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PIEZOELECTRIC PLASTIC TRANSDUCERS:
a feasibility study

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Research Department, Engineering Division
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PIEZOELECTRIC PLASTIC TRANSDUCERS – A FEASIBILITY STUDY

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Summary

The properties of certain piezoelectric plastics are outlined and these are used to postulate transducer designs. The characteristics of two types of dome radiator which were made from these materials are discussed in detail.

Whilst these transducers were able to produce subjectively reasonable sound levels when incorporated in a loudspeaker system, they proved to be considerably less sensitive than their moving coil counterparts. They were also prone to violent resonance modes which proved difficult to damp.

The ability of piezoelectric transducers to reproduce very high frequencies at high levels and without serious directional problems may recommend their use for acoustic scale modelling.

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PIEZOELECTRIC PLASTIC TRANSDUCERS - A FEASIBILITY STUDY

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M.A. Parker., B.Sc.

1. Introduction

Piezoelectric transducers offer advantages over their electro-mechanical counterparts of simplicity of construction, and mechanical and electrical ruggedness. For these reasons they have become quite commonplace in certain areas of sound reproduction. Contemporary designs (1) base their operation on the piezoelectric properties of particular ceramic materials, these being the first piezoelectric substances to be manufactured commercially. The designs generally comprise a ceramic element linked to a horn-loaded diaphram by a lever. This mechanism serves as an impedance transformer between the high mechanical impedance of the ceramic and the relatively low impedance of the air. Whilst achieving a reasonable efficiency, these devices often show rather severe response irregularities (see Fig. 1) attributable to resonances in their necessarily complex drive structures. This limitation renders the transducers suitable only for high sound-level applications where quality is not the first consideration.

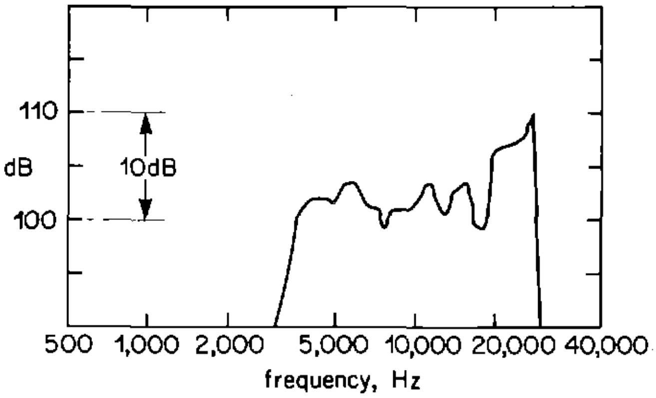


Fig. 1 Response of a typical ceramic piezoelectric tweeter.

The piezoelectric effect was first observed in synthetic polymers (plastics) some years ago but it was not until the discovery of very significant piezoelectricity in polyvinylidene (di-) fluoride (P.V.D.F.) that practical applications were envisaged. Development of the material has been concentrated in the area of underwater ultrasonics [2] where efficient coupling of the plastic to the water is simplified by the similar acoustic impedances of the two media. To date, however application of this plastic to audio transducers has been limited.

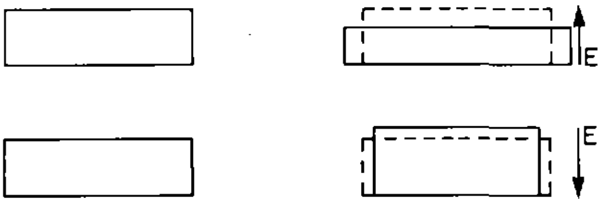
For broadcasting purposes any tweeter made from this material would be required to have a specification comparable to that of conventional units and, more specifically, similar to that used at present in the BBC LS5/8 loudspeaker system. [3] Whilst this tweeter provides adequate volume and quality on most programme material, burnout of the unit is possible on continuous high level, high frequency signals such as can occur in tape spooling and electronic pop music. Some additional output power would therefore be desirable from a new unit.

This report describes brief experiments designed to evaluate the use of piezoelectric plastic transducers in monitoring quality loudspeakers. The study was not intended to be exhaustive and indeed a few questions remain unanswered. However sufficient work has been done to allow valid conclusions to be made.

2. Transducer design considerations

2.1. Piezoelectricity in plastics

Piezoelectricity may be defined as the property of a material to change shape under the influence of an applied electric field. In general the volume of the material remains substantially constant and inverse strains occur both parallel and normal to the applied field (see Fig. 2). Usually reversal of the field results in a sign change of the two strains.

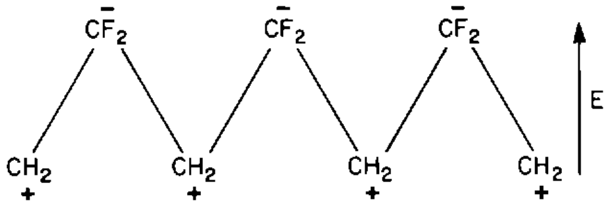


(i) Unstressed material.

(ii) Material under the influence of field E.

Fig. 2 – Piezoelectric deformation

In polyvinylidene fluoride the effects may be attributed to the crystalline content of the plastic and in particular the so-called β-phase structure [2]. The structure of this phase may be represented in a simplified form as a sawtooth shaped chain as shown in Fig. 3. The charge distribution in this chain is such that an electric field applied in the direction shown would tend to compress the corrugated structure causing a strain parallel to the applied field and an inverse strain co-axial with the polymer chain. Reversal of the field will produce a correspondingly reversed strain.



CH_2 = one carbon atom bonded to two hydrogen atoms.

CF_2 = one carbon atom bonded to two fluorine atoms.

—— = carbon to carbon bond

Fig. 3 — Polyvinylidene fluoride — β phase structure

Little bulk piezoelectricity is observed in the material as originally cast because the molecular orientation is entirely random. Polarizing of the molecular dipoles (i.e. rotation of the molecular chains about their axes) occurs when the material is subjected to a high electric field just below its dielectric breakdown at elevated temperatures. If the field is maintained while the plastic is cooled, the polarization is 'set' into the structure of the material. Subsequent application of a driving field causes an area strain of the material and a corresponding thickness change. This mechanism is discussed in greater detail in Appendix 2. The polarizing and driving fields are generated by applying a voltage across aluminium electrodes evaporated on to both surfaces of the film.

