PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Absorbing target for radiation force measurements below 1 MHz

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ABSTRACT

Radiation Force Balance (RFB) measurements are a widely accepted and standardised method of determining ultrasonic power. Many RFBs incorporate an absorbing target and at frequencies above 1 MHz there are a range of ultrasonically anechoic materials that are available for this purpose. Below 1 MHz wavelengths increase and the range of candidate materials for use as absorbing targets is reduced.

This paper introduces a new anechoic target material specifically designed for use in the frequency range 200 kHz to 1.5 MHz. It is based upon a pre-existing and proven material formulation but with modifications to its geometrical front surface to enhance its echo reduction. Experimental results are presented of both its performance in isolation, as well as part of a lower frequency RFB system.

Keywords: Radiation Force Balance, Anechoic, Absorber

1. INTRODUCTION

A Radiation Force Balance (RFB) is a device that permits rapid quantification of ultrasonic power. Their use has become sufficiently well-established that there is an IEC standard dedicated to the design and performance of RFBs (1). All RFBs require some form of ultrasonic absorbing material, either directly in the acoustic pathway (as an absorbing target) or indirectly to absorb the signal scattered from a reflecting target. The efficiency of these absorbing materials is critical to the functioning of the RFB and therefore performance levels for absorbers are specified within the relevant standards for physiotherapy (1) and HITU (2) regimes.

Absorbing materials are commercially available (3) that meet the criteria established in the relevant IEC standards (1) (2) for the frequency range 1 MHz to 20 MHz. Recently however, there are a number of therapeutic ultrasound devices coming to market with operating frequencies below 0.5 MHz and a forthcoming IEC standard (4) will cater for these. Consequently, absorbing materials designed for operation below 1 MHz are required to enable RFBs to operate in this frequency range.

In this study four materials were characterised over the frequency range 0.2 MHz to 1.5 MHz to assess their echo reduction. Three of these are commercially available as AptFlex F28, AptFlex F28P and AptFlex F48. This paper also introduces a new material AptFlex F48P, specifically designed to provide superior performance in the sub-1 MHz region. All these materials (produced by Acoustic Polymers Ltd) are micro-bubble filled materials with an acoustic impedance matched to water. AptFlex F28 and F28P are optimised for frequencies above 1 MHz and have previously been characterised by the National Physical Laboratory (NPL) in London over the frequency range 1 MHz to 20 MHz at room temperature. The "P" suffix indicates that the material has a pyramidal structured surface.

AptFlex F48 is designed so that at room temperature it offers greater absorption below 1 MHz and has also had its echo reduction assessed at NPL over the frequency range 200 kHz to 1.0 MHz. The new material AptFlex F48P incorporates a structured surface akin to the differences between F28 and F28P albeit with the dimensions of the structured features scaled to longer wavelength; F48P has yet to be tested at NPL.

2. THEORETICAL BACKGROUND

The definition of Echo Reduction (ER) from (5) is the reduction in pressure amplitude of an

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ultrasonic plane wave resulting from its reflection from an interface between two media,

$$ER = -20\ log_{10}\left(\frac{p_r}{p_i}\right)\ dB \tag{1}$$

where

p_r is the pressure amplitude of the reflected longitudinal wave;

p_i is the pressure amplitude of the incident longitudinal wave.

Direct measurement of the incident pressure is often difficult to achieve without introducing perturbations to the incident field itself. Therefore, as detailed elsewhere (5), echo reduction is often evaluated by considering the reflection from a reference reflector (typically a polished acoustic mirror of known properties and thickness that is long relative to wavelength). Echo reduction is then calculated as

$$ER = -20\ log_{10}\left(\frac{p_r}{\hat{p}_r}\right)\ dB \tag{2}$$

where

$\hat{p}_r(f) = p_r(f)\,.R_{p,reflector}$. For a stainless-steel reflector immersed in water at 20°C, $R_{p,reflector}$ has a value of 0.9389.

3. DESIGN RATIONALE AND IMPLEMENTATION

The pressure reflection coefficient at the interface between two different media is given by

$$R_p = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{3}$$

where

Z_1 and Z_2 are the characteristic impedances of the two media.

