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ACOUSTIC SCALING: A RE-EVALUATION OF THE ACOUSTIC MODEL OF MANCHESTER, STUDIO 7

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1. INTRODUCTION

In the fields of building and architecture, the concept of constructing a small scale model of a proposed space for the purpose of making measurements and assessments is self-evident. It has been used in the past by architects and designers to enable them to plan the space effectively. Such modelling becomes more cost effective as the size of the proposed construction increases and the modelling costs become a smaller part of the total. It also helps avoid mistakes which, on a large scale, can be very expensive to rectify.

These considerations apply equally well to the modelling of the acoustics of the proposed construction. It is therefore not surprising that acoustic scale modelling techniques, of a more or less primitive form, have been applied for many years. Prior to the development of acoustic measurement techniques and criteria for acoustic quality, a two-dimensional approach using 'ripple tanks' represented the useful limit of acoustic scale modelling methods.

With the development of transducers and measurement techniques, it became possible to utilize three-dimensional models using three-dimensional acoustic waves in a compressible fluid medium. Air is most commonly used for this purpose although other fluids may be used. To maintain the proper scale for the model sound waves, the wavelength must be reduced by the scaling factor which, in air, is equal to the geometric scale factor of the model. In general, for modelling large structures on a reasonable scale, this scaling of the wavelength is equivalent to an increase in the frequency of the sound.

As an extension of the two-dimensional ripple-tank models, three-dimensional geometric models can be use in the same way to study reflections, energy distribution and focussing. Using air, scale factors up to 50:1, or even 100:1 are technically feasible if a very limited equivalent frequency range is acceptable.

If, instead of making the internal surfaces of the model perfectly reflecting at all frequencies, the surface impedance and structural absorptions of the proposed structure are modelled, then additional quantitative measurements such as reverberation time, early-to-late energy ratios and other more or less meaningful objective criteria can be made. However, at scale factors greater than about 20:1, the selection of suitable materials for the modelling of surface or structural absorption over a wide frequency range becomes increasingly more difficult and the benefits obtained from further reductions in the size of the model become less, even for models of very large structures.

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In broadcasting studios, unlike concert halls, the main requirement is that the sound quality received by a microphone should be satisfactory. This therefore permits, in addition to the objective measurements, a meaningful subjective assessment. Subjective assessments are possible for selected seat positions in models of concert halls but are complicated by the requirement to model both the effects on the sound field of the listener's body and the binaural hearing process itself, a matter which has not been completely resolved even at full-scale. In the model of a broadcasting studio, the sound from the model as recorded by a representative microphone arrangement can, after reversing the scaling process, be judged as if it had originated in a full-size studio.

To make these subjective assessments using scaled recognisable real signals such as human voice, solo instruments and full orchestra, requires that three preliminary conditions be satisfied. First, the test signal must not be contaminated by any acoustic qualities of its own. For real signals, this means that it must originate in a space equivalent to a free-field. Second, a means of scaling the frequency spectrum whilst retaining a reasonable sound quality in terms of signal-to-noise ratio and distortion must be available. Third, the means of reproducing and recording the scaled acoustic signals within the model, also with reasonable quality in terms of signal-to-noise ratio, distortion and freedom from colorations, must be available. The necessary electro-acoustic transducers ideally must also reproduce the directionality of the source and of a typical microphone respectively. The development of instrumentation to satisfy these conditions is however a separate subject [1].

The difficulties associated with meeting these requirements limit the practical acoustic scaling factors to about 10:1 if a usable frequency range appropriate to music rather than speech is to be achieved.

To maintain the proper acoustic geometry, the sound energy absorption as a function of distance in the medium within the model must be scaled. For normal atmospheric air the increase in attenuation per unit distance is greater than proportional to the frequency in the frequency range of interest in acoustic scale modelling. This excess loss is caused by the interaction of water vapour and oxygen molecules. Two different strategies are therefore available for the reduction of the excess loss, to reduce either the oxygen content or the water vapour content. Both are inconvenient and expensive, but removing the water vapour is more convenient and is probably cheaper than using an oxygen-free gas.

