frequency absorption (as previously mentioned), but also allows more space for mounting the various layers of materials on top of the beams, simplifying the construction.

However, there is no reason why such structures cannot be free-standing in larger spaces: for example, within open-office areas, or in a corner of a large garage. Indeed, the extra ‘breathing space’ beyond the walls will tend to be beneficial to the low-frequency control, but an external isolation-shell may also be required if that provided by the acoustic-control shell, alone, is not considered to be adequate when other people are working (or neighbours are sleeping) nearby.

3.6 Additional absorption at the rear wall

In a unidirectional room, such as a control room or a voice-over room, it can be advantageous to mount a large wide-band absorber to cover the whole of the rear wall (i.e., behind the head of the listener or performer). Such an installation is shown in Figure 5, with the typical panel-distribution and dimensions shown in Figure 6. (Further details of the functioning of these absorbers can be found in reference [4], but a good overview can also be found in reference [6].) The side-walls and the ceiling shown in Figure 5 would be lined with the wood-wool material inside the room, but if it was desired to cover the surface in front of the panels, it should only be done with an acoustically-transparent fabric, perhaps stretched over open wooden frames. In the Figure 5 photograph, the surface behind the panels is a layer of felt over the wooden frame of the back wall (although a wood-wool material can also be used).

Figure 5 A rear-wall wide-band absorber, as typically used in a control room or a dedicated voice-over room

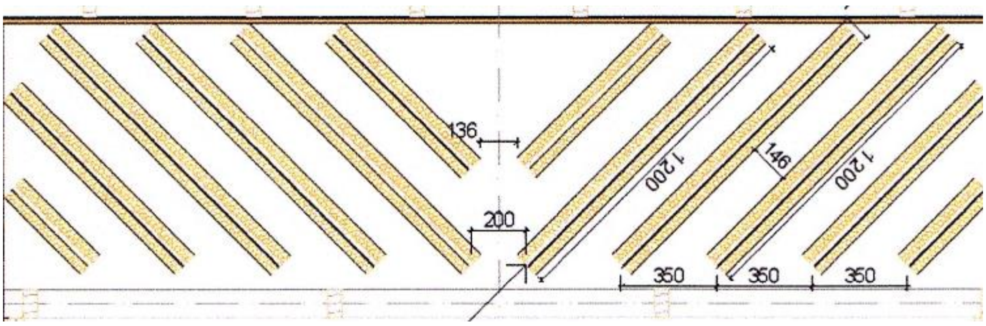

Figure 6 The typical arrangement of the panels in absorbers such as that shown in Figure 5.

The key issues shown in Figure 6 are the 45° angles of the panels (relative to the rear wall), the light contact between the fibrous-covering on the panels and the porous rear-surface of the absorber, and the 350 mm spacing between the leading edges of the panel cores. Reducing the length of the panels will raise the lower frequency to which the absorber will be effective, but the sizes shown are very effective with smaller monitor systems (which do not generate particularly high SPLs around 30 Hz or below). The panel cores need to be solid, and 18 mm chipboard has proved to be practical for this purpose. A 3.5 kg/m^2 deadsheet is usually attached to one side of the panel, to damp any panel resonances, and each side is covered with 40 mm to 50 mm of a fibrous material (such as of those mentioned in Section 3.3) with a density of 40 to 60 kg/m^3.

3.7 Weight distribution and alternative methods

The weight of the walls described above will be in the order of 50 kg/m^2. Consequently, a wall of three metres height will put a load of about 150 kg on each linear metre of the floor on which it stands. In addition, the walls typically carry the distributed weight of the ceiling – which would tend to weigh about 50 kg/m^2, or slightly more. Clearly, such treatments are best mounted on strong floors. However, in cases where the floor-loading capabilities are not considered to be adequate to support this weight, other mounting options are available, such as mounting the ceiling beams on rubber blocks, seated on steel L-brackets which are securely screwed to the structural walls (if available). Other forms of absorbent suspended-ceilings may also be viable options if the height of the room permits them to achieve adequate LF absorption.

3.8 Decay-time (RT) performance

Almost every room will be built in different surrounding constructions, which can affect the low-frequency performance, but the typical decay-time to be expected is shown in Figure 7, below.