Whilst small volumes of the material are capable of achieving quite high power conversions at adequate efficiency, the resultant movement is too small to radiate significant acoustic power in air. A simple transducer of the type shown in Fig. 4 for instance and used widely for radiation in water would be simple to construct and possess no in-band resonance, but would be virtually inaudible. Conversely, highly complex mechanical gearing and horn loading would result in high efficiency but would be no simpler than the ceramic transducers currently available. With these factors in mind two designs were considered.

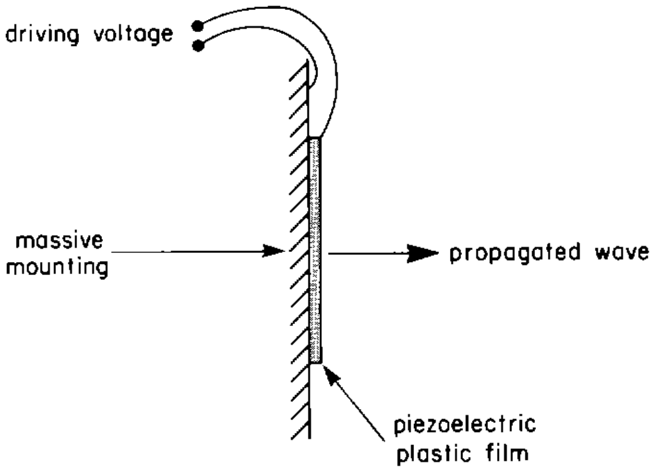


Fig. 4 — Simple Piezoelectric radiator

2.2. Possible transducer designs

2.2.1. Bi-Morph Motor

The transformation of the small volume displacement produced by the plastic to the relatively large volume displacement needed to radiate significant power in air, may be implemented by employing a laminar structure of two oppositely polarized polyvinylidene fluoride films. Application of a driving field normal to the plane of the laminate results in an area contraction in one layer and an expansion in the other thus bending the composite.

One approach, therefore, was to drive a conventional passive dome with a bi-morph as shown in Fig. 5. The segmented ring would behave as a radial array of bi-morph strips. The outer edge would be secured to a base and the inner edge to the dome. This design however would be likely to suffer similar resonance modes to a conventional dome tweeter and thus would show little advantage in that respect.

2.2.2. Hemispherical Active Dome

A major advantage of thermoplastics over ceramics is that they can be readily moulded or vacuum formed. An alternative, simpler form of construction was therefore possible, namely that of forming a thin hemispherical shell of the piezoelectric plastic. A given dimensional strain of the material would thus result in a proportional dimensional change of the dome, a large volume displacement of air being generated by a small volume displacement of the plastic. The unit

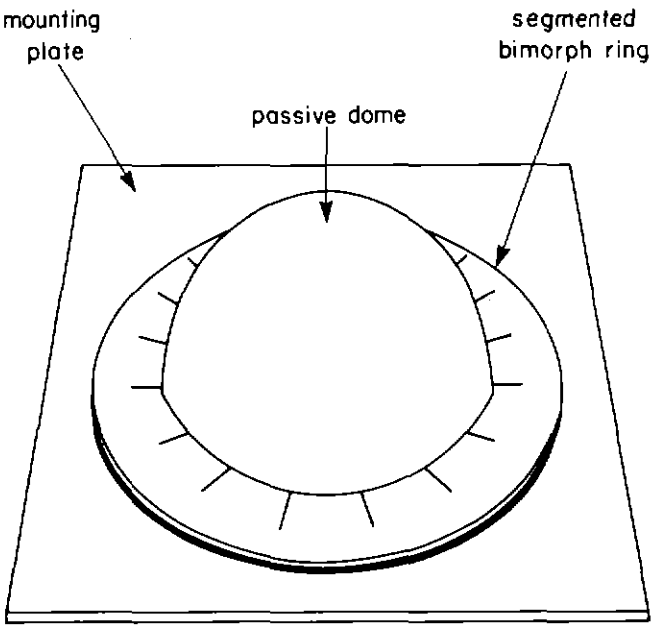


Fig. 5 — Possible configuration of a bimorph unit

should emit an almost hemispherical wavefront and thus be free of the dimensional constraints and directional problems of conventional 'piston' type radiators. In practice the wavefront is not perfectly hemispherical because the base of the dome is fixed. This limitation was not thought to be critical since the device was required to radiate uniformly only up to about 45^{0} off axis. Because of the simplicity of construction and operation and the novelty of the design it was decided to make some experimental units.

3. Construction of dome units

From theoretical considerations it can be deduced that the output of a dome radiator of piezoelectric material is approximately proportional to its radius to the eighth power, for a constant driving field (See Appendix 1 Eq.1). It is therefore advantageous to make the unit as large as possible within the constraint of the limiting physical size of the complete loudspeaker system. Initially, however, the only plastic available for experimentation was 25μm polyvinylidene fluoride sheet and it was considered that a dome no larger than 5 cm in diameter could be constructed from this material without it being too fragile.

A dome of this size has a calculated output at 2 kHz of about 60 dB (relative to 20 μPa) at one metre rising at 12 dB per octave for a drive voltage of 250 Vr.m.s. This voltage gives the same V.A. consumption as the maximum for a conventional tweeter. This sound pressure is too low for any practical system but the unit was still thought to be of use in assessing output quality and in checking the theoretical predictions.

Subsequently samples of thicker polyvinyl chloride were obtained and some 11 cm diameter units were constructed. Whilst this plastic is not as piezoelectrically sensitive as polyvinylidene fluoride its structure is otherwise quite similar and it proved valuable in the investigation of the general characteristics of larger domes.

The construction of all the units was similar. A disc of the plastic was vacuum formed into a hemispherical shell, a small surrounding skirt being left for mounting purposes. Both surfaces of the dome were then metallized by vacuum deposition, this coating being extended slightly onto the skirt. The dome, supported by its forming mould, was then polarized in an oven and was subsequently fixed by its skirt to an aluminium base-plate using a silver-loaded adhesive. A piece of sound absorbing felt was incorporated inside the dome to reduce any standing wave effects. This construction is shown in Fig. 6 & 7. The vacuum forming and polarizing conditions were found to be quite critical and the experimentally derived optima are shown in Table 2. in the Appendix 3.