For acoustic scale modelling it is not merely necessary to reduce the sound energy loss per unit distance but to obtain the proper scaled characteristic for the loss as a function of frequency. Figure 1 shows a plot of the normal air absorption as a function of frequency for 50% and 60% relative humidity and the scaled absorption parameter as a function of the scaled frequency for air with relative humidities of 1% and 2%. The similarity between the real and scaled characteristics is remarkable and purely co-incidental. It is not so for scaling factors other than near to 8:1 [2].

Thus in all of this work, before any measurement or listening tests (recordings) are made, it is necessary to dry the model and the air within down to a relative humidity of between 1% and 2%. The achievement of such low humidities is difficult but is, by now, a well-known art in the field of acoustic modelling. The accurate measurement of relative humidities of about 1% in a small closed volume is also difficult but is, again, solvable and a separate subject.

2. EARLIER WORK ON ACOUSTIC SCALE MODELLING IN THE BBC

The fundamental principles of acoustic scale modelling as applicable to the BBC were investigated during the period up to about 1974. The work culminated in an 8:1 scale model of the then largest music studio in the BBC, Studio 1 at Maida Vale. Following this work, and taking the generally satisfactory results as confirmation of the validity of the technique, a model was constructed of a proposed new music studio for Manchester (subsequently to become known as Manchester, Studio 7). The general principles of the preliminary design were shown to be satisfactory. Following from the experience with Maida Vale Studio 1, a number of different ceiling heights were experimented with. It was again found that, at least for the sound quality as recorded by a microphone, the ceiling height was not a significant parameter. A number of different average reverberation times were also assessed, ranging from 1.9 to 2.75 seconds. The surprising result obtained was a distinct preference for longer reverberation times than had been thought desirable for a studio of this volume. Even the longest reverberation time tested (2.75 seconds) was judged more favourably than the previously assumed optimum of 1.9 seconds. The final choice of 2.25 seconds was made and the studio design adjusted to give this figure. A second important discovery made during this work was that, especially at low frequencies, the modular acoustic treatment was much more effective in the large space of the studio (approximately 8300m^3) than in the reverberation room (200m^3). These two factors together reduced the quantity of acoustic treatment which was going to be required in the studio and, by allowing more accurate ordering of materials saved a considerable amount of money. The financial savings made in this aspect alone offset a large proportion of the costs of the entire modelling work for the studio.

The main features of the model were all included in the studio design. These were the shape and size of the studio, the disposition of the diffusing ribs, the type and distribution of the acoustic treatment and the design reverberation time (2.25 seconds).

As a further development of the work on acoustic scale modelling and to take advantage of a rare opportunity to observe the progress (acoustically) of the construction of a large music studio, visits were made to the construction site to measure reverberation times inside the studio as the acoustic treatment was installed.

The first of these visits, when the shell was completed but without any intentional acoustic absorption, showed that the low frequency reverberation time was much shorter than had been expected. The second visit to the site took place after the initial installation of the low frequency modular absorbers and the third after the addition of the first phase of wide band modular absorbers. At this stage it was evident that there was a great deal of excess low frequency absorption, giving a reverberation time of just over 1 second at 50Hz, and insufficient high frequency absorption, giving a reverberation time of 3 seconds at 2kHz. Changes were made at this stage to correct the reverberation time function and the studio was handed over to the users with an average reverberation time of 1.9 seconds over the frequency range 50Hz to 4kHz.

3. REASONS FOR RE-EVALUATION OF THE MANCHESTER STUDIO 7 MODEL

Although the completed studio reproduced many of the features of the model, there were inevitably some structural details which were changed in the period between the initial proposal on which the model had been based and the final, detailed construction drawings. Most of these changes had no acoustic consequences but there were some details of the interior of the studio which had not been included in the model study. When the studio shell was completed it was immediately apparent that there was an excess of low frequency structural absorption. This excess had consequences on the whole of the remaining acoustic design and was responsible, ultimately, for the average reverberation time being shorter than the design figure. The cause of the excess absorption was not proven but the wooden-faced ventilation trunking was the prime suspect. One reason for reconstructing and re-evaluating the model was to determine the cause of the excess low frequency absorption. To this end, a different philosophy for the model design was adopted. Instead of attempting to model only the absorption of the interior surfaces as for the first model, the new model was to be constructed as a scaled structure with all of the relevant materials being as near as possible to structurally scaled versions of the materials actually used in the studio rather than simulations of their full scale absorption characteristics. The reverberation time results obtained in the real studio during the construction and the installation of the acoustic treatment were to be used to check the behaviour of the components of the model during its construction.