If the two media have the same characteristic impedance, then there is no reflection at the interface. However, this is not a sufficient condition for an effective anechoic material since once acoustic energy passes into the material it must then be absorbed. Absorption is typically represented mathematically by allowing the physical quantities to be complex-valued. For the materials used in this study, the real component of the impedance of the base materials is closely matched to water. At the frequencies of interest to this study the absorption in water is negligible, and thus the imaginary component of the acoustic impedance of water tends to zero. For an absorbing material however, this is not the case and the lossy/absorbent behaviour can be represented by a non-zero imaginary component. Using the equation for reflection coefficient, the impact that an imaginary component on the echo reduction can be seen.

For the situation of an anechoic material in water, let the impedance of the water be Z_1, and the impedance of the absorbing medium be $Z_2 = Z_2' + jZ_2''$. The pressure reflection coefficient is thus

$$R_p = \frac{Z_2' + jZ_2'' - Z_1}{Z_2' + jZ_2'' + Z_1}. \tag{4}$$

Assume that the real part of the impedance of the absorbing material is matched to water (i.e. $Z_2' = Z_1$). The excess pressure reflection coefficient due to the loss component is then expressed as

$$R_p = \frac{(Z_2'')^2 + j2Z_2'Z_2''}{(Z_2'')^2 + 4(Z_2')^2} \tag{5}$$

This is a particularly informative result. To obtain an R_p value with an amplitude of 0.01 (equivalent to an echo reduction of 40 dB) would require the ratio of $\frac{Z_2''}{Z_2'}$ to be 0.02. For clarity, even though an anechoic material has a real part of impedance that is matched to water, it cannot have an imaginary component greater than $^{1}/_{50}{}^{th}$ the size of the real part if echo reduction is to remain below 40 dB. However, such a low level of loss would require anechoic materials to be many wavelengths thick in order to achieve experimentally useful levels of absorption and would therefore be impractical.

Note that Equations (3) to (5) are all derived for a planar interface between the two media (as shown in the left-hand section of Figure 1). An alternative approach, to overcome the limitations exposed by Figure 1 and permit the use of materials with higher losses, would be to ensure there is not an abrupt transition between the lossless and lossy media.