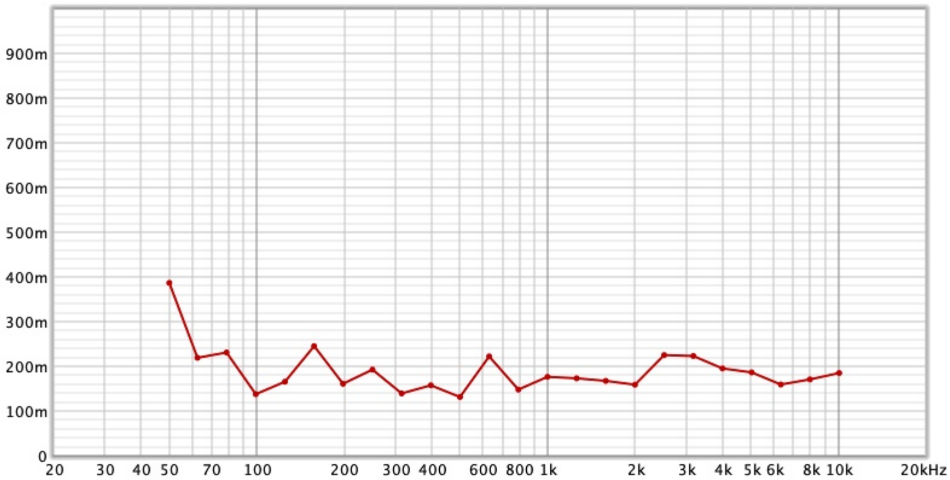

Figure 7 The typical decay-time which can be expected (vertical scale in milliseconds)

As can be seen, the result of furniture and equipment being inside the room can make the response somewhat irregular, but as long as the decay curve remains below or around the modal-threshold limit shown in Figure 1, the irregularities should remain inaudible. Furthermore, the general curve, if octave smoothed, also closely conforms with the decay-time recommendations of Toyashima, shown in Figure 2. So, once the resonances are adequately controlled, the performance of the room is basically a question of the reflexion patterns, and (in the case of a control room) the positioning (and subsequent acoustic loading) of the loudspeakers.

4 MODELLING CONSIDERATIONS

4.1 General

Many successful studio rooms have been constructed for a wide variety of uses by employing the concepts described in this paper. Nevertheless, queries continually arise from people who try to model the constructions with their computer programs, or who try to ‘reverse engineer’ the measured results from a finished room. The tendencies are that either the calculations do not match the expectations, or that some very simple treatments can yield similar results.

However, most readily available computer programs aimed at modelling room-acoustics rely on the summation of sound absorption coefficients over all of the surfaces within a room; and these figures, along with details of the geometry of the room, yield estimates of ‘reverberation’ times (decay times). This process can also be reversed, to make estimates of the amount of absorption required to meet a target reverberation-time, but there are a number of assumptions implicit in this process. Most importantly, the sound field within the room is assumed to be diffuse. (A diffuse field is one in which the sound is statistically uniform in the space − which means that, at any instant and at any point in the room, the sound could be coming from any direction.) This idealised sound field only exists approximately in rooms that are very large compared to a wavelength, and which contain very little sound absorption. A ‘reverberation chamber’ is a laboratory that is designed specifically to approach this ideal, and it is within these laboratories that the sound absorption coefficients of most building materials are measured. The resultant absorption coefficient is known as the ‘random incidence absorption coefficient’, but it is valid only for those specific conditions.

In the case of a general-purpose recording/performing room, musical instruments could be positioned anywhere in a room, and microphones could be orientated in any direction. There is therefore a certain degree of randomness in the direction of incidence with which any sound will be likely to strike the absorbent surfaces, but this does not imply that the standard random-incidence absorption figures for the areas covered can be used when modelling with simple techniques. Moreover, no random-incidence sound-fields can develop in rooms with very low decay-times, so no diffuse fields can exist. Consequently, calculations using standard absorption figures for the materials are not normally relevant to the circumstances.