4. CONSTRUCTION OF THE MODEL AND THE RESULTS OBTAINED

The studio dimensions are 26.6m x 22.2m x 14.025m high, giving a gross volume of 8282m^3. The walls and ceiling of the real studio are constructed from cast, reinforced concrete with a plastered and painted inner surface to a total thickness of 300mm. The diffusing ribs which form a feature of this studio are pre-cast concrete sections bolted through the walls. Such a structure should have a very low absorption coefficient at all frequencies. The floor of the studio consists of 25mm thick, varnished wood strips on battens set into the top screed of the concrete floor. In modelling the empty shell, the aim was to obtain as low an absorption coefficient as possible at all frequencies to provide the enclosure within which the remainder of the work could be carried out.

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The model was constructed from 25mm dense particle board (chipboard) with a three-coat epoxy-based paint finish. It was made in sections, following the natural lines of the interior design, for ease of construction and to permit dismantling and storage.

The reverberation time of the empty model shell was as shown in Fig. 2(a). Fig. 2(b) shows, for comparison, the calculated reverberation time of the empty studio. The studio was not measured in this condition; the ventilation trunking was already installed at the time of the first measurement.

In the studio, the extract ventilation trunking covers consist essentially of $310m^3$ of 25mm thick blockboard over an airspace 785mm wide and 175mm deep. Dimensional analysis of the resulting resonant system formed by the mass of the front panel, the combined compliance of the enclosed airspace and the inherent panel stiffness shows that the resonant frequency will be scaled by the scaling factor if all dimensions are reduced by the scaling factor and the density and Young's Modulus of the front panel are unchanged. Material properties for timber are highly anisotropic, virtually unobtainable and in any case vary within wide limits. However, based on some data originally collected for the purpose of loudspeaker cabinet design, it was thought that 3mm, 3-ply plywood would be a reasonable model of the 25mm blockboard if the panels were cut with the outer layer grains running parallel to the long axis (i.e. the height) of the trunking. The construction and fixing of the model trunking followed the same principles as in the studio, as far as was possible within the limits of the scale size. Measurements of the effective absorption coefficients of the trunking in the model when compared with the estimates for the full-size trunking showed differences mostly within 10% at the low frequency end of the spectrum. The frequency of the resonant peak of absorption was also reproduced to within about 10%. At higher frequencies there were serious discrepancies in the absorption coefficients which could not be accounted for by extensive testing of the model ventilation trunking. It is possible that the real and model ventilation trunking behaved in the same way at high frequencies or that the origin of the difference is not in the ventilation trunking but in the residual absorption of the empty shell. As there were no measurements of the bare studio shell reverberation time there is no way of separating these two possibilities.

The low frequency modular absorbers in the studio were also subject to some uncertainty since they had been extensively modified in an attempt to rectify the uneven reverberation time at a fairly late stage in the construction. The final state of the modules with their 25mm blockboard front panels were modelled in the same way as the ventilation trunking. The results from the model were difficult to compare with those of the studio because of the lack of definitive measurements on the final state of the modules but estimates were made and a general similarity was found over the whole frequency range. Both results showed high absorption coefficients, up to about 0.9, despite the addition of 25mm thick blockboard front panels to "disable" the absorbers at low frequencies.

The remaining acoustic details consisting of the wide-band modular absorbers, the orchestral rostrum, the audience seating and the model orchestra were non-controversial and were designed and installed in the model without any problems. The measured absorption coefficients of these materials were generally similar to those in the studio but local deviations of up to 50% were noted. Many of these discrepancies occurred when the effective absorbing area of the material under consideration was small, for example with the orchestral rostrum, or when there was already a great deal of absorption in the room. It illustrated clearly the poor accuracy of absorption coefficient measurements under such conditions.