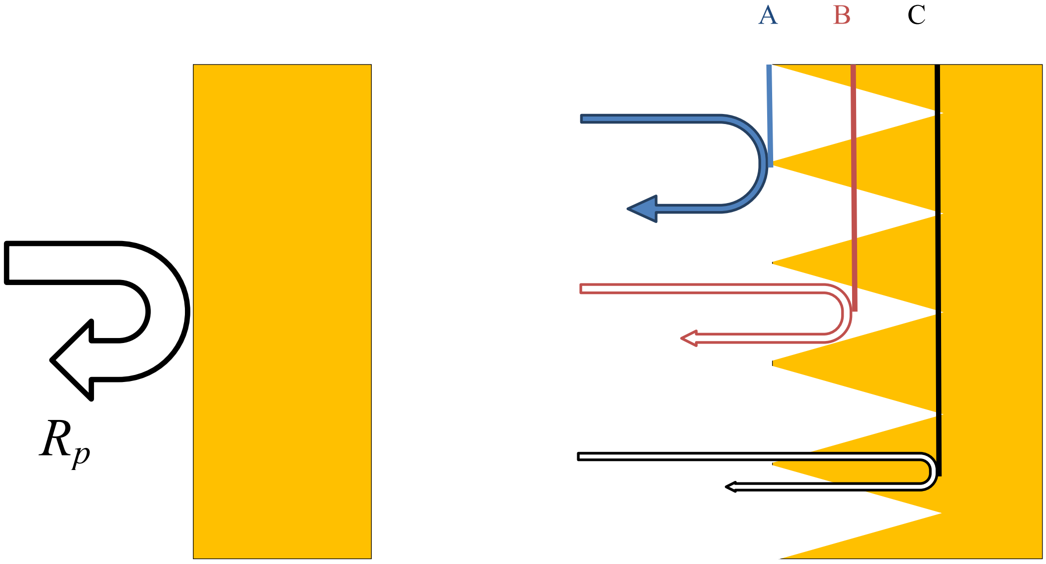

Figure 1 – Surface geometry and its impact upon reflections

Consider an absorbing material with a structured surface as shown in the right-hand section of Figure 1. An incident wave at plane A (the apex of the structured wedges) encounters an area averaged acoustic impedance that is dominated by the water surrounding the material surface; the contribution from the lossy component of the anechoic material is small and thus there is only a small reflection from this position. As the incident wave proceeds from left to right it sees gradually more and more of the contribution from absorbing material. However, this increasing contribution to the imaginary part of impedance increases gradually, not abruptly. By the time the wave has reached plane B, 50% of the surface it encounters has only a real component whilst the other 50% has an additional imaginary component. Upon reaching plane C, the wave experiences all of the imaginary component of the lossy material. There will be some small reflection from each of these planes, but their sum total will be less than in the planar case. In practice, there are not the 3 discrete planes A to C, but gradient in acoustic impedance within infinitesimal changes from one position to the next. This transition in impedance permits the use of much more lossy materials.

Structured surfaces offer further advantages as well. As shown above, the reflections occur at spatial distributed planes and thus there will be phase differences between each of the reflected wave components. Thus, there will be interference effects between the different reflected wave components. Moreover, the incoming waves are not arriving at normal incidence to the surface of the material and therefore will be reflected in a range of directions. These latter two effects serve to change a specular reflection (from a planar surface) into a more diffuse one (from a structured surface).

These effects have previously been shown to have a significant enhancement on the performance of higher frequency anechoic materials, and that philosophy is applied within this paper to materials operating below 1 MHz. One final note is that care needs to be taken to ensure that reflections from a structured surface do not exhibit coherent reflections at discrete angles (corresponding to normal incidence on the sides of wedge structure). For this reason, when designing the new absorbing target described in this paper, the wedge structures have 4 different orientations in order to absorb incoming waves from various directions. A photograph of the structured surface of the new low frequency absorber, called F48P, can be found in Figure 2. The total thickness of the tile is only 20mm whereas the wavelength at 200 kHz in water is 7.4mm; the tile is thus less than 3 wavelengths thick at the lowest frequency used in this study.

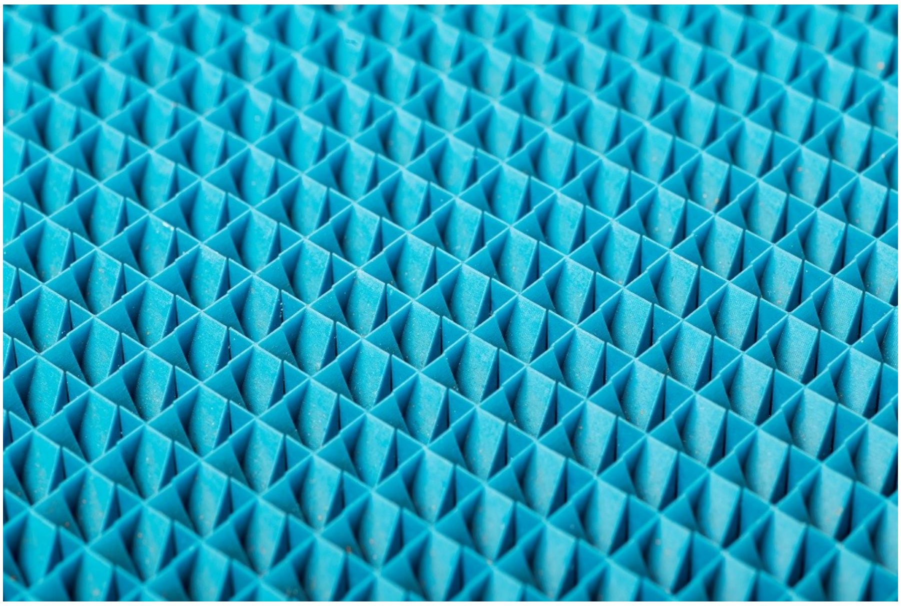

Figure 2 - Structured surface of F48P

4. EXPERIMENTAL METHOD

Echo reduction was measured on material samples using the method detailed in a forthcoming specification IEC 63081 (5) and summarised for completeness here. Three transducers (with centre frequencies 300 kHz, 500 kHz and 1 MHz) were used to cover the required frequency range. A polished stainless-steel block (50mm thick) was used to approximate a perfect reflector. Each transducer was used in pulse-echo mode and its rotation was adjusted in two rotation axes to maximise the reflected signal. A reference reflection signal was first acquired by looking at the signal reflected by the stainless-steel reflector. The target material was then inserted between transducer and reflector and the transducers' axial position was then adjusted to ensure that the signal reflected from both sample and reference reflector had the same time delay. Signals were time-gated to eliminate spurious reflections from other parts of the experimental apparatus and the echo reduction was determined, as a function of frequency, using Equation (2).

