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MODULAR ACOUSTIC DIFFUSER:

The development and performance of a modular acoustic diffuser

R. Walker, B.Sc.(Eng), C.Eng., F.I.O.A., M.I.E.E. *and* M.D.M. Baird, M.I.E.T.

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THE BRITISH BROADCASTING CORPORATION

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Summary

The development of a prototype modular acoustic diffuser into a commercially reproducible product is described. The difficulties with materials, manufacturing processes and with fire-safety considerations are discussed. Acoustic measurements carried out on the final production modules showed that the diffuser met the acoustic requirements, despite simplifications and departures from the theoretical construction. In near-field conditions typical of installations in small studios and control rooms, the reflection characteristics depart significantly from the predictions of the far-field theory.

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1. INTRODUCTION

The use of special acoustic diffusing elements in the design of many types of room is commonplace. Some form of deliberate acoustic diffusion has been incorporated into studios virtually since the beginning of broadcasting. More recently, structures based on number theory have been developed [1]. These overcome many of the defects inherent in simple geometric diffusing shapes and have achieved wide acceptance in studios, control rooms and public performance spaces [2–5].

In order to assist in the control of one particular type of acoustic problem, the BBC developed a type of acoustic diffuser which did not then exist in a commercial form [6].

Tests on this modular diffuser, and an experimental installation, showed that it dramatically reduced the problem for which it had been specially designed. It was also generally applicable, especially as it conformed to the standard dimensions of the most common kind of modular acoustic treatment, and to the dimensions of standard suspended ceiling structures (at least, metric ones).

The construction of the prototype diffusers was expensive (at least, it was thought to be so at the time) and the resulting diffuser was relatively unattractive and heavy. However, all of the original tests and the experimental installation were done using those hand-assembled, prototype modules. In addition, it later became evident that the experimental modules did not have a very long service lifetime. In the test installation, over a period of about three years, the modules eventually began to fall to pieces, because of creep in the adhesive. Despite this, the users of the area containing the experimental installation were reluctant to permit its removal until a replacement batch of diffusers had become available.

2. ACOUSTIC BACKGROUND

The theoretical background to the design of diffusing elements based on number theory is given in Refs. 1 and 3. In brief, such a diffuser consists of a one- or two-dimensional array of rectangular open ‘wells’ of differing depths. The depths are arranged so that phases of the reflections from their top surfaces (that is, after the sound wavefront has travelled from the top of the well to the bottom and back again) form an interference pattern, as though from an irregular diffraction grating. By appropriate design, it is possible to create diffraction patterns corresponding to (nearly) uniform reflection; that is, creating an approximation to Lambertian reflection in either two or three dimensions, depending on the type of diffuser.

The background and theoretical basis of the BBC design is given in Ref. 6. The numerical basis of that particular design resulted not in a uniform reflection pattern but in a selective cancellation of the reflected energy in the specular direction, at some frequencies. The otherwise uniform reflection pattern contained a null in the direction where a flat plate would have had its maximum response. This module was primarily intended to diffuse the mid-frequency sound energy which otherwise gets trapped between ceiling and floor surfaces in many studios and control rooms*. In the BBC-design, the side-walls of the wells were omitted. This modification greatly simplified the construction, without significantly affecting the acoustic performance, at least for normal-incidence sound.

The final design of the modular diffuser consisted essentially of a 12 × 12 array of square-section prisms of different heights, arranged adjacent to each other. The cell size was nominally 47.5 mm square and the heights ranged up to 200 mm. Fig. 1 *(overleaf)* shows the general appearance. The overall dimensions of the module were 594 × 594 mm, to fit into standard 600 mm-centre suspended ceiling grids.

3. PROTOTYPE CONSTRUCTION

The prototype diffusers were made from square-section rigid polyvinyl chloride (pvc) tube of about 2 mm wall thickness. This material was not available as a standard product with a section of 47.5 mm. Instead, for the prototypes, the nearest stock size of 45 mm square was used. This resulted in an overall size of 540 mm

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* The problem frequently arises when the wall surfaces of a room are very heavily treated with acoustic absorption, in order to obtain low values of reverberation time. It is not generally feasible to treat the floor and ceiling surfaces with so much acoustic absorption; the usual carpet- and ceiling-tile finishes provide high-frequency absorption only. The result is a lack of absorption between about 500 Hz and 2000 Hz, for sound travelling between floor and ceiling. Having a null in the direction normal to the diffuser surface assists in the attenuation and scattering of that energy.

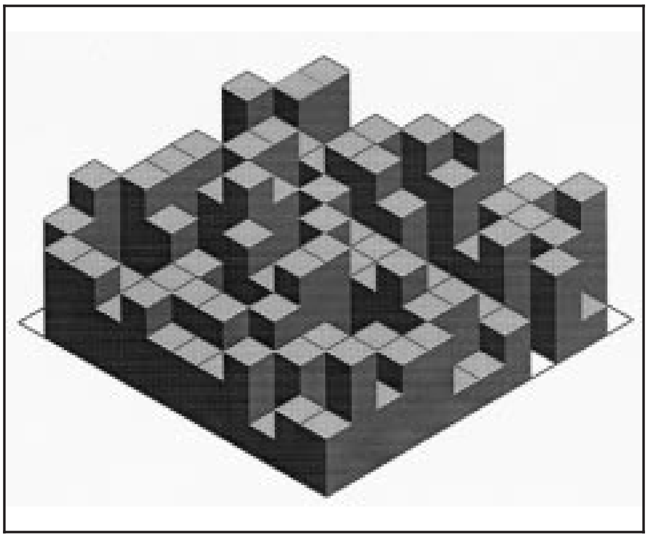

Fig. 1 - General appearance of diffuser.