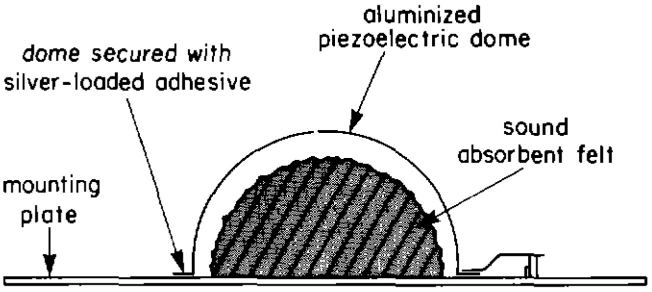


Fig. 6 — Construction of dome units

4. Performance of dome units

4.1. Frequency response

Because only high frequencies were involved in frequency response measurements on these units, preliminary tests were carried out on a bench, with reflecting surfaces close the dome obscured by sound absorbing material (See Fig. 8). A 3mm measuring microphone was placed about 10 cm from the smaller dome and 20 cm from the larger dome for most axial and polar response measurements. In this way any reflected signals were

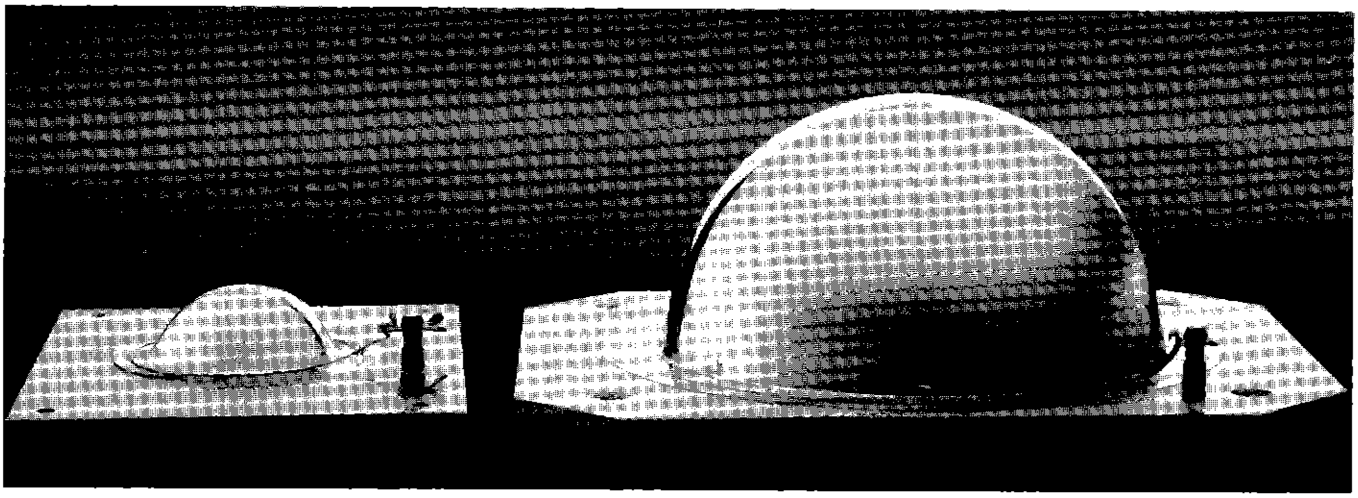


Fig. 7 – Photograph of 5 cm and 11 cm piezoelectric tweeters

significantly smaller than the direct path signal and their phases almost randomly distributed. This method gave greater versatility and ease of measurement than use of a free-field room. Some smooth response plots were obtained by this method which confirmed its effectiveness.

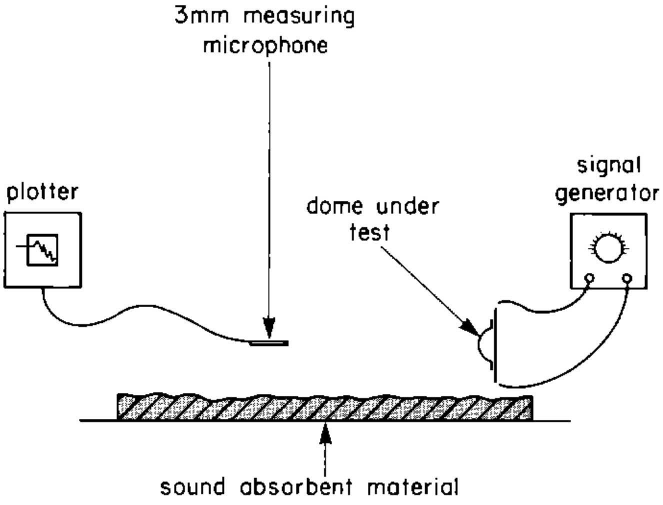


Fig. 8 – Frequency response measurements

For the 5 cm polyvinylidene fluoride dome the frequency response plot of the untreated dome (Fig. 9) revealed considerable irregularities. Some of these were removed by mounting the tweeter on a large plate, thereby reducing the effect of interference from sound diffracted at the edge of the plate. The main cause of the irregularities however appeared to be the 'break up' of the dome itself into a series of modes. These modes comprise waves normal to the surface of the dome which travel tangentially until they are reflected at its base.

To attenuate these reflections a layer of diluted plasticised P.V.A. emulsion was painted around the lower 5 mm of the dome. With the compound still wet the response showed a considerable improvement in terms of smoothness (Fig. 10), although a marked resonance was still present at 10 kHz. This anomaly was attributed to the imperfect shape of the dome resulting in a localised resonance at its crown. However when the emulsion dried the response deteriorated somewhat indicating a reduced damping effect. Other damping agents were tried but none proved as effective as the wet P.V.A. emulsion.

As expected, the output showed a general 12 dB per octave rise which extended over the whole audio band. The maximum output at 2 kHz was about 60 dB (rel to 20 μPa) at a drive voltage of 300 V r.m.s. This compares favourably with the theoretical figure given in Appendix 1. Exceeding 300 V r.m.s. caused local over-heating of the dome resulting in depolarizing and ultimately in melting.

The off axis response (Fig. 11) showed the device to be considerably less directional than a piston-type radiator of similar size.

The 11 cm polyvinyl chloride dome appeared to have more coarsely-spaced resonant modes which proved difficult to damp effectively. In spite of having a fundamental resonance at about 16 kHz and therefore being mass controlled above this frequency its output extended to 200 kHz (See Fig. 12). At 2 kHz it had a maximum output of 65 dB (relative to 20 μPa) at one metre for a drive voltage of 100 V r.m.s. This showed the expected increase in output over the smaller, dome,

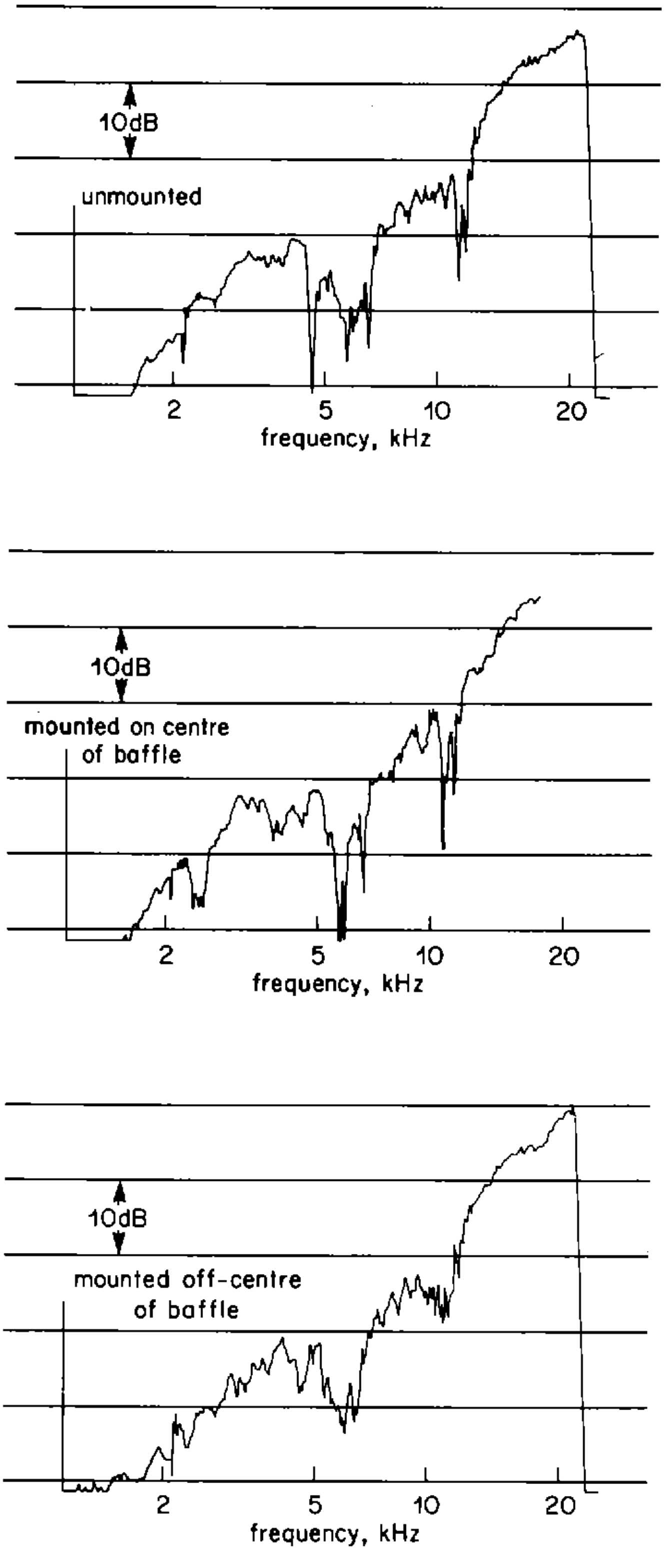


Fig. 9 – Frequency response of untreated 5 cm dome

although this was not as large as if the two had been constructed from the same material, P.V.C. being considerably less sensitive piezoelectrically, than P.V.D.F.

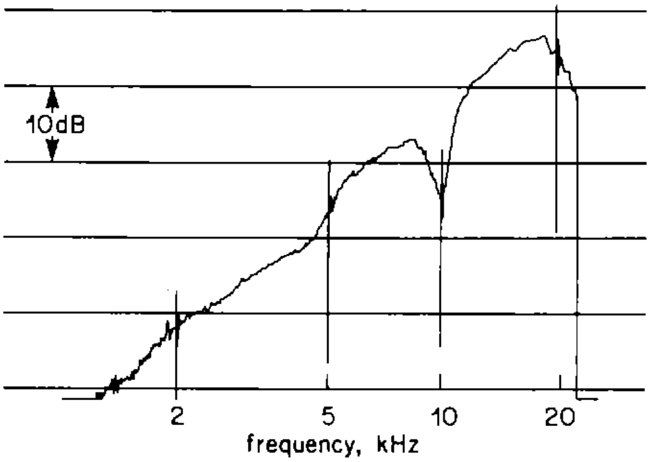


Fig. 10 – Frequency response of treated 5 cm dome

4.2. Optical measurements

Using laser interference techniques* the displacement of various points on the surface of the 5 cm dome were measured against frequency (Fig. 13).

The essence of this technique is that a direct beam of light from a laser is split, and remixed after one part has been reflected from the transducer and the other from a fixed mirror. An interference pattern results, which changes phase (i.e. light for dark and vice versa) for every half wavelength change in path length difference. Readings were taken of the dome excitation voltage needed to 'blur' the interference pattern; this corresponds to a dome movement of plus and minus a quarter of a wavelength of light. The results (app 4) reveal that above about 1 kHz the dome breaks up into a series of modes which seem little affected by the application of a damping compound. This leads to one of two conclusions: either this latter application of P.V.A. emulsion was somehow different to that carried out when conducting frequency response measurements, or the compound smooths the response by some mechanism other than by damping. For instance if the damping agent were acting as a precise reflective barrier one could assume that the energy released into the dome by virtue of a piezoelectric displacement would remain in the form of a mechanical resonance, until dissipated by acoustic and mechanical losses. If these modes were sufficiently numerous a smooth overall frequency response would result.

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* Work carried out by E.W. Taylor.

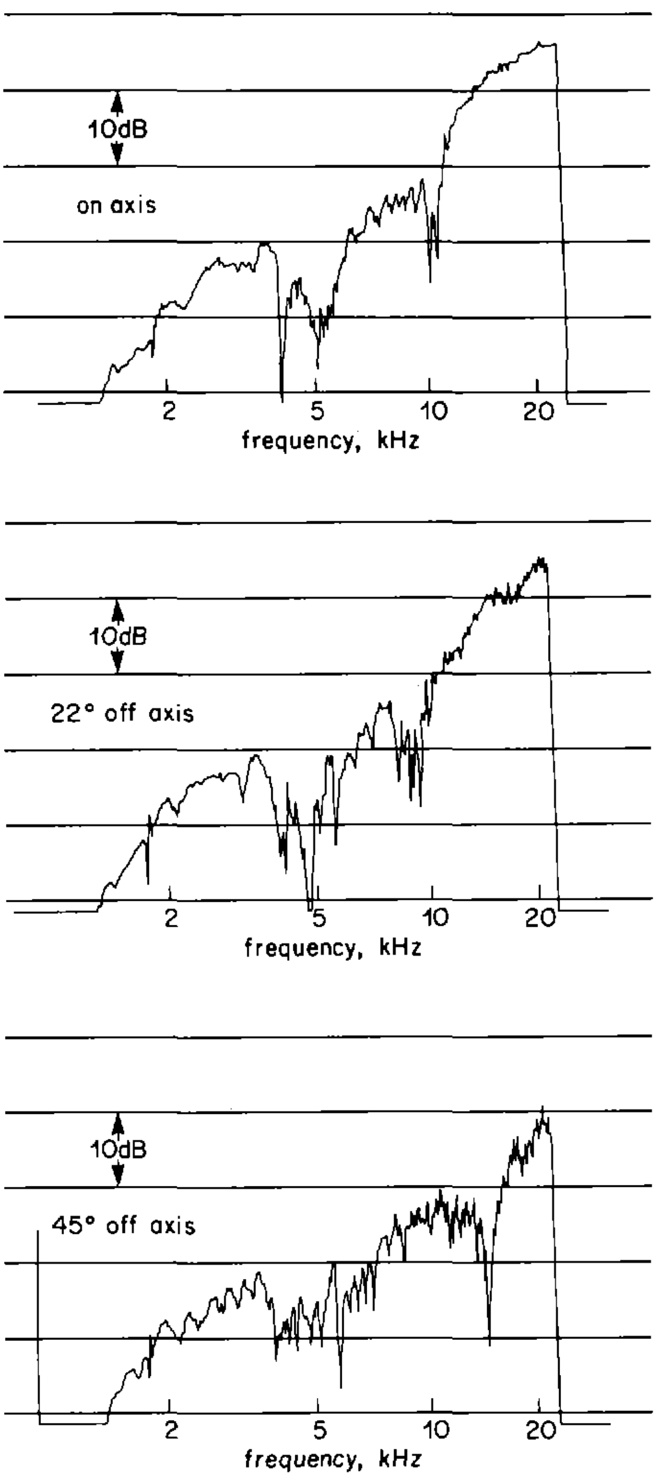

Fig. 11 – Off - axis response of untreated 5 cm dome

Perhaps then rather than damp out modes a better approach is to increase their number such that no frequency is preferentially excited.

5. Listening Tests

A step-up transformer was designed to drive the units from a conventional amplifier, thereby providing up to 700 V r.m.s. output. Approximate equalization was achieved by driving the transformer via an inductance which, combined with the capacitive nature of the load, yielded the desired 12 dB per octave roll-off. A 1/3 octave graphic equaliser was used to modify the input signal to the tweeter to minimize the subjective effects of response irregularities, so that brief listening tests were possible.

The 5 cm polyvinylidene fluoride dome produced an acceptable sound quality but the output of the system was limited to 100 dB peak unweighted at one metre on most programme material, depending upon its spectral energy content. The unit was heard to be notably free from off-axis high frequency roll-off.

The sound quality from the 11 cm polyvinyl chloride unit however, appeared highly coloured. Little subjective improvement could be obtained by equalization and thus it was concluded that the anomalies were due to serious resonances in the dome.

6. Conclusions

It can be concluded that piezoelectric plastics and in particular polyvinylidene fluoride can be formed simply into high frequency audio transducers. It is difficult to obtain high sound levels from this type of unit at the low-frequency end of a conventional tweeter range without sacrificing quality. A tweeter manufactured from this material did however perform satisfactorily in a loudspeaker system producing an overall maximum sound pressure level on programme of 100 dB s.p.l. at one metre.

The various units constructed showed widely varying sensitivities for a particular size and plastic. This suggests that a more effective polarizing of the plastic might be possible.

The ability of this type of transducer to reproduce high frequencies at high levels and without excessive directionality recommends its use for acoustic scale modelling.

Whilst at the time of writing the dome tweeter construction was a novel application of a piezoelectric plastic, a proprietory unit based on similar principles has since been demonstrated.

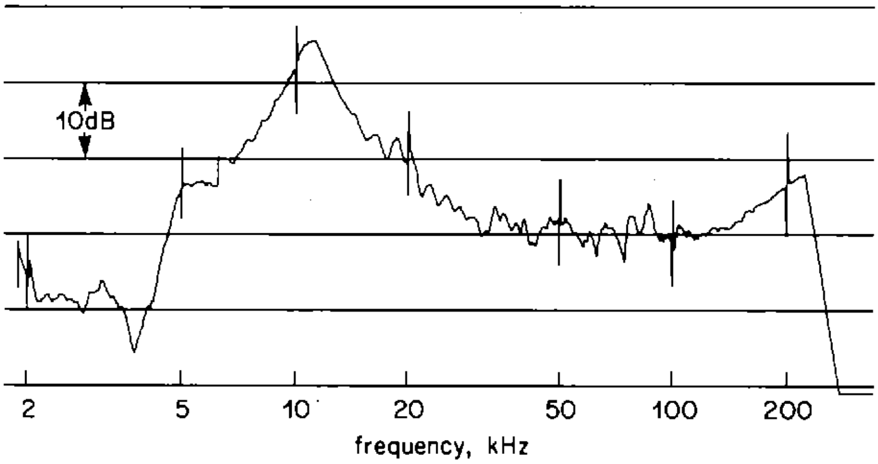

Fig. 12 – Response of 11 cm P.V.C. dome

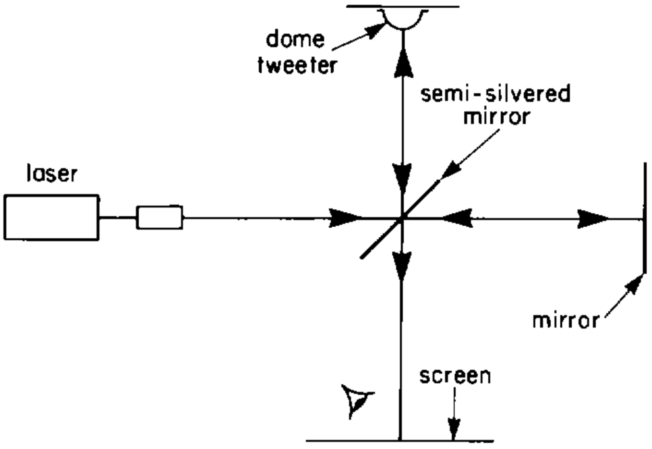

Fig. 13 – Schematic diagram of laser interferometer

7. Acknowledgements

Acknowledgement is due to Mr. R.M. Quilliam of the Marconi company Ltd., for his helpful discussions and for providing samples of piezoelectric plastic.

8. References

1. Bost, J.R., 1974; A new type of tweeter horn employing a piezoelectric driver, J.A.E.S., September 1974.
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Appendix 1.

Calculation of the output of a hemispherical dome radiator

For a breathing hemisphere the acoustic radiation impedance in air may be written[(4)]

$$Z_s = \frac{\tfrac{1}{2}\rho_o\, ckr}{1 + jkr}$$

where ρ_o = density of air
c = velocity of sound
k = wave number
r = radius of dome

of which the real part is

$$R_s = \frac{\tfrac{1}{2}\rho_o\, ck^2 r^2}{1 + k^2 r^2}$$

For a dimensional strain 'x' in the area of the plastic film the dimensions of the hemisphere will vary in proportion. The volume of the hemisphere may be written

$$V = \frac{2}{3}\pi r^3$$

Thus the incremental change in volume of the hemisphere δV will be:

$$\delta V = \frac{2}{3}\pi (r + rx)^3 - \frac{2}{3}\pi r^3$$

$$\simeq 2\pi r^3 x \qquad \text{for small } x$$

Therefore the volume velocity, U, for a dimensional strain of x peak to peak, at an excitation frequency f, is given by :

$$U = \delta V . \frac{\pi}{\sqrt{2}} f$$

$$= \sqrt{2}\pi^2 r^3 .\ xf$$

The output power (non reactive) for a dimensional strain of x peak to peak is

$$W_1 = U^2 \quad R_s$$

$$= 2\pi^4 \; r^6 \; x^2 \; f^2 \quad . \quad \frac{\frac{1}{2}\rho_0 c k^2 r^2}{1 + k^2 r^2}$$

$$k = \frac{2\pi}{\lambda} \qquad = \frac{2\pi f}{c}$$

$$W_1 = \frac{4\pi^6 \; r^8 x^2 \; f^4 \; \rho_0 c}{c^2 + 4\pi^2 \; f^2 \; r^2} \qquad (1)$$

The quoted value of piezoelectric coefficient, d, for polyvinylidene fluoride is 1.66 x 10^{-11} $V^{-1}m$.(5) By substitution in (1) for a 5 cm dome operating at 2 kHz

$$W_1 = 4.63 \times 10^{-21} \text{ W per unit field drive (1Vp to p)}$$

at a practical driving voltage of 250 V r.m.s. (700 v p to p) across a 25 μm film

$$W = 4.63 \times 10^{-21} \times \left(\frac{700}{(25 \times 10^{-6})}\right)^2$$

$$= 3.63 \times 10^{-6} \text{ W radiated acoustic output}$$

This is equivalent to a sound pressure level at one metre in anechoic surroundings of 58.6 dB.

In a similar way the value of W for an 11 cm diameter dome of 100 μm P.V.C. may be found using an experimentally derived value of 'd' of 1.8 x 10^{-13} V^{-1} m

For the same driving field as before

$$W = 9.38 \times 10^{-5} \; W \equiv 74 \text{ dB s.p.l.}$$

Appendix 2.

The mechanism of Piezoelectricity in Plastics.

Whilst polyvinylidene fluoride yields the highest piezoelectric coefficient found in plastics and was therefore the most suitable material for experimental work the comparative rarity of the substance necessitated the use of polyvinyl chloride for some experiments. The mechanism of piezoelectricity in this polymer is substantially similar, the magnitude of the effect being smaller.

Taking polyvinylidene fluoride as a typical example the polymer may be represented thus:

The highly electro-negative nature of the fluoride pair tends to redistribute charge within the structure resulting in the electrical polarization shown. The polar nature of the polymer and the restricted carbon bond angle give rise to two possible phases for the plastic.

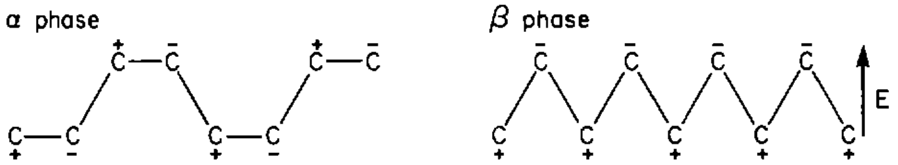

Fig. 14. Molecular structure of polyvinylidene fluoride

In the cast material the α phase predominates but bulk mechanical deformation tends to convert the crystalline material to the β phase and hence extruded film is predominantly of this form. This is of some importance since it is the β structure that is known to give rise to the high piezoelectric effect in the polymer.

With regard to Fig. 14 it can be seen that an electric field applied in the direction indicated would tend to compress the corrugated structure. This causes a molecular strain both co-linear with the applied field and co-axial with the polymerised chain. In the cast material the chain and dipole orientation are entirely random, so that little bulk piezoelectricity is observed. (Extrusion tends to align the molecules in the direction of extrusion and it is therefore important if a sheet of material is required to be isotropic in its plane that it is extruded along two orthogonal axes). The dipole moments are polarized by applying an electric field normal to the sheet at an intensity just below the dielectric breakdown of the plastic. The temperature must initially be raised to allow the chains to rotate; polarization is then frozen into the plastic by maintaining the field while the material cools to room temperature.

Appendix 3

Dome manufacturing techniques.

1. Vacuum forming

The various domes were formed from flat sheets of the particular plastic. A disc was cut out and placed in the vacuum mould. The basic construction of the mould is shown in Fig. 15.

The mould was then heated slowly in an oven to an optimum forming temperature (Table 2) this being found merely by experimentation. Air was then evacuated from beneath the plastic disc until it filled the mould. Whilst maintaining this partial vacuum the whole structure was then cooled to room temperature.

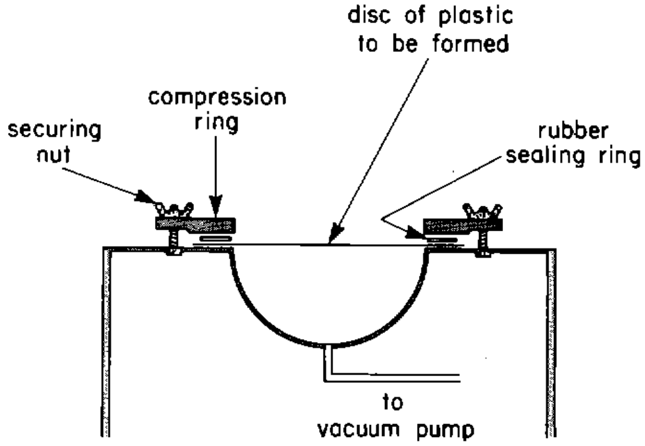

Fig. 15. Vacuum forming mould

TABLE 2

Plastic used	Optimum forming temp.	Comments
Polyvinylidene flouride	183°C ± 4°C	Optimum forming temperature close to melting point
Polyvinyl chloride	125°C ± 5°C	Non-critical and good vacuum forming characteristic

2. Metal evaporating

The plastic dome was first cleaned with an organic solvent. In the case of the smaller dome it was then mounted as shown in Fig.16. in the vacuum chamber. The chamber was evacuated down to a pressure of 0.1μm Hg. The actual evaporation was carried out in three stages with a pause between each to allow the apparatus to cool. This process was then repeated for the reverse side of the dome.

In the case of the larger unit the aluminium had to be evaporated from three directions on to the convex surface. This was necessary because the filament tended to deposit metal along a 'line of sight' path and the larger hemisphere had nearly parallel sides. In all cases aluminium was used as the evaporating metal because of its low cost and good electrical conductivity.

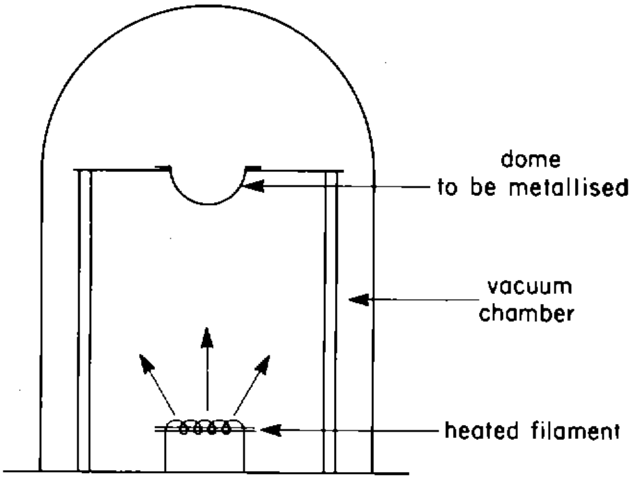

Fig. 16. Vacuum deposition chamber

Appendix 4

Interferometric measurements

The following graphs represent the sensitivity of the 5 cm P.V.D.F. dome with respect to frequency, derived by interferometric means (see section 4.2.). The sensitivity is measured in terms of the relative drive voltage needed to produce, at the specified point on the dome, a peak-to-peak displacement of ½ a wavelength of red light.

Graphs 17-20 apply to the undamped dome (see sec. 4.1.) and Graph 21 is provided as a comparison and is of a damped dome.

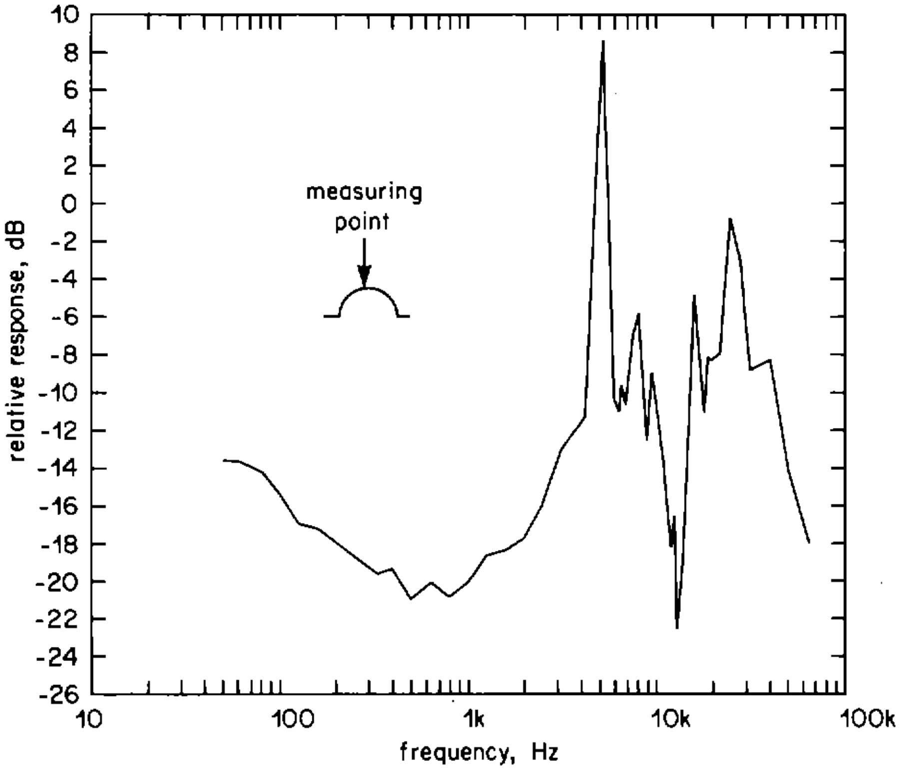

Fig. 17
Displacement of 5 cm dome
V_s *frequency*

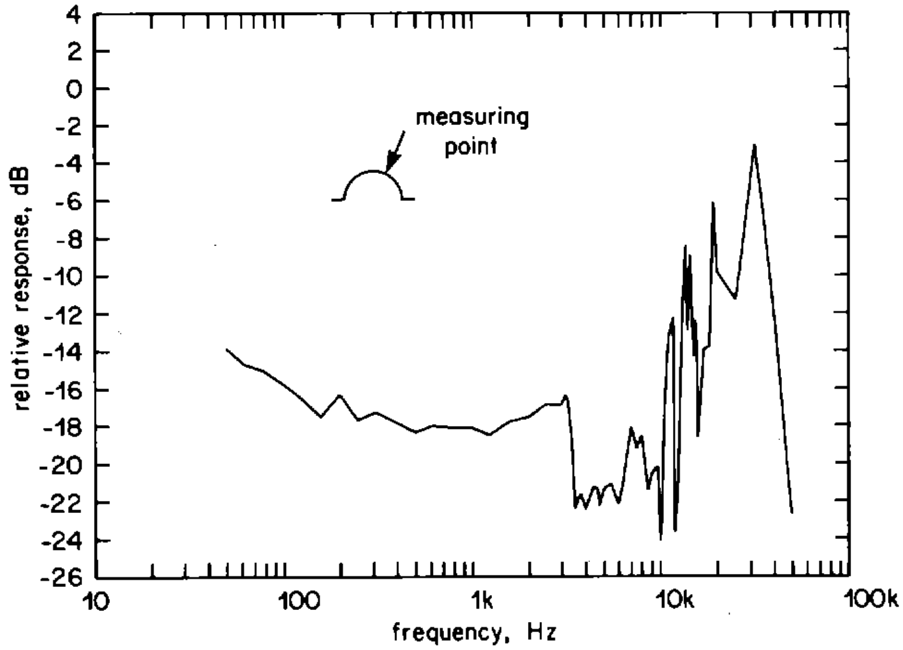

Fig. 18
22½° off axis

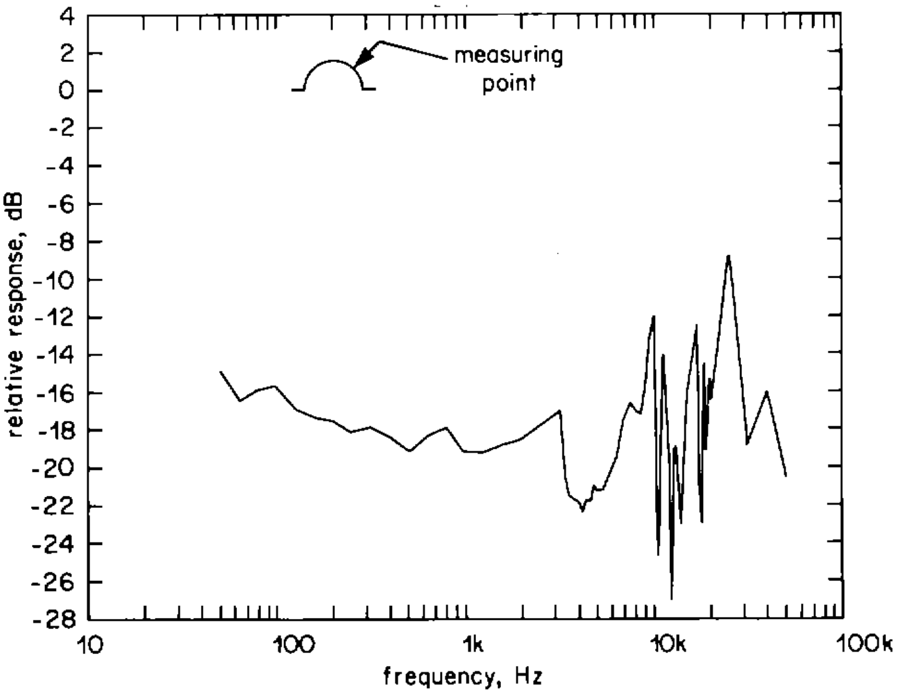

Fig. 19
45° off axis

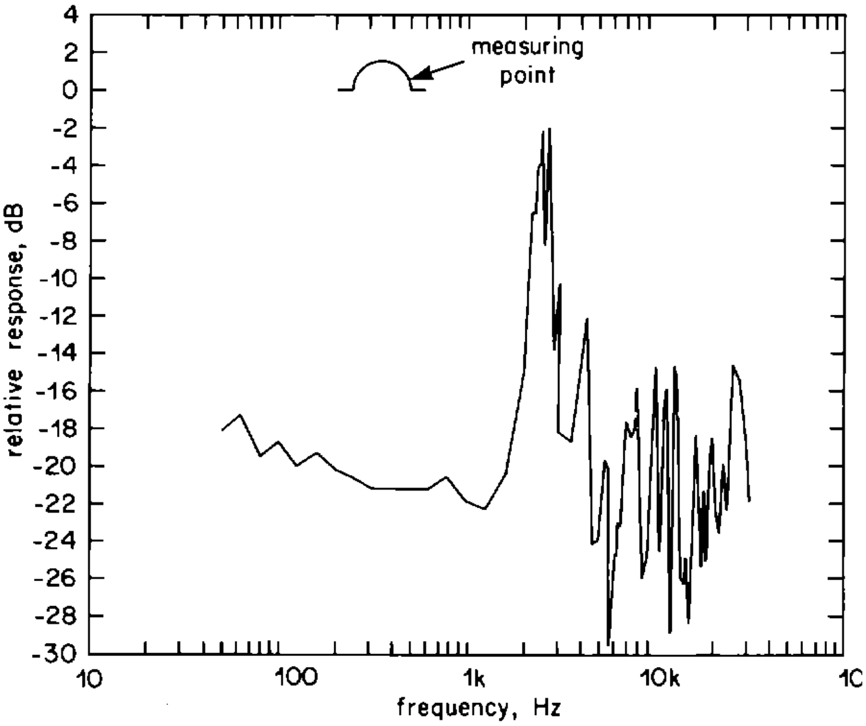

Fig. 20
67½° off axis
(for undamped dome)