During the characterisation of structured materials, angle of incidence can have a substantial effect on the value of echo reduction recorded. This is due to the back reflections at certain combinations of angle and frequency resulting in potential constructive and destructive interference effects. Consequently, signals were acquired at seven different angular orientations and averaged.

F48 has previously been characterised by the NPL at frequencies below 1.5 MHz. This material was therefore chosen as a candidate material to validate the in-house experimental configuration for the determination of ER. Figure 3 displays the results from Precision Acoustics Limited (PAL) and NPL measurements and the close agreement provides confidence in the validity of the method.

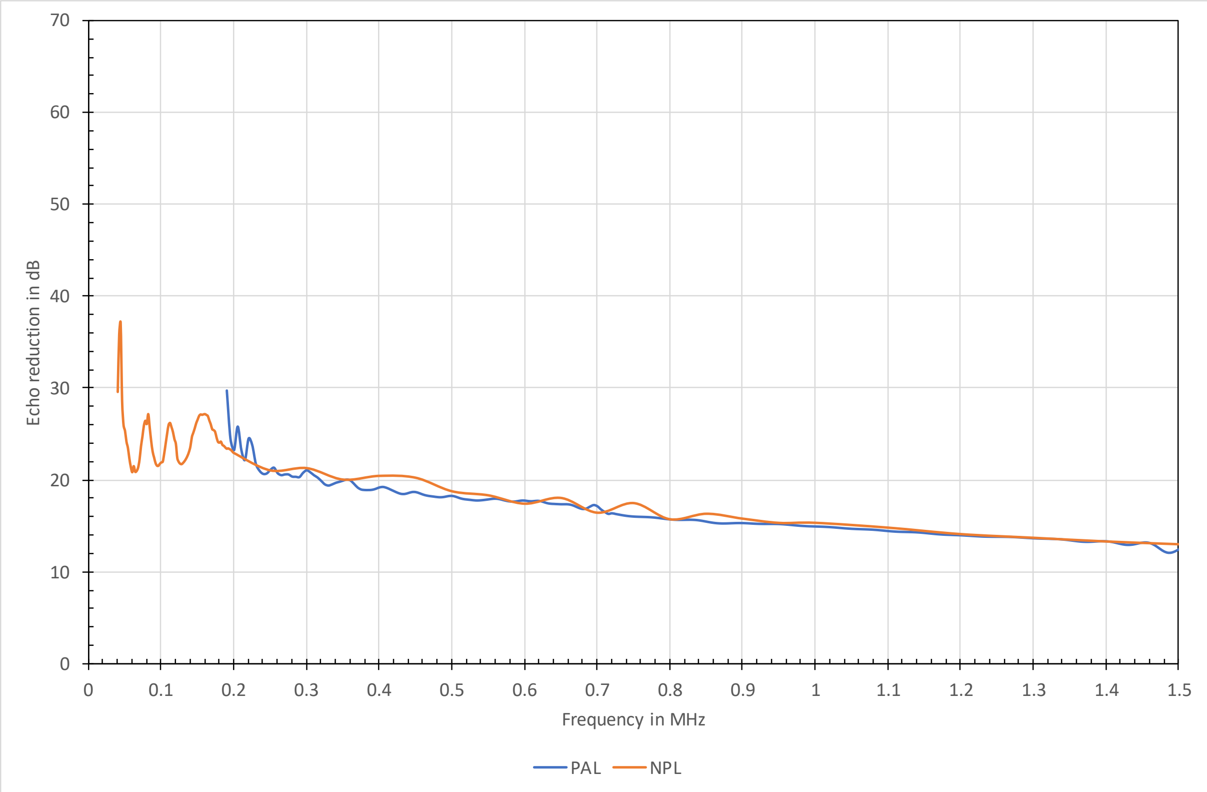

Figure 3 - Echo reduction of F48 (validation exercise)