Fig. 3(a) shows the reverberation time characteristic as measured in the completed studio. Fig. 3(b) shows the equivalent characteristic in the model. In both cases, the studio and model were complete with the final version of the acoustic treatment installed and with the orchestral rostrum and the audience seating present.

Though reasonably close for acoustic design work, the completed model reverberation times were too long by about 15% at low and mid frequencies and about 20% at high frequencies. However, the general shape of the studio reverberation time characteristic has been reproduced fairly well, even in the detail of the slight rise in average reverberation time between 500Hz and about 3kHz.

5. DISCUSSION OF RESULTS

Reference has been made to the poor reliability of some of the results. The measurement of reverberation time, especially at low frequencies, is itself somewhat inaccurate. Even in such a large volume as this orchestral music studio, individual variations between decays are large. Meaningful results can only be obtained by averaging a very large number of decays at points distributed throughout the volume of the space. Until the recent development of automated equipment this was a laborious and time-consuming exercise. In such a large space it is also difficult to explore the whole volume adequately, especially vertically. During the course of the measurements in the studio, two items became available which simplified the measurements. The first was the development of microprocessor-controlled reverberation time measuring equipment (ART) which, because it had true screen storage of the decays (rather than a long persistence phosphor), was much easier to use for relatively long reverberation times. Being automatic, it also simplified the analysis of large numbers of decays. The second item was a rotating microphone boom which, by continuous rotation, carried out a spatial averaging process (over a limited space) automatically. Such techniques, if applied carefully, may give results to within +/- 2%. It is unlikely that any of the results from the studio were so accurate. They are however, probably within +/- 5%.

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Even though this equipment was used for some of the later measurements in the studio, it could not always be used. For example, when measuring the effects of the orchestra, it was not possible to ask the subjects to remain quiet in a very noisy environment for about one hour. Such occasions were dealt with by the much quicker but very much less accurate method of recording the effects of explosions (in this case, pistol shots) from a number of different locations. The recordings were subsequently analysed in the conventional way. The errors involved in such measurements could be +/- 10%.

In the model, the automatic equipment could not be used because it did not cover the whole of the required frequency range. A small rotating microphone boom was constructed but it could not rotate continuously and was used merely to move the microphone to the next position between measurements. Even so, the generally more comfortable conditions of a familiar laboratory and the shorter reverberation times of the model contributed to improved accuracy with the older, manually operated equipment. With the exception of one or two calibration errors, the measurment errors of reverberation time in the model are probably less than 3%.

The errors in the measurement of reverberation times are not of themselves very important or serious. However, to obtain a figure for sound absorption requires the subtraction of two values for the total absorption, each obtained from a measurement of reverberation time. If the total absorption in each case is large and the difference caused by the material under test is small then the errors in the measurement of reverberation times are greatly magnified.

The errors in measured absorption coefficient caused in this was can be illustrated by some calculated examples. For the first case, take the example of the model ventilation trunking. This was installed in an acoustically otherwise nearly empty room. At low frequencies the trunking had a relatively high coefficient of sound absorption, 0.4 at 63Hz. Errors of +/- 5% in the two reverberation times from which this result was derived lead to a range of answers for the absorption +/- 13%. In contrast, take the example of the audience seating in the studio. This was installed in an otherwise completely acoustically treated room. At 1kHz it appeared to have an absorption coefficient of 0.73. Applying the same 5% error bands to the reverberation times gives results in the range 0.98 to 0.47, an error band of +/- 35%. The errors are even worse if the material being assessed has a low absorption coefficient. Taking the same example of the audience seating, but at 250Hz, the range of values of absorption coefficient for a +/- 5% error in reverberation times is 0.34 to -0.26, with a median value of 0.03!

Thus, in the measurement of acoustic absorption coefficient away from the environment of a laboratory reverberation room, errors which can sometimes be very large must be expected and accepted as inevitable.