What is more, the modelling of the plasterboard/deadsheet/plasterboard outer sandwiches, whilst being complicated in itself, is further complicated by the rigidity/flexibility of the frames to which they may be fixed, as well as by the nature of, and distance to, the structures beyond them. Increasing the rigidity of a frame and its coverings will increase the isolation (whilst reducing the absorption at very low frequencies), but finding realistic figures to feed into any computer program is not an easy task once a whole wall is completed, because the interactions within the structures are so complex.

It is also worth bearing in mind that the standard absorption figures, themselves, are only approximations, and that the batch-to-batch variations in many materials can also be considerable. Indeed, Cox and D’Antonio showed how a single sample of material could show a considerable spread of absorption values when sent to 24 different accredited laboratories for testing [8]. Error bars of over ±20% were evident over most of the frequency range, as can be seen in Figure 8. At the lower frequencies, the lower measured-value could be around half that of the upper one, provided by a different laboratory, as the results are very dependent on precisely how the measurements are made. (There is no ‘universally correct’ method.)

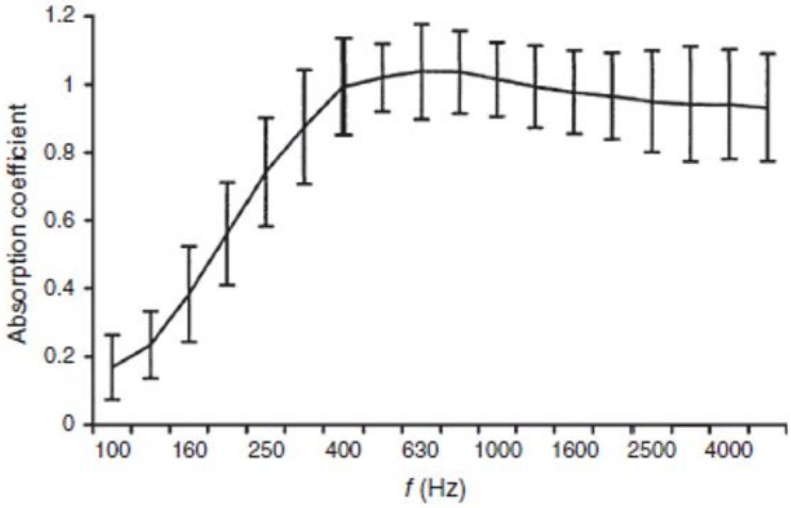

Figure 8 Comparison of measured absorption coefficients for a single sample in 24 laboratories. The mean absorption coefficient across all laboratories is shown, along with error bars indicating 95% confidence in any one laboratory measurement. (Courtesy of Cox and D'antonio [8])

4.2 Directional rooms

Practical rooms are very far from being of diffuse-field natures, and some very specific characteristics need to be taken into consideration if their performance is to be predicted. In the case of a control room with flush-mounted loudspeakers, the front wall can be made hard and rigid. This will add life to speech in the room, whilst also tending to extend and flatten the low-frequency response from the loudspeakers by increasing the loading and removing the possibility of reflexions returning from behind them. Nevertheless, such a means of mounting the loudspeakers (or mounting them very close to the front wall) would strongly drive the axial front/back modes of the room, but if the rear wall is fitted with an adequately-sized absorption system (for example, as shown in Figure 5) it will largely suppress the front/back modes. Consequently, if the absorber system is sufficiently absorbent to suppress those axial modes, which tend to be the most dominant in the room, it will also suppress all of the major tangential modes that could be driven by the loudspeakers, as well as all of the possible oblique modes. However, to do this effectively, the absorber needs to be physically deep because it will receive the direct sound-waves from the two loudspeakers at a largely perpendicular angle of incidence, *and* simultaneously (so any remaining LF reflexion would be largely in phase). For this reason, if trying to calculate the effect on the loudspeaker response of an absorber at the rear wall, it is little use inserting random-incidence coefficients into a modelling program.