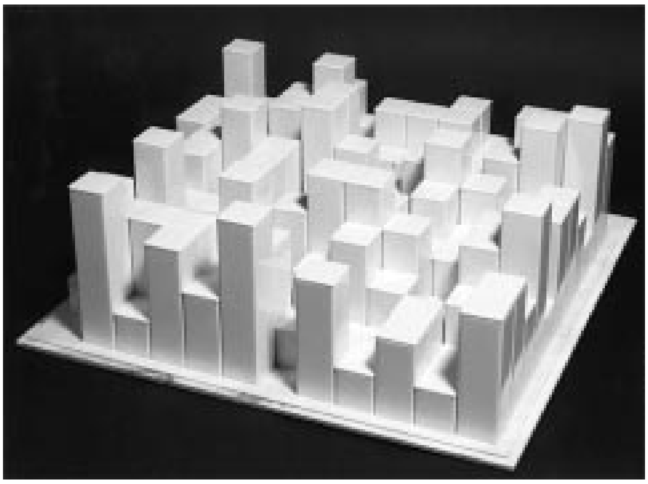

Fig. 2 - Final appearance of prototype diffuser.

square and left a 20 mm border all round. The end-caps were also available as standard items. They were moulded in high-density polyethylene. Sections of tube, cut to the correct lengths, were assembled by hand on a plywood base. The base was machine slotted to locate the tube sections. The tube sections were glued in position, both to each other and to the baseboard. Fig. 2 shows the final appearance of the prototype diffuser. The total weight was about 10 kg. An estimate of about £35 was made for the unit cost of these prototype modules.

A set of 16 of these prototypes was constructed for use in measurements and tests. An experimental installation in the Television Music Studio Annexe proved to be entirely satisfactory, at least acoustically.

4. ALTERNATIVE CONSTRUCTIONS

At the time, it was felt that the hand-assembled modules were unsatisfactory. They were rather heavier than the target weight of about 5 – 6 kg, set by the load-bearing properties of typical suspended ceiling structures. (This was not, of course, a significant problem for wall-mounting.) They were also fairly unattractive because of the narrow gaps between the tubes and the general fabricated appearance. It was also thought at the time that the unit cost was too high.

The main problem with the prototype modules was the lack of fire-resistance of the material. Plastics such as pvc emit large quantities of dangerous fumes in fires. Plastics like polyethylene frequently assist the spread of fires by melting and falling onto other combustible materials, especially when used in ceilings. The use of relatively large numbers of modules, each consisting of about 10 kg of such materials in the ceilings of technical areas was completely unacceptable, as a long-term proposition.

It was thought that some form of moulding or casting technique could produce one-piece units in quantity, at a reasonable cost. One of the difficulties with any form of moulding process was extracting the finished diffuser from the mould. The 200 mm deep by 47 mm wide, straight-sided, rectangular-section elements made extraction difficult, whatever the moulding process. The shape was such that either expansion or contraction during hardening would cause some part of the diffuser to grip the mould. In most tests of moulding processes, the rectangular section elements had to be modified to include a release (or ‘draw’) angle.

4.1 Vacuum forming

The first idea for mass production of cheap and light modules was the vacuum-forming of a relatively thin plastic sheet. As a fire-hazard, the small quantity of material involved should have been acceptable, even if the material itself was not especially fire-resistant. Similar materials and constructions are used widely and in significant quantities, even in technical areas, in the form of lighting diffusers.

Two problems arose to prevent the use of that method of manufacture. The first was the difficulty of moulding the deep and narrow profile of the diffuser. That problem might have proved insurmountable, had the principle been pursued. The main, and over-whelming, obstacle was the non-acceptance of those types of material by the (BBC) fire safety managers. This was despite the fact that substantial amounts of similar materials are, usually, already present in the form of light fittings. It was found that, in technical areas and along escape routes, the maximum permissible quantities of such materials are limited to about those that already exist in the form of light fittings.

A vacuum-formed version of the diffuser, with a maximum depth of 50 mm rather than 200 mm, was successfully developed. This has been used in some areas for experimental purposes. Because of its limited depth, it had a restricted performance at low frequencies. Fig. 3 shows a photograph of one of these mouldings.

4.2 Moulded plaster

In principle, moulded hard plaster would form an ideal construction material. It is an intrinsically cheap material which is in common use and is capable of providing a high-quality surface finish.

In practice, it requires reinforcement to ensure adequate strength. It is heavy and would require an advanced moulding technique to achieve the thin sections necessary to achieve reasonably low finished weight.

Some experiments were carried out by a commercial plaster-moulder, one who specialised in architectural mouldings. Again, because of the deep sections, the diffuser had to be hand-layed. The final weight, about 20 kg, was excessive and the manufacturing time taken, and the consequent cost, was also excessive.

Some discussions were held with another specialist plaster moulder*, who had developed a high-pressure moulding technique. This was already being applied to a similar acoustic product, although of significantly less complexity. The standard of production was high and the unit marginal costs very low indeed. However, the investment required to produce a suitable mould was considered to be excessive. Ultimately, a module similar enough to the BBC design to be considered as a replacement was produced commercially by the company**.

4.3 Casting using foam materials

The two great difficulties with any moulding technique producing thin-walled sections are the requirement for (and consequent expense of) a two-part mould, and the difficulties with material flow in the narrow internal spaces. With materials like reinforced plaster or filled polymers, the mould-closing forces necessary for the 600 mm square diffuser would have been measured in hundreds of tonnes. The mould has to withstand those forces without serious distortion. This can only be achieved by heavy, metal moulds, with their attendant high manufacturing costs.

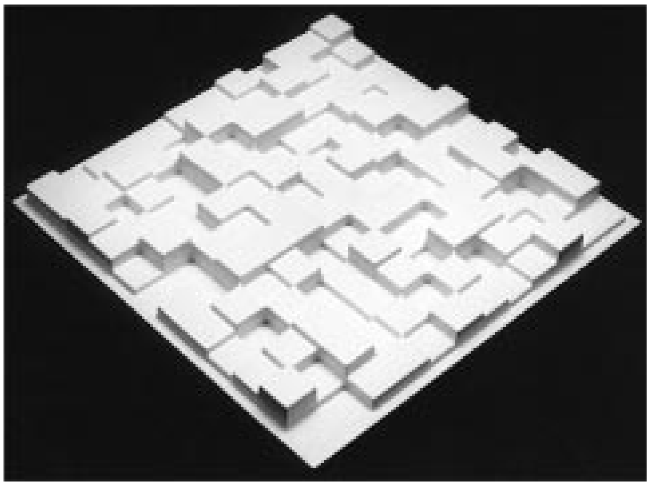

Fig. 3 - Vacuum-formed, shallow diffuser.