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Many of the results obtained for the performance of individual items in the studio showed significant differences between the full size and the model, even considering the possible measurement errors discussed above. However, in all cases, the general shape of the results obtained showed similar trends. Even by normal acoustic standards where exact repeatability is rarely obtained, the modelling appeared to be somewhat inaccurate. However, the basis on which this model was constructed was rather different from the usual modelling of the absorption coefficient characteristics. With the sole exception of the audience seating, this model was constructed entirely from an understanding of the physical bases on which the various elements were supposed to work and not from a knowledge of the actual performance of the elements. Given this consideration, the results obtained for the model elements are reasonably close to those obtained in the full size studio.

The sole exception to this approach was the audience seating arrangement. Although a study of the construction was used as the basis of the model design, measured results for the full size seating were used to confirm the model performance. This was done because the seating, and especially the upholstery, represented acoustic absorption of a type not previously encountered in modelling and of which there was no prior experience.

Within the overall limits of accuracy already discussed, this re-evaluation of the modelling technique has confirmed that the ventilation trunking in the studio was the prime cause of the initial excess low frequency sound absorption. It was also confirmed that the present understanding of the way in which most types of materials behave acoustically is essentially correct. In particular, the low frequency absorption of resonant panels has been verified. In the two separate cases of the ventilation trunking and the front panels of the 'disabled' low frequency modular absorbers, relatively thick wooden panels were shown to have high absorption coefficients at low frequencies.

This re-evaluation has also shown that mechanical and structural considerations can be used to predict the acoustic performance of common types of acoustic absorption at different scales provided that the details of the construction are sufficiently well known and accurately reproduced.

The model has also demonstrated that the measurement of the acoustic properties of materials is subject to errors, especially when the room in which the measurement is being carried out contains other acoustic absorption.

Most of the arguments and discussions in this paper relate to the construction of an acoustic scale model of an existing studio. That, indeed, was the purpose of the work. However, all of the considerations apply equally well to working in the reverse direction, that is, constructing a full size version of an existing model. It is in this direction that acoustic scale modelling is most commonly thought of and in which the financial justifications for the technique are usually to be found. Throughout the remainder of this section, the terminology of modelling can be considered to be equally applicable in either of these two directions.

The construction principles used for this model are not necessarily the only ones or even the optimum ones. It may be more accurate to model the actual absorption coefficient characteristics of the materials to be used. By rigorously accurate modelling of such a kind, a scaled reproduction of an arbitrarily high degree of accuracy can be obtained. However, it is not always possible to establish the true acoustic behaviour of materials, perhaps because they do not behave in the appropriate way until assembled at the correct size or in the correct sized space. It is also probably uneconomic and it is certainly self defeating to copy slavishly every small detail of acoustic absorption coefficient. To do so would require extensive measurements of the performance of the full size and the model materials in the appropriate environments. Given such measurements, the acoustic design could proceed in a normal fashion without the aid of the model which would then effectively have served no purpose.

The real strength of the acoustic modelling technique lies not in the prediction of infinitesimal acoustic differences which are in any case unlikely to be reproduced exactly, but in the prediction of major acoustic details. It has been demonstrated that mechanical and structural considerations can be used to predict the behaviour of materials and constructions to a reasonable degree of accuracy. It is the avoidance of gross acoustic defects and the consequent severe financial penalties that can justify the expense of constructing an acoustic model.

6. SUBJECTIVE ASSESSMENT

The completed model of Manchester Studio 7 was assessed subjectively by the usual method of recording in the model a selection of scaled musical passages which themselves contained no acoustical information about the room in which they were originally recorded. The improved electro-acoustic transducers needed to do this are described elsewhere [1]. The recordings from the model were compared subjectively with recordings of the same musical passages recorded at normal speed in the full size studio by means of monitoring loudspeakers and conventional microphones. The difficulties encountered in carrying out this comparison are also recorded in Reference 1.

Despite the differences in reverberation times between the studio and the model, the two recordings were very similar to each other. Some slight additional colorations from the scale model loudspeaker and a very slightly higher background noise level and non-linear distortion in the model recordings made the two recordings instantly identifiable on an ABAB comparison. Otherwise, and especially acoustically, they were indistinguishable.