The commercially available higher frequency absorbers F28 and F28P were then characterised in the range 0.2 MHz to 1.5 MHz. Whilst the echo reduction of this material has been determined above 1 MHz, no data below 1 MHz has previously been obtained. This data can be found in Figure 4. Finally, the low frequency absorber F48 and the newly developed structured variant of this material F48P were quantified. The echo reduction for these materials is displayed in Figure 5.

5. RESULTS AND DISCUSSION

As seen in Figure 4, F28's echo reduction performance remains relatively constant at 22 dB across the frequency range used in this study. Below 250 kHz F28 and F28P exhibit statistically identical ER performance. However, as frequency increases, adding structure to the material drastically improves its echo reduction. At frequencies above 1.1 MHz, the structured F28P is at least 15 dB better than the non-structured F28. Interestingly, although F48 was optimised for sub-1MHz operation, a comparison between Figure 3 and Figure 4, shows that F28 has superior ER performance above 250 kHz.

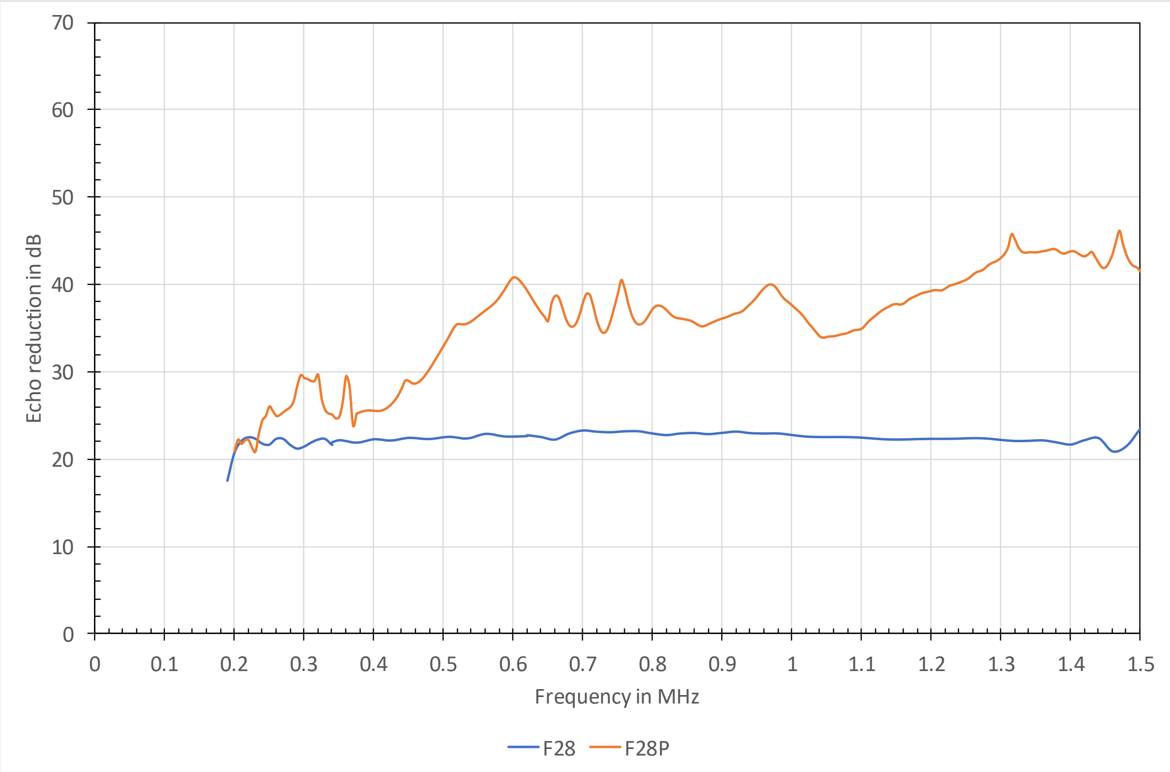

Figure 4 - Echo reduction of F28 and F28P

The effect of a structured surface is even more evident for the low frequency absorbing materials (see Figure 5). Even at 250 kHz the structured surface enhances the echo reduction by 15 dB. At 500 kHz F48P exhibits 25 dB more echo reduction than F48 and this enhancement extends to more than 35 dB above 1.1 MHz. The ER of F48P is more than 50 dB in the range 0.75 MHz to 1.45 MHz.

An ER of 50 dB corresponds to an amplitude reflection factor of 0.32%. This is an order of magnitude better than the performance requirement (3.5% amplitude reflection factor) specified in the relevant IEC standard (1). Moreover, this means that the new material F48P exceeds this performance requirement at all frequencies measured in this study.

The plots shown for F28P and F48P are not as smooth or flat as the unstructured materials due to averaging over seven positions and the scattering caused by the pyramids.

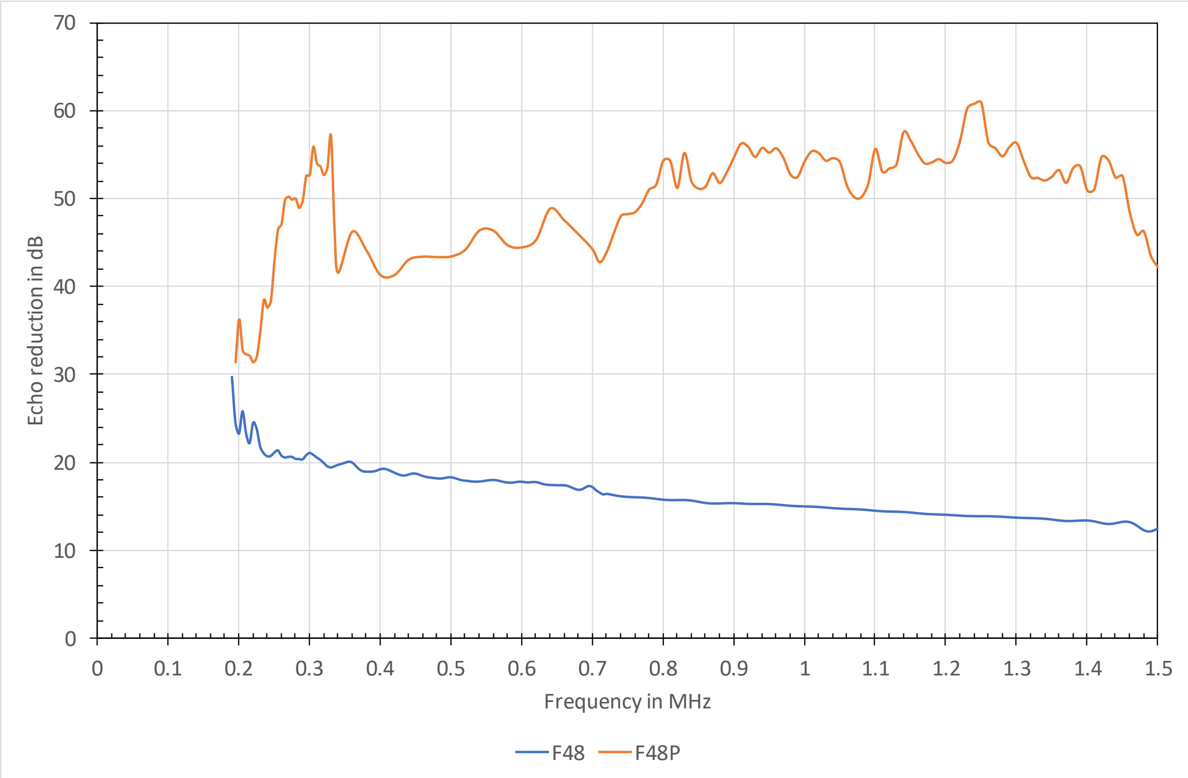

Figure 5 - Echo reduction of F48 and F48P

6. IMPLEMENTATION WITHIN AN RFB

The results thus far indicate that the new material has acoustic properties that exceed those required of an absorbing RFB target. The only task remaining is to install the new material in an RFB and evaluate its performance as a complete system.

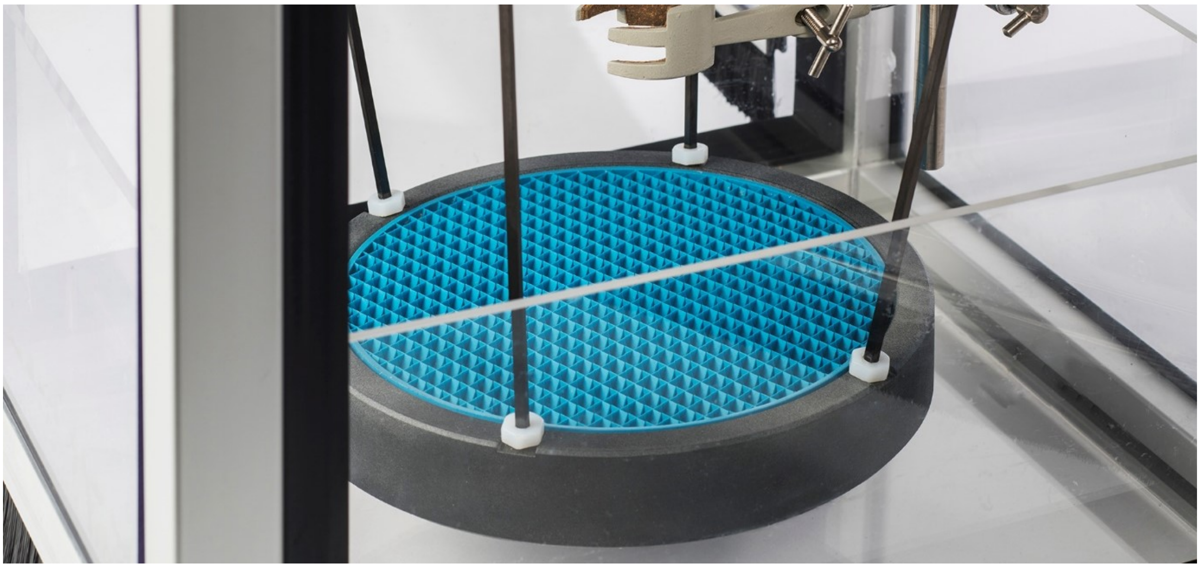

Figure 6 - F48P installed as an RFB target

Figure 6 shows a sample of F48P mounted as an absorbing target and suspended below a micro-balance to act as an RFB. This balance was sent to NPL for calibration over the frequency range 400 kHz to 600 kHz. The RFB correction factor (the ratio of the ultrasonic power displayed by the RFB to the applied power) is shown in the table below.

Table 1 – Correction factors obtained during RFB Calibration

Frequency	Correction factor
400 kHz	1.00
450 kHz	1.00
500 kHz	1.00
550 kHz	1.00
600 kHz	0.99

The overall expanded uncertainty of the NPL measurement is 7%. Further work is ongoing to obtain NPL calibrated values for RFBs based upon F48P over a wider frequency range. With a correction factor so close to unity, the F48P target is providing an excellent approximation to an idealised absorbing target.

7. CONCLUSIONS

Echo reduction measurements for new and existing absorbing target materials are presented and were conducted using the method described in the forthcoming IEC specification (5). This paper demonstrates how crucial adding structure to the target material is when maximising echo reduction for anechoic materials. Even when the real part of impedance is matched to the surrounding media, an abrupt transition in the imaginary component limits the achievable ER. It was shown in this paper that applying a structured surface to the anechoic material provides a gradual, spatially distributed, impedance transformation. As a consequence, high echo reductions can be achieved in a tile that remains spatially compact.

The modifications to the structure of F48P improve the ER by at least 20 dB above 250 kHz. F48P outperforms all the materials characterised. Intriguingly, F28 has a greater echo reduction than F48 from 400 kHz upwards. Over the frequency range 200 kHz to 1.5 MHz, F48P has a reflection factor below the limit specified in the relevant IEC standard (1). It is thus a suitable RFB target for standard compliant measurements. An F48P target has been calibrated at the NPL as a part of a radiation force balance to accurately measure ultrasonic power from 400 kHz to 600 kHz.

8. REFERENCES

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