As stated in Sections 2.1 and 3.2, the floors of such rooms will usually be hard and rigid, so it is beneficial if the ceilings which face them are capable of considerable LF absorption (although the situation is ameliorated by the fact that the low frequencies from the monitor loudspeakers will usually be generated at a height somewhere mid-way in the room). When mounted at this height, the loudspeakers will not drive the lowest *vertical* modes because they are not near a vertical boundary. Therefore, because the lowest vertical modes will never be driven, there is no need for the ceiling to be highly absorbent at those frequencies unless a floor-mounted sub-woofer is also used. (If this causes problems, the sub can usually be re-positioned.)

Likewise, the absorption by the side walls is also rendered less demanding than for the rear wall if the loudspeakers are mounted away from the sides of the room. Once again, by doing this, the lowest *lateral* modes will not be driven, and to boot, all parts of each wall will be at different distances (and angles of incidence) from the loudspeakers. Work by Colam, in 2002, showed how the side-walls may be subjected to what are effectively surface waves, travelling *along* them, rather than *towards* or *into* them over the majority of their lengths [8]. Once more therefore, random-incidence absorption figures may be inappropriate for calculation purposes in such circumstances, because the angles of incidence will be known quite precisely.

Moreover, the situation regarding the side-wall absorption and the lateral modes also needs careful consideration in the light of the fact that the low-frequency content of a stereo mix will rarely be emanating from one loudspeaker only. In the days of vinyl records, one-sided bass would have made a disc very hard to track with a stylus, and would also put a greater strain on the reproduction system at higher levels because of only one loudspeaker having to deliver most of the bass, but even beyond vinyl, the tradition of mixing bass-instruments towards the centre has been shown to have other benefits, both technically and artistically. It is also the case that the practice has *acoustic* benefits, as well, because it means that the centre-imaged low-frequencies will be driven from *two separate loudspeaker sources*, physically displaced.

If the loudspeakers are spaced away from the side walls, the results of this are twofold. Firstly, some of the lateral modes at the front of the room may actually be driven destructively (by the loudspeakers being at opposing places on the modal pathways). Secondly, the distance to the two sources will be different at each point along the length of a side wall, so the phase-relationship of the two arrivals will vary with the distance into the room. The way in which the side walls are insonified is therefore completely different from the way in which the sound strikes the rear wall, and consequently, if the different surfaces were designed by reference to standard absorption coefficients, inappropriate conclusions would inevitably be drawn. Each side-wall also faces its absorbent 'twin', so neither one faces a reflective surface in the way that the rear wall and ceiling are opposed

5 CONCLUSIONS

A method has been described for the construction of acoustic-control shells for studio rooms of high performance, and which are suitable for application in domestic or 'non-commercial' circumstances (floor-loading permitting). The rooms can be built by non-specialist 'DIY' people, with resort to only basic tools and standard building materials. After completion, the rooms need no further acoustic treatment whatsoever, and no 'tuning'. Although no attempt has been made to compromise the acoustic design with any decorative demands, Figure 4 shows that the rooms can be rendered aesthetically pleasing by lightly painting the wood-wool surfaces. The fabric which covers the rear absorber can permit further scope for aesthetic improvisation. However, many people seem to be quite content to work in a plainer environment if the results of their work are reliable, and the provision of simple ventilation systems can add a very pleasant freshness to the air.

The acoustic designs take into account the directional nature of the typical operation of such rooms, and the short decay-times preclude the possibility of any diffuse sound-fields existing. Consequently, for optimum performance, the absorbers need to be designed with the appropriate sound-incidence angles in mind, but this can create difficulties with the use of design programs which are based on standard absorption-coefficients, measured in diffuse fields, because diffuse fields never occur in these rooms. What is more, where space is at a premium, the optimum absorption at the lower frequencies will need to be achieved by different mechanisms on the different surfaces because the loudspeakers do not drive these surfaces in similar manners, and normally do not drive the lowest modes in all directions.

Taking all of these things into account at the design stage can permit considerable economies to be made (in both cost and space) without any loss of acoustic performance compared to highly-professional environments. However, these benefits cannot be enjoyed if rooms are simply designed to comply with any pre-determined decay-time, or by relying on standard absorption coefficients for the materials used.

6 ACKNOWLEDGEMENTS

Photographs courtesy of Julius Newell (Figures 3 and 4) and Sergey Lednev (Figure 5).

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