7. CONCLUSIONS

Using mainly structural and mechanical considerations, a new acoustic scale model of Manchester, Studio 7 has been constructed. The model has reproduced the essential acoustic features of the studio to a reasonable degree of accuracy although the intermediate calculations of absorption coefficients show large differences. With the sole exception of the audience seating and its supporting structure, no corrections were made to the achieved acoustic performance of the model components in an effort to match their performance to that of the full size components in the full size studio.

Some of the value of the intermediate measurements of reverberation time in the full size studio during its construction has been lost because of the later changes in the acoustic treatment. These changes were brought about mainly by the excessive low frequency absorption of the ventilation trunking which was not included in the earlier model because details of the trunking were not shown on the drawings at that time. Acoustic scale modelling can only be of value if comprehensive details of the proposed construction are available and remain unchanged after the completion of the modelling. This does require that any features which could have acoustic implications are finally settled at a fairly early stage in the design.

Unless a great deal of time and effort is expended on getting exact and detailed matches between model and full size components, the acoustic scale modelling technique is, at best, only as accurate as full scale acoustic design. Indeed, this is obvious - if it were more accurate then the full scale design would be more accurate for the same reasons. The main advantage in modelling is that changes may be made much more readily. The final acoustic design of the model can be reproduced in the full size structure only within the tolerances imposed by the reproduction of the model components at full scale. These tolerances are almost inevitable so that it is equally inevitable that the full size structure will differ from the model in small details. It is these almost inevitable differences which made any effort to obtain exact matches of individual components a waste of time. It will generally be more economical to plan for at least one correction to the acoustic treatment in order to compensate for all of the small differences simultaneously. If the acoustic scale modelling has been carried out accurately using structural and mechanical considerations, and all of the internal details have been considered, then there will be no serious acoustic defects in the full size structure. The final correction will therefore be a relatively minor matter. It is in the avoidance of large errors and the consequential expensive, sometimes impossible remedial work that acoustic scale modelling has its real value as an aid to room design.

8. REFERENCES

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9. ACKNOWLEDGEMENTS

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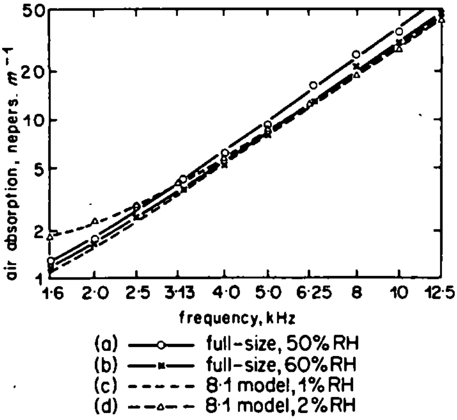

Fig. 1 Comparison of scale and full-size air absorption characteristics.

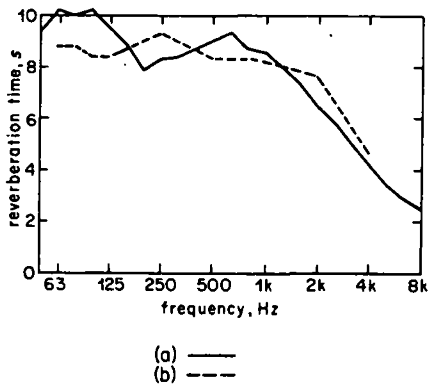

Fig. 2 Reverberation time of empty studio. (a) Model, measured (b) Studio, calculated.

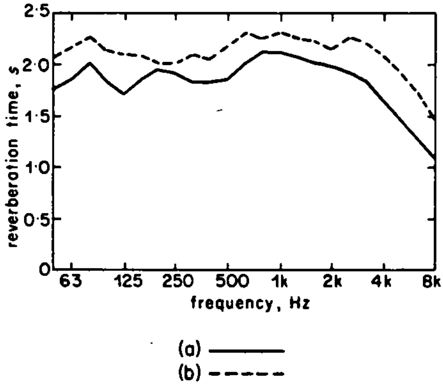

Fig. 3 Reverberation time of the completed studio. (a) Studio, (b) Model.