The suitability of additive manufacturing materials in a 1:10 scale reverberation chamber

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ABSTRACT
Acoustic scale modelling continues to be an important tool in auditorium design, however the main obstacle to its use is the difficulty, time and cost associated with creating suitably accurate models. Additive manufacturing (AM), or 3D-printing, presents exciting new possibilities to reduce or even overcome these challenges. The acoustic properties of AM materials required investigation. A 1:10 scale reverberation chamber was constructed and two materials, ABS plastic and nylon, were tested to ISO 354. This paper reports the results of the experiments.

Keywords: Scale modelling, 3D-printing, Sound absorption
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1 INTRODUCTION
As the way sound interacts with a space is very complex and hard to predict, it has always been common practice to create a model of some kind to test the acoustic performance at the design stage of a building. This is particularly apparent with concert halls because only the reverberation time can be predicted without such assistance (and not always accurately) when other objective measures such as lateral energy, diffusion, clarity and sound strength have been shown to be important when assessing acoustical quality.

1.1 Basic principles of scale modelling
The traditional approach is to construct an accurate scale model of the proposed space and test the acoustics very much how one would test a real room. Acoustic scale models date back to work by Spandöck in the 1930s (1) and utilize the very simple relationship between the speed of sound \(c\), frequency \(f\) and wavelength \(\lambda\) shown in Equation 1.

\[ c = f\lambda \]  

As the dimensions in a model are scaled down, it can be said that the wavelengths of a particular frequency are scaled down in accordance with it. Assuming the speed of sound remains constant because the same medium (i.e. air) is used, it can be seen that the frequencies of the sound in question must be increased in direct proportion. For example, a 1 kHz sine tone in a full-scale space would be modelled using a 10 kHz sine tone in a 1:10 scale model.

1.2 Small modelling’s relevance
The work by Spandöck was developed by the likes of Jordan (2) and Barron (3), and by the 1980s it had become a sophisticated discipline that was a central process in auditorium design (4). This prominence has waned over the last 30 years as computer-modelling techniques have increased in accuracy and reliability, thus avoiding its major drawback: the time and cost associated with constructing a suitably accurate model. Barron commented in the 1980s that to test the design of an auditorium in this way would generally equate to 1% of the total build cost, approximately double the usual fee for acoustic consultancy with most of this extra cost accountable to the model construction.

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This was a major barrier to their use even when computer simulation was not a viable alternative. Even when the cost was surmountable, models could take weeks or even months to build and generally required the employment of specialist model makers. Add this to the considerable time required to carry out measurements, and it is easy to conclude that it is a rather problematic design tool. This led to advocates working with models at smaller scales such as 1:50 rather than 1:10. Although this puts extra requirements on the data acquisition system due the frequencies of interest being higher (in excess 100 kHz rather than 50 kHz), such an approach did prove successful without ever fully overcoming the obstacle of time and cost (4).

Such concerns may appear to be a relic of the past: computer modelling techniques today allow unlimited design changes with ease and are able to supply a vast assortment of reliable acoustic data in minutes and hours, rather than weeks and months. But although they enjoy a far from mainstream use, scale modelling techniques are still called upon today. At the recent Auditorium Acoustics conference in Paris (October 2015), no less than 5 concert hall designs made use of scale models in some way (5,6,7,8,9), the justification being that for all their intricacy and flexibility, computer models inherently simplify the complex behaviour of sound whereas scale models represent it perfectly.

That is not to say there is an either/or debate. What scale models offer is a way of ensuring that what a computer model is telling you can be relied upon. One such example is the Philharmonie de Paris (6) where a 1:10 scale model was used to validate the acoustic predictions of the concert hall’s coupled volume, something computer models have been shown to poorly represent due to their oversimplification of diffraction (10). Perfect soundwave representation also makes them valuable for research into sound behavior.

1.3 Aims and objectives

Having established that the motivation to use scale modelling remains significant in some cases, the question is can the major shortcoming, i.e. the costly and time consuming construction process be improved upon? A potential solution to this may lie with additive manufacturing (AM), also known as 3D-printing, a technology long tipped to revolutionise many industries. Yet as things stand, little exploration as to its incorporation has been carried out.

The aim of this paper is to start a dialogue as to how this technology could benefit the production of scale models in the coming years. Its implementation is likely to be a gradual one and is prone to change as quickly as the technology develops. With this in mind, the first objective is to determine that the acoustic properties of available materials are comparable to materials currently used: this forms the sole aim of this paper. If there is strong agreement, then such materials can be incorporated with confidence.