As an alternative, it was thought that a solid cast diffuser might be acceptable, if the material density could be made low enough. The mould volume was about 45 litres, requiring a finished density of about 150 kg/m^3 for a reasonable final weight.

Some types of plastic foam material will expand on curing to produce a lightweight foam with a solid surface skin.

Tests on these materials showed that a satisfactory skin was not produced unless the material was cured under closely-controlled conditions, in a pre-heated mould. The material characteristics were unpleasant during foam production and curing. The cured polyurethane material was also not acceptable to the fire authorities.

4.4 Casting using filled materials

Some moulding tests were carried out using inherently non-flammable materials; for example, vermiculite filler with a cement binder. Although the final density achieved was reasonably acceptable, the strength and surface finish were not adequate.

4.5 Commercial moulding using self-skinning plastic foam

Discussions were held with a commercial moulder of injection-moulded, self-skinning polyurethene foam. Samples of high quality mouldings were examined and estimates obtained for the preparation of a mould. In the event, the costs were too high. The polyurethene

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* Acoustic GRG Products of Smarden, UK.

** On behalf of RPG Diffusor Systems Inc., of Upper Marlboro USA.

material was also unacceptable to the fire authorities.

4.6 Timber

Some early prototypes were made of solid timber sections. These were visually attractive, but weighed about 45 kg. They were thought to be too expensive to produce and far too heavy for most applications.

Many commercial acoustic diffusers are made from solid timber or timber-based materials. They suffer from the same drawbacks.

4.7 Fabrication using metal or wood

Many possibilities for the fabrication of the diffusers from metal or wooden components were considered. In one realisation, a combination of metal strips folded to form the front surface and one set of side walls and pre-cut metal sheets to form the other side-walls of the cells could be used. They were to be joined by gluing or soldering.

Apart from models, no complete test of any of these methods was carried out. It was thought to be too difficult to produce a visually acceptable product, without excessive finishing processes. The manufacturing labour costs would also be high, even before the addition of the finishing-process costs.

The module strength, however, would have been excellent and the total weight very low. If made entirely of metal, they would also have been completely non-flammable.

4.8 Glass-reinforced plastic

The only process tested that produced an acceptable surface finish at a reasonable weight and with relatively low mould manufacturing costs was the use of glass-reinforced polyester resin. To enable the module to be extracted from the mould, a 1½° draw angle was necessary. Significant force also had to be used — to the extent that the back surface had to include special reinforcement to withstand the loads. In order to achieve a reasonable degree of fire-resistance, it was necessary to use a relatively thick fire-retardant gel coat. The construction process was essentially manual. The gel coat, reinforcement fibre and polyester resin were hand layed, in a one-part mould.

The final wall thickness was about 2 mm. The surface finish was excellent, although minor airholes usually had to be filled by hand. It could be obtained as a self-coloured finish or spray-painted afterwards. The strength was, if anything, excessive for the application, but thinner wall sections could not be achieved reliably. At about 7.5 kg, the module was somewhat heavier than the target weight, but acceptable for most purposes. At about £140, the final production cost was also much greater than had been hoped for.

Although the materials used were described as being “reduced flammability” (Class 1 to BS476, Part 7 and Class 0 to Section E15 of the 1976 Building Regulations), the BBC fire safety managers had some reservations about their use. The insurance safety experts insisted on the addition of a fire-resistant sheet (6 mm vermiculite), which had to be permanently fixed in the back of the module. A fire-test was commissioned at a commercial Laboratory (SGS Yarsley Technical Centre, Redhill). This showed that the diffuser did not compromise the fire-integrity of a standard false ceiling. It remained entirely solid, though significantly charred, when subjected to the test fire load of 105 kWhr (a peak thermal load estimated at about 1 MW). It also emitted some additional smoke fumes during the test, compared with a standard ceiling tile.

This development of the modular diffuser was continued to the point at which commercial production could be undertaken. Fig. 4 shows a photograph of a finished production module.

5. PERFORMANCE TESTS

The experimental installation in the Television Music studio had shown that significant beneficial effects were achieved in practice, even with a very low density of installation (less than 20% in that case).

Objective measurements were carried out when the first batch of production modules became available. The measurements had been delayed until that point because the form of the production modules was significantly different to any of the developmental constructions.

5.1 Absorption coefficient

For a device whose main function was the reflection of sound energy, it was necessary for the intrinsic absorption to be reasonably small.

A standard ISO absorption coefficient test was carried out on a set of 25 modules, arranged in a single contiguous patch. The sample was spaced approximately 300 mm above the floor surface, supported on the normal ceiling-tile test frame. This was intended to simulate their use in a suspended ceiling. The results were calculated, using as a basis, the plan area of the sample. They are shown in Fig. 5.

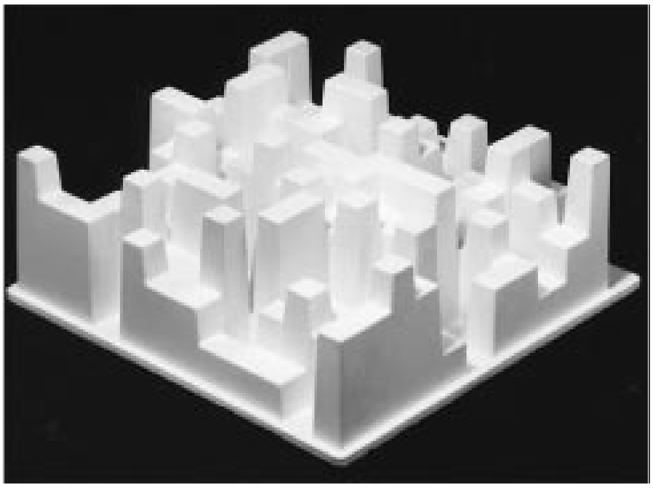

Fig. 4 - Final production diffuser.

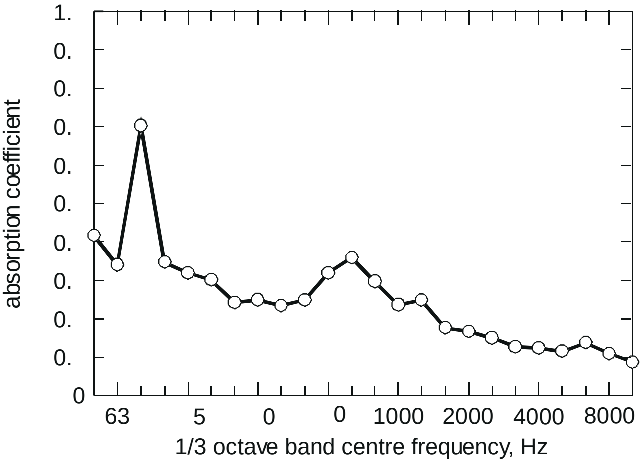

Fig 5 - Absorption coefficient of final production diffuser.

At most frequencies, the absorption coefficient was about 0.3 at low frequencies, falling to 0.1 at higher frequencies. This is somewhat higher than was hoped, but was not unreasonable. The modules have an actual surface area of approximately four times their plan area. Based on that area, the intrinsic surface absorption coefficients lay in the range 0.075 to 0.025. These values were as expected for such materials. Some excess absorption may have arisen from the supporting structure and the panels used to enclose the sides of the sample — at such low values of absorption many normally insignificant factors become important.

The absorption coefficient characteristic contains three or four anomalous peaks. The one at 80 Hz, which reaches an absorption coefficient of 0.7, was probably due to the mounting conditions and resonances of the sample as a whole (or of individual complete modules) on the suspension system. It would probably not occur in a normal suspended ceiling system, because it would be supported much more frequently by stiff tension members rather than the rather flexible beams of the test arrangement.

The second and third absorption peaks, at 630 Hz and 1250 Hz, reaching 0.35 and 0.25 respectively, are almost certainly due to the obscure excess absorption mechanism described in Ref. 7. In that reference, a mechanism for excess absorption is described which depends on resonance interactions between adjacent cells in the diffuser. The mechanism involves large volume airflows from one cell into a neighbouring cell at certain mutual resonance frequencies. Because the airflow is forced to travel over the sharp edge of the cell divider, the path is very restricted and the normal air viscosity loss (which is practically insignificant in unconfined flows) becomes dominant. Absorption coefficient peaks up to 0.8 – 1.0 are predicted. The simplified BBC diffuser has no cell dividers, but it is probable that some residue of the effect is present. The peak effective absorption coefficients of about 0.35 and 0.25 are not unduly problematical, although they are higher than would be ideal.

The fourth absorption peak, at 6300 Hz, is small: it may have been a measurement uncertainty or it may have been due to mechanical resonances of particular parts of the diffuser. For example, all of the square top surfaces of the ‘blocks’ making up the diffuser are about the same size as each other and have similar edge mounting conditions. It is possible that these very stiff and quite light panels could all resonate at 6300 Hz. In either case, the effect is small enough to be negligible for practical purposes.

5.2 Directional response

The measurement of directionality of a reflecting surface is non-trivial. The immediate question to be asked is: “how far away from the reflector should the source and receiver be?”. All of the theory, both for the BBC design and for others, is for the far-field response; that is, at distances for both source and receiver where the wavefronts are plane and the size of the object insignificant. This is a theoretical ideal which is difficult to approach in development and testing and which almost never applies in practice, especially in small rooms*.

Ref. 8 describes measurement techniques which involve source-sample and receiver-sample distances of about 9.1 m and 4.6 m respectively. The sample sizes

* The special case of repeated floor-ceiling reflections, which the BBC diffuser was specially designed to counter, approaches the far-field condition because of the repetition. In the later part of the sound decay where this problem becomes evident, say after about 0.2 s, the sound may have travelled about 65 m; that is more than 20 double reflections. Without additional diffusion, the wavefornts are then likely to be practically plane.

were either 0.6 × 2.4 m or 1.2 × 2.4 m, depending on the type of measurement. These are not strictly far-field dimensions, although they are reasonably representative of some types of installations, especially in large performance spaces. Ref. 8 also includes some comparisons between the measured directivities of a flat sheet and the theoretical responses. The agreements are very close, showing that the methods of both calculation and measurement are valid.

Fig. 6 shows three calculated responses, as an example of the differences in effective response which can be caused by variations of source and receiver distances. It shows the spatial response of a flat sheet, 2.4 m square, as the angle between the receiver position and the normal is changed. In the orthogonal direction, the source, the normal to the sheet, and receiver are co-planar. In Fig. 6(a) the source is located on the normal to the sheet, at a distance of 9.1 m. The receiver distance is 4.6 m. The frequency is 564 Hz. These conditions correspond to those of Fig. 23 in Ref. 8, for the wavelength "λ = D/4 = 24" ". Apart from deviations caused by the differences in angular sampling intervals (and probably differences in the resolution of the numerical summations of wavelet contributions) the results are identical. Fig. 6(b) shows the calculated response for the same conditions except with source and receiver distances that are 10 times larger. The characteristic, regular lobe structure is now clearly evident. This is close to the theoretical far-field spatial response, as normally calculated for many acoustic examples. The source and receiver distances involved, namely 91 m and 46 m respectively, are rarely encountered in interior acoustic designs.

Fig. 6(c) shows the calculated response for a source distance of 2.8 m and a receiver distance of 2.0 m. These distances are representative of those encountered in normal control rooms and small studios. Clearly, the pattern of reflection is very different, with little evidence of the pronounced lobe structure. These distances are also the ones used for the measurements described in this Report.

In carrying out measurements of directionality, some means must be found to eliminate other reflections (for example, from the surfaces of the test room) and to separate the signals representing the incident and reflected sound waves. The latter co-exist in the same space, although potentially at different times. The geometry of the measuring arrangement and the instrumentation used must be capable of distinguishing between them. It is not practicable, in ordinary room-acoustic work, to make the distinction by other physical means, such as highly directional sources and/or receivers, as might be done in radio-frequency or ultra-sonic measurements.

The effects of the room boundaries might be minimised by making the room very large or using an exterior measurement field. Alternatively, by making the room surfaces very absorbent, as in an anechoic chamber, the effects of reflections from the room surfaces can be reduced. The use of time-domain window techniques[9] to separate the incident and reflected sound can also assist in the rejection of reflections from the room boundaries. Other measurement techniques for separating the incident and reflected sound based on acoustic holography (that is measurement and processing of the combined field[10 – 12]), might also be employed. These also require the use of an anechoic room.

Despite the foregoing limitations, an anechoic chamber was used for the measurement of the reflection characteristics of the BBC modular diffusers. This was partly because a suitable large open space was not available. However, as measurements at very short distances, typical of control room and small studio installations, were required, this was not a serious disadvantage.

One of the difficulties with relying on absorption to control the effects of reflections from the measurement room was the large area of boundary surface in comparison with a typical test sample. Even in a high-quality anechoic chamber[13], the sum of the residual reflections from the whole of the interior surface can be significant in comparison with the wanted reflection from a practical-sized test sample. This was to form a slight, but significant, limitation to the measurements.

Fig. 7 *(see page 8)* shows the geometry of the test arrangement. With this arrangement it was possible to achieve a time-domain discrimination between incident and reflected sound of about 10 ms for all receiver angles between 0° and +50° and for source angles of 0° and –30°. With a half-Hanning window[9, 14] a frequency resolution of about 150 Hz could be obtained.

Measurements of reflection amplitudes were made* for a 2 × 2 array of diffuser modules (total size 1.2 × 1.2 m) with source angles of 0° and –30° for steps of receiver angle from 0° to 50° in 2° steps. An identical set of measurements was also carried out for a flat sheet of the same overall size. Measurements were confined to a plane normal to the test sample. All of the results have been equalised to the direct response of the loudspeaker, as measured in the room without the test

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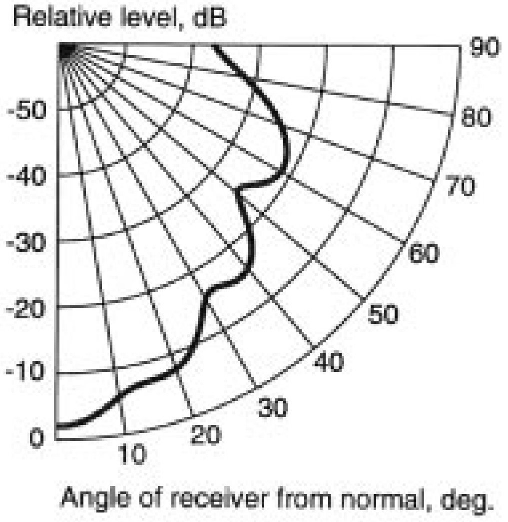
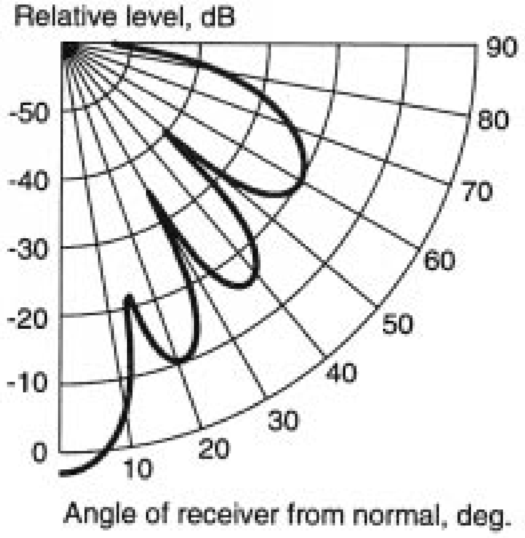
* The measurements and data processing were carried out by J. Rabone.

(a) As Ref. 8



(b) ‘far-field’



(c) ‘near-field’

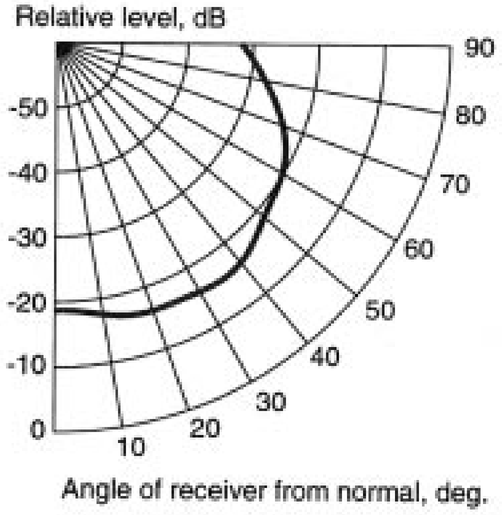


Fig. 6 - Calculated flat sheet responses.

object present, and in the position which would have corresponded to the geometric image of the microphone had the test object been present. This compensated for the (slightly) irregular frequency response of the loudspeaker and the overall path loss due to the loudspeaker-microphone distance. It did not compensate for the additional variation in response of the loudspeaker with radiation angle. These were assumed to be small over the range of angles used.

The measured data required extensive post-processing in order to make them suitable for existing computer presentation programs. After much experimentation, a standard mathematical processing package (Mathematica ®) was used to generate contour plots of sound level as a function of direction and frequency. This required an interpolation function to be applied to the data arrays in order to obtain logarithmic frequency spacing for presentation in the usual form for audio acoustic results.

Many forms of presentation of the results are possible. The three-dimensional nature of the results ideally required a three-dimension presentation. Any other presentation (for example, polar plots of directionality for a small sample of frequencies or frequency response plots at particular angles) are so selective as to be virtually useless. Three-dimensional presentations in the form of contour plots do, at least, contain all of the data. All of the results presented in this Report are in that form.

The general background interference from the walls of the anechoic room limited the measurable range of reflected sound to about 20 dB. At some angles and frequencies, the measurable range approached 10 dB. Thus, the range of the results was limited to 20 dB at most frequencies and angles and 10 dB at some particular combinations of angle and frequency. This especially affected the depths of the measured minima in the responses. These might otherwise have been rather deeper than they appear. This does not significantly affect the overall appearance of the results nor the conclusions derived from them.

Fig. 8 shows the directivity response obtained from the diffuser array with normal incidence sound. This should be compared with Fig. 9 which shows the results of the same measurement for a flat plate. The diffuser clearly disrupts the regular sidelobe ripple response of the flat plate. At most angles and frequencies, no significant structures are visible in the results for the diffuser array. At low frequencies (300 – 400 Hz) and possibly at very high frequencies (8 – 10 kHz) there is some evidence of specular reflection from the diffuser array outside its design operating frequency range of 688 – 3600 Hz. (The horizontal streaks visible in Fig. 8 at about 20°, 30° and 40° are measurement artifacts and should be ignored.) There is very little evidence in Fig. 8 of the theoretical (far-field) response nulls at 688 Hz and harmonics thereof. In principle, the response for either a diffuser or a flat plate for normally-incident sound should be symmetrical about the normal. Figs. 8 and 9 therefore only show one half of the total hemispherical reflection response.

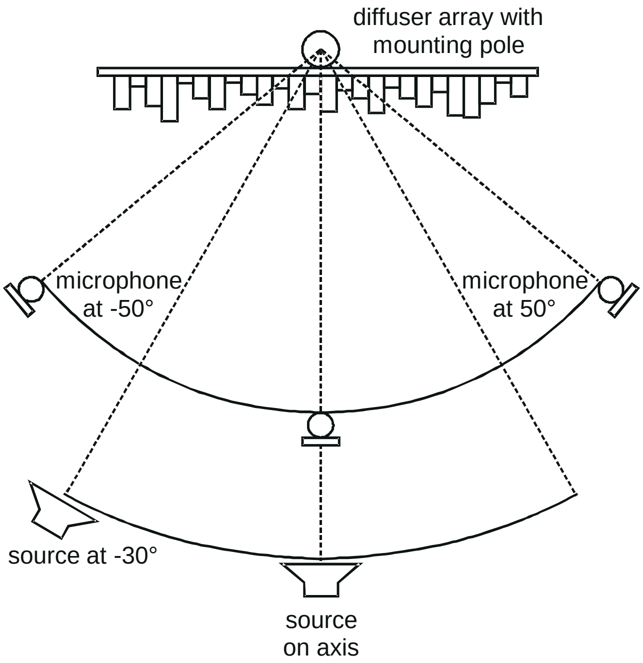


Fig. 7 - Geometry of test arrangement in anechic room.

Thus, the effective working frequency range of the diffuser, for normal incidence, extends upwards from about 600 Hz.

Fig. 10 *(see page 10) s*hows the diffuser response for sound that is incident at –30° relative to the normal. Fig. 11 *(see page 11)* shows the corresponding response of the flat plate. For the diffuser, the response is shown for angles between –50° and 50° because, theoretically, it should be uniform over the whole hemisphere, at least in the far-field. The flat plate response clearly shows the low-frequency specular response, although the specular angle appears to be about 24° rather than 30°. (This may have been due to cumulative errors in the measurement of angles. The error is not important to the main argument.) Fig. 11 also shows the symmetrical side-lobe ripple response.

The spatial response of the diffuser for sound incident at –30° is complicated. At frequencies below the design lower limit of 668 Hz there is a clear specular reflection at about 20 – 30°, the apparent direction of which is slightly frequency dependent. The general appearance compares quite closely with that for the flat plate in the

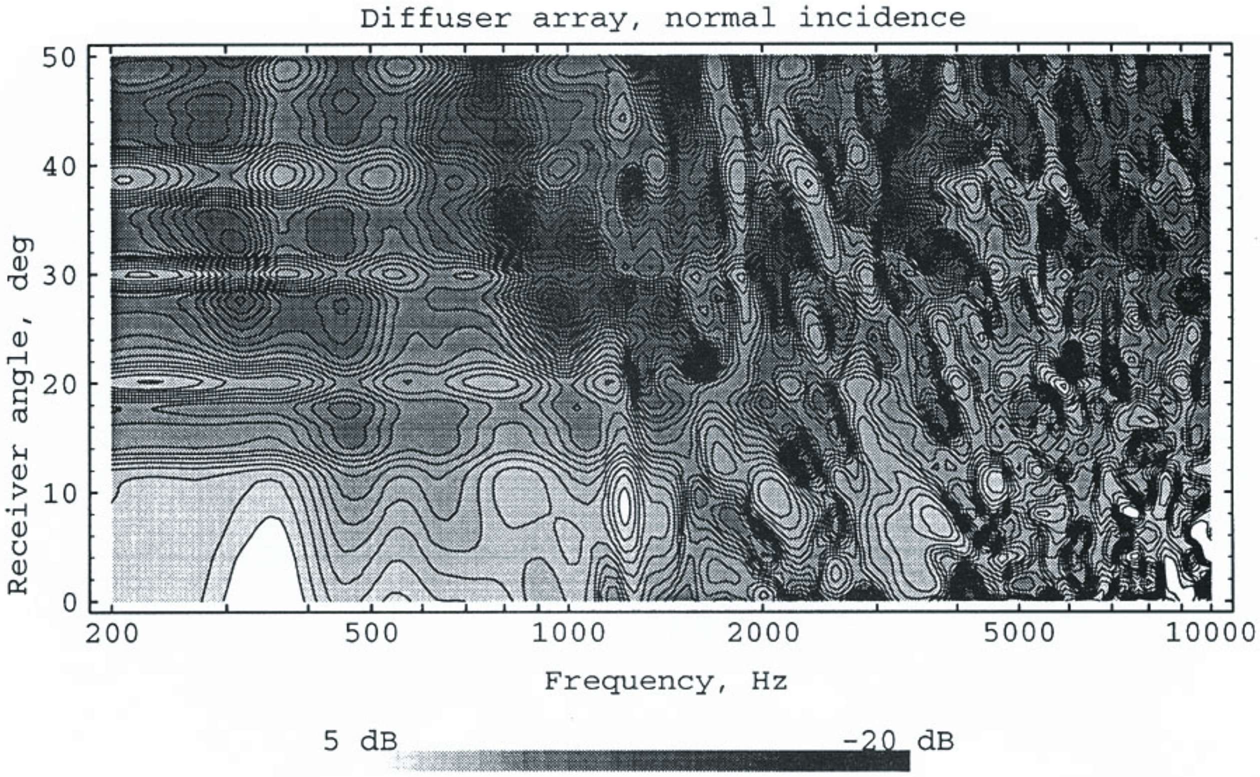


Fig. 8 - Response of diffusers for normal incidence.

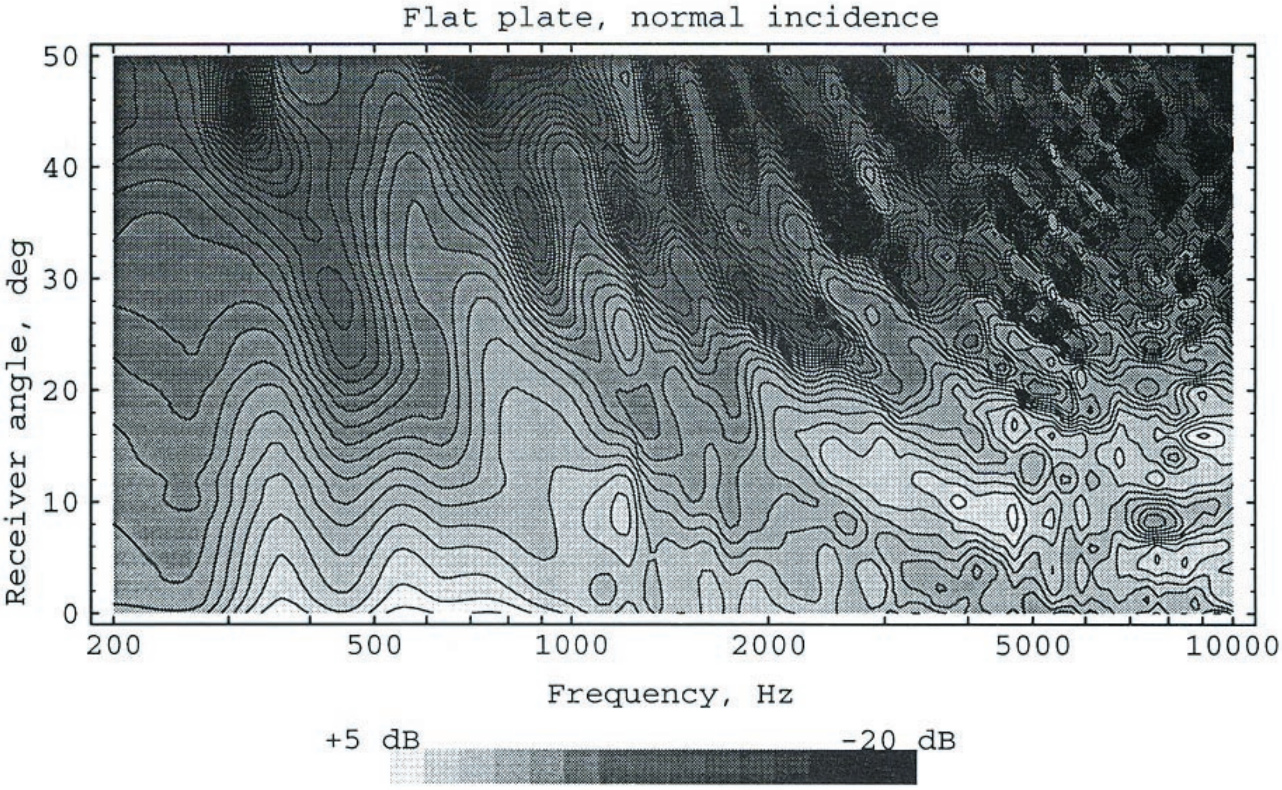


Fig. 9 - Response of flat plate, for normal incidence.

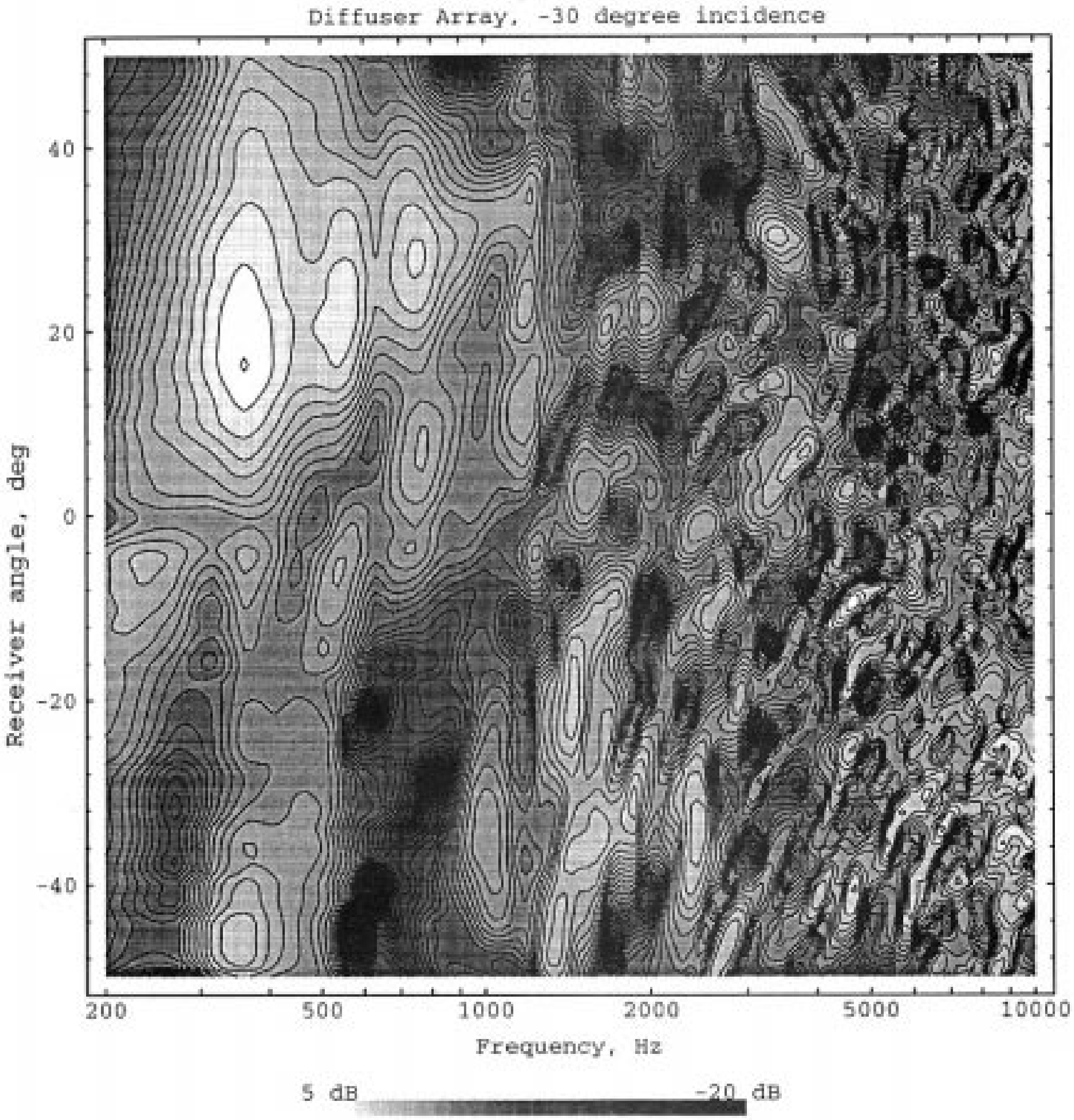


Fig. 10 - Response of diffuser array for –30° incidence.

same frequency and angle ranges. In the non-specular quandrant, the levels are significantly lower. These results show that, as expected, the diffuser array behaves in a similar way to a flat sheet at frequencies below its design lower limit.

At higher frequencies, the diffuser array again shows a reasonably uniform reflection pattern. It is especially notable that the typical reflection amplitudes in the non-specular quadrant are similar to those in the specular quadrant, showing that the reflection of frequencies within the normal working range is nearly omni-directional (in the reflection half-space). There is no significant evidence of pronounced structures in the reflection response in either quadrant. Again, there is very little evidence of the theoretical nulls in the response at 688 Hz and harmonics.

At frequencies above the design upper limit of about 3600 Hz, the array clearly still behaves as a diffuser, as would any highly irregular surface. At these higher frequencies, there is some evidence that the diffuser tends to reflect more sound energy in the non-specular direction than in the specular direction, that is, back towards the source rather than away from it. This is not very surprising — without the cell wall dividers, the diffuser has a large exposed surface area to sound incident from the side. It therefore behaves as an effective and reasonably omni-directional diffuser, even above its design frequency range. To some degree, this behaviour was anticipated, but the uniformity of the high-frequency response was a unexpected bonus.

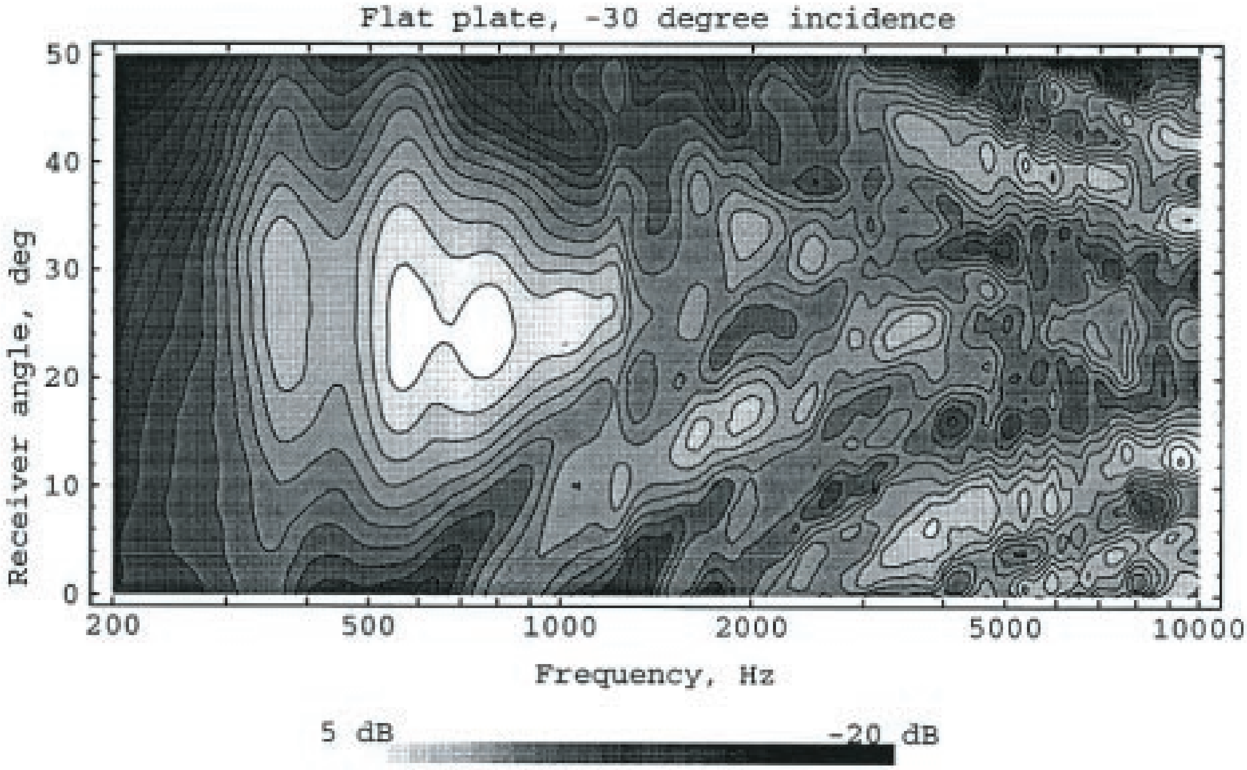


Fig. 11 - Response of flat plate, –30°incidence.

Thus, the effective working frequency range of the diffuser at oblique angles of incidence extends upwards from about 800 – 900 Hz.

6. CONCLUSIONS

The development of a modular acoustic diffuser from the original, hand-built prototype has been a difficult and complicated job. Most of the difficulties arose from the complex shape, especially the deep and narrow recesses. The final design is much more expensive than had been hoped. However, it compares moderately well with other similar products.

The satisfying of various fire authorities and fire-safety regulations also presented severe difficulties and seriously limited the range of usable materials.

Acoustic tests carried out on the final version of the diffuser have shown it to have reasonably low absorption characteristics.

The reflection characteristics have been shown to be much as expected, although the theoretical predictions were based on the far-field theory. In the near-field conditions typical of most such diffuser installations, the module has a useful frequency range from about 600 Hz upwards for normally-incident sound and about 800 – 900 Hz for oblique-incident sound. At very high frequencies, the module behaves as an effective, near-random diffuser, even though the (far-field) frequency range is theoretically limited to about 3600 Hz.

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