2 ADDITIVE MANUFACTURING (AM)

AM covers a large number of technologies, all with the same fundamental property: building objects by the application of successive layers of material. Two of the most common are fused deposition modelling (FDM) and selective laser sintering (SLS), which form the basis of this paper. The general process chain is identical for all methods: after the part has been defined, it is drawn in a computer-aided design (CAD) programme and is then typically converted into a stereolithography (STL) file. The machine then slices this STL file into numerous horizontal segments, which then form the layer-by-layer additive process of production.

2.1 Fused deposition modelling (FDM)

In an FDM printer, a spool of plastic wire known as the filament is fed into the machine, which heats it up to its melting point and is then deposited by a fine nozzle onto a platform in discrete lines where it immediately hardens. Once a horizontal layer is complete, the platform lowers and the printer begins the next layer by applying more plastic on top. An additional nozzle supplies support material since lines cannot be deposited on thin air. This is most necessary when building shapes with overhangs for example, and this support material can be removed either by cutting it away or by dissolving it in a special chemical bath. An important design consideration is that extreme overhangs cannot support material; most machines have a typical limit of 45°.

As the material is laid in distinct lines, the concentration of these lines can be adjusted depending on the machine, allowing for less material to be used and thus different densities. The “sparse” setting
builds solid parts with a semi-hollow honeycomb structure allowing for parts to be up to 65% lighter than subtractive methods. This process is typically limited to plastics due to the process and there are numerous types available, ABS being the most typical.

2.2 Selective laser sintering (SLS)

With the SLS process, the material starts off in powder form. The chamber of the printer is heated to just below the melting point of the power and a laser then draws thin lines, melting and fusing particles together to form a layer of material. A new layer of powder is distributed over the top and the process is repeated. Unlike FDM, this process doesn’t require additional support material because the remaining powder that is not sintered by the laser acts as a support.

The materials are generally solid although with a slight porosity due to the nature of its creation. Nylon is the most typical material, although others have been developed including wood (made from wood chip powder) and metals such as aluminium.

2.3 Benefits of AM to scale modelling

The methods described in the previous sections are in stark contrast to traditional manufacturing methods, which are either subtractive or employ moulds. This leads to the most fundamental virtue of AM: ‘manufacturing complexity is free’, as eloquently described by Lipson and Kurman (11). That is the cost, time and most crucially skill to produce very complicated shapes with a very high level of accuracy is the same as producing very simple ones. On top of this, a single AM machine can create an almost unlimited variety of shapes therefore negating any requirement to purchase or modify machinery or train machine operators. This flexibility and new costing model are the two main reasons why AM is being tipped to revolutionise manufacturing. It especially lends itself to one-off products and prototyping where it is already a very valuable tool.

From this, the potential benefits to the production of acoustic scale models are obvious. AM could lessen or even remove the need for highly skilled model makers and place the acoustician at the heart of both the model design and manufacturing process. On top of this, it could allow complicated geometric forms to be created with ease without any extra cost implication. As well as offering potential cost savings, it could potentially allow for changes to be more readily made to the model at various stages of the process.

That is not to say AM can provide an instant revolution to this field. At present, the maximum print-size of available machines is an inhibitive factor: the largest desktop printers have a maximum dimension of approximately 300 mm, with only the largest industrial printers able to print parts up to 1000 mm in size. Even a 1:50 scale model of a large concert hall is likely to have dimensions in excess of 1000 mm making printing in one single part impractical. Also the cost of such materials at present doesn’t make it a more attractive option in comparison to traditional methods of manufacture, but is likely to become more affordable in the coming years.

It has been said that AM is ‘still in its infancy in terms of the developmental “S-curve” and that innovations are continuously appearing (12). These are likely to include the ability to print larger parts, the introduction of new materials, the ability to print a model consisting of multiple materials with a single machine, and the ability to create hybrid materials with unique properties. Ultimately, the possibilities for this technology to benefit acoustic scale modelling are vast.

3 EXPERIMENTAL PROCEDURE

As a starting point to this research, it was decided to measure the acoustic absorption of two common AM materials.

- ABS plastic, manufactured using fused deposition modelling (FDM).
- Nylon, manufactured using selective laser sintering (SLS)

It was decided to test them with a method based on the ISO 354 standard (13) as this is the generally accepted approach. This is the measurement of the random incidence sound absorption: that is the average absorption coefficient over all angles of incidence. A scale of 1:10 was chosen, partly due to the performance of the hardware available (described in 3.1), but also because data for a commonly used scale model material (MDF) were available at this scale. Comparing results with known materials will not only aid conclusions as to their suitability, but also with determining the validity of the testing procedure. This is particularly important as it is a well-known limitation of the ISO 354 method that obtained results can vary significantly for different reverberation chambers.
3.1 Data acquisition system

Due to the interest in ultrasonic frequencies, the hardware required to carry out measurements in a scale model obviously differs from that of measurements in a full-scale space. Such a system was not available at the University, so had to be developed from scratch and Figure 1 shows a simple schematic of the system employed. Further details are available in (14).

3.1.1 Microphone

Small diaphragm microphones are necessary as they have a superior frequency range and have less influence over the sound field at high frequencies. Typically, ¼” or ⅛” capsules are utilised: A Brüel and Kjaer 4135 ¼” microphone was available and according to test data benefits from a flat frequency response up to 100 kHz (±2 dB at 0° incidence). It should be noted the directionality above 15 kHz (1.5 kHz at 1:10 scale) is significant and an ⅛” microphone with a nose cone would have provided superior performance. But comparable ¼” capsules have been used in auditorium testing e.g. (15).

Small capsule microphones inherently have a lower sensitivity, so was connected to a Brüel and Kjaer Nexus 2690 conditioning amplifier in order to provide an optimal signal. This was connected to an M-Audio Firewire 1814 sound card running a sample rate of 192 kHz which was shown to have a flat frequency response (-2 dB) up to 80 kHz.

3.1.2 Sound source

The requirements for the sound source mirror that of the microphone: that is the production of adequate sound levels throughout the desired frequency range, and with ideally omnidirectional propagation. One approach is to create a miniature dodecahedron loudspeaker such as devices created by Hidaka (16) and Jeon (17). The challenge was to locate drivers with a sufficient frequency response and sufficiently small so the cabinet would not interfere with the sound field to an unsatisfactory degree. It was decided to adopt this approach for practical reasons, i.e. it is relatively straightforward to design and implement, but the alternative spark-source method often employed, e.g. in (3), holds certain advantages and will be considered in future developments.

The selection of electromagnetic transducer was made based on size and available data, details of...

Figure 2: 3D-printed miniature dodecahedron loudspeaker
which are available in (14). The enclosure was designed, 3D printed in ABS plastic using an FDM machine and the speakers glued in place, see Figure 2. Each face of the final design consisted of an equilateral pentagon with sides of 26 mm, providing a radius of 36 mm. It was powered using a simple 20 W Class-D power amplifier.

The loudspeaker was tested in London South Bank University’s anechoic chamber. The average frequency performance in third octave bands is shown (full-scale equivalent at 1:10 scale) in Figure 3, based on 18 measurement positions at a distance of 30 cm. This shows that there is significant energy in all third octave bands of interest, suggesting its suitability for measurements up to the 5 kHz third octave band at 1:10. ISO 3382-1 states that sound levels are required to be 35 dB above background in order to measure $T_{20}$ reliably (18) but this requirement has to be increased for the high frequency bands if numeric air-absorption correction is applied, with a decay range in excess of 60 dB being necessary (19). From this it can be concluded that sound levels produced by the loudspeaker are sufficient to derive $T_{20}$ at all third octave bands from 125 Hz up to 4 kHz at 1:10 scale.

![Figure 3: Frequency response of the miniature dodecahedron loudspeaker (scaled 1:10)](image)

The directivity according to the anechoic measurements is plotted in relation to the ISO 3382-1 requirements in Figure 4 (overleaf). This shows that the directivity is not ideal and can be partly put down to the dimensions of the speaker: a radius of 36 mm gives a theoretical cut-off frequency of approximately 4.5 kHz (450 Hz at 1:10 scale) (20), significantly below the 10 kHz required to be comparable to full-scale loudspeakers. One method of improvement would be to adopt Hidaka’s approach and produce a secondary speaker utilising piezoelectric transducers especially for frequencies above 20 kHz (16), or to adopt a spark source as discussed previously.

3.1.3 Software

Scale model measurements require extra processing, including rescaling the measurements to the full-scale equivalent frequency range and computational correction for air absorption if required. Packages, such as the MIDAS system (21) have been developed over the years but few are commercially available: Dirac, created by Acoustic Engineering and supplied by Brüel and Kjaer being the only known example. As this wasn’t readily available, it was decided to develop a system utilising MATLAB, with the ITA Toolbox developed by Aachen University (22) providing the basis of the data processing. Further details are available in (14).

The major adaptation was the correction of excess air absorption. For a model to be accurate, the rate of attenuation due to air needs to be comparable with the equivalent frequencies at full-scale. As the equivalent distance travelled by sound within the model is scaled down in accordance with the scale factor ($\sigma$), the required rate of attenuation for a given full-scale frequency ($L_f$) must satisfy Equation 2.

$$L_{\text{eff}} = \sigma L_f$$  \hspace{1cm} (2)

As $L$ increases exponentially with frequency, the discrepancy between the two sides of equation 2 will increase. Therefore, for high frequencies (notably above 10 kHz), absorption is going to be dominated by the air in the model rather than absorption from the surfaces, and thus will result in
predicted reverberation times much shorter than reality. Replacing the air in the model with nitrogen, or reducing the air’s relative humidity to between 1 and 2 percent have both been used. However, this is a time consuming, requires a higher quality of construction and thus a costly process.

The approach carried out was to numerically adjust each step of the energy decay curve using the formula set out in (19). As the correction required is very much dependent on the atmospheric conditions, a microcomputer with a temperature, humidity and pressure sensor was synchronized with each measurement to provide accurate data. The compensation algorithm was applied to the energy decay curve after the noise was subtracted and Lundey’s method of tail correction (23) had been applied. This was to prevent the compensation from affecting the noise the floor.

3.2 The reverberation chamber

The construction of a scale reverberation chamber was necessary to promote a diffuse sound field. It was decided to construct the chamber out of 10 mm thick Perspex and the dimensions used (0.76 m × 0.63 m × 0.42 m) were a 1:10 scale representation of London South Bank University’s reverberation chamber (see Figure 5). Although this achieves compliance with ISO 354 in terms of volume and dimension ratios, it would have been desirable to construct it to be an irregular shape: something that is often very impractical at full-scale. This would reduce the density of modes at low frequencies, improving the diffusivity of the sound field and thus lead to more reliable results. However, considering the time scale of this project this wasn’t deemed practical, plus it was of potential future interest to see how the scale model compared with the full-scale space.

![Figure 4: Maximum deviation of directivity of the dodecahedron loudspeaker (1:10 scale)](image)

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![Figure 5: The 1:10 scale reverberation chamber and data acquisition system](image)

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The chamber was calibrated using the ISO 354 methodology, i.e. increasing the number of hanging diffusers (made out of 0.5 mm thick acetate) until the measured absorption coefficient of a very absorbent test specimen ceases to increase. The full-scale equivalent absorption area of the calibrated chamber is shown in Figure 6, and is compared to upper limit required to comply with ISO 354.

This shows a prominent peak most notably in the 315 and 400 Hz third octave bands, and doesn’t adhere to the requirement of being a smooth curve, with peaks and dips within 15% of the mean of the 2 adjacent bands.

The most likely explanation is due to the so-called coincidence effect. This occurs when the projected wavelength of a sound wave corresponds with the bending waves of the partition: the critical frequency of which is affected by the partition’s stiffness. At this critical frequency, the mass law where the sound reduction index increases by 6 dB per doubling of frequency no longer applies and there is what is known as a “coincidence dip” and would result in a loss of sound energy from the system. For 10 mm thick Perspex this was calculated to be approximately 3.5 kHz and thus within the 315 and 400 Hz third octave bands at 1:10 scale. At the time of writing, further investigation is required.

3.3 The test specimens

Two of the most frequently used AM materials were tested, of which rectangular slabs were printed as shown in Figure 7 (Left). ABS plastic was printed using a Stratasys Fortus 360mc FDM machine. The layer thickness was set to its highest setting (0.313 mm) and the material density was set to “sparse”, meaning the interior of the material was partially filled with a honeycomb structure. The nylon test specimen was printed by a Formiga P110 SLS machine. The layer thickness was 0.1 mm and the parts were not polished or treated. This gave it a somewhat matte finish, in contrast to the ABS sample.

Due to the size restrictions of the machines, it was necessary to print the test specimens in 4 parts, each with dimensions of 160 by 156.25 mm. This gave total dimensions of 320 by 313 mm equating to just over 10 m² at full-scale: the minimum requirement of the ISO 354 standard. The thickness of the samples was 4 mm in both cases.

The measured absorption coefficients were compared to an MDF sample of identical size and thickness. This material is typically used to create the reflective surfaces of scale models and so comparison would lead to a conclusion as to the material’s suitability. In order to validate the testing procedure, a 15mm thick MDF test specimen was compared to results obtained by Jeon (17) using a
very similar procedure.

The samples were mounted on the side wall of the reverberation chamber as shown in Figure 7 (Right). It was held in place with PVC tape in order to prevent and air gap behind the specimen. Four microphone positions and 3 loudspeaker positions were used, complying with ISO 354.

4 RESULTS

Figure 8 shows the measured absorption coefficients of 15mm thick MDF, in comparison to data collected by Jeon (17). Initially the MDF was mounted with 0.5mm thick acetate (type A mounting, fixed with PVC tape) in order to reduce the so-called “edge effect”. However, this appeared to have a negative impact on results, particularly in the mid-frequency range. This was most likely due to the fact a perfect seal between the specimen and frame was not achieved. The results obtained for 15 mm thick MDF without a frame were largely in agreement. Jeon doesn’t state whether the edges of his samples were sealed, but because of this it was decided not to mount specimens in any experimentation. The extra absorptive area of the edges was taken into account by adding this to the surface area.

![Figure 7: Left - The AM test materials. FDM ABS plastic (Top), SLS Nylon (bottom)  
Right - AM material being tested within the reverberation chamber](image)

![Figure 8: Comparison of the measured absorption coefficients (1:10 scale) of 15mm MDF with known data](image)
is limited to the thickness tested (i.e. 4 mm) and scale (i.e. 1:10). Observing the results, it can be seen that the ABS specimen was slightly more absorbent at low frequencies (100 – 315 Hz) and that nylon was more absorbent at high frequencies (2 kHz – 4 kHz). This can be attributed to ABS being a less dense material (due to its honeycomb structure) and thus expected to have a lower stiffness. Even so, the differences observed cannot be considered significant.

5 CONCLUSIONS AND FURTHER WORK

The aim of this paper was to explore how additive manufacturing (AM) could aid the production of acoustic scale models for performance spaces. The challenges of the scale modelling process were highlighted, and the potential benefits of using AM materials put forward: namely that complex geometries such as balcony fronts and reflectors could be created more simply and with a guaranteed greater accuracy.

A 1:10 scale reverberation chamber was constructed; and although the diffusivity and uniformity of the sound field within the empty chamber wasn’t desirable, it was adequate to determine comparable absorption coefficients of different materials. In fact, the measured absorption of MDF showed a strong agreement with data obtained from a previous and unrelated procedure (17) leading to the conclusion that the data acquired was suitably reliable.

Measurements of ABS and nylon, produced using two different AM methods both showed a strong acoustic similarity to that of MDF, leading to the conclusion that both could be incorporated into 1:10 scale models with confidence.

Although this work has had a positive outcome, this is only the start of exploration into how additive manufacturing could be used and it is hoped this will start a greater dialogue on how this exciting technology can be incorporated into this field.

The obvious initial steps are to test the suitability of these materials at smaller scales, namely 1:50. Due to the current size restrictions placed on parts and the cost of production, it is envisaged that working at this scale will see the greatest benefit, especially in the short term. Such tests couldn’t be carried out here due to the unavailability of suitable equipment. Developments to the data acquisition system are planned and it is hoped this will be possible in the future. It is certainly of prime interest to see the absorptive qualities at frequencies in excess of 100 kHz, necessary at 1:50 scale, because it is known that wood requires varnishing to be suitably reflective in this region (3). Determining whether the AM materials tested require treatment, i.e. polishing, is of prime importance.

Additionally, due to cost constraints only one thickness was tested and thus the results obtained are somewhat limited. Although 4 mm is in all likely hood a reasonable thickness for concert hall detailing (especially at 1:50), the performance of higher thicknesses is of concern. This is particularly apparent with the FDM process where “sparse” densities with a honeycomb structure can be used. It will be important to know whether this setting is suitable at greater thicknesses as it certainly is beneficial in terms of cost.

The materials under test were two of the most common but there are numerous others available,
including rubber like materials and SLS powders derived from wood or even metals. The number of materials available is bound to grow in the coming years and is likely to include porous materials such as foam that could be of significant interest when it comes to modelling audiences. Assessing the suitability of these materials will be required as they become available and usable.

Beyond testing the suitability of AM materials, the next stage is to actually incorporate them in to scale models. At this point it is not envisaged that an entire model will be constructed in this way, but rather it is reserved for complex, curved surfaces where it will be most beneficial. How this can be done practically requires careful thought and investigation. Cost/benefit analysis will also be necessary, as due to the rather speculative nature of this paper such considerations were deemed premature. This is likely to change as the technology improves and becomes more accessible, so will need to be regularly revisited.

As well as concert hall design, this technology certainly could add benefit to research, particularly investigation into diffusion and scattering behaviour where the ability to create very complex diffusing shapes is of interest. It is hoped this paper helps to highlight the potential uses of AM in acoustics, and that in the future its full benefit to design and research can be realised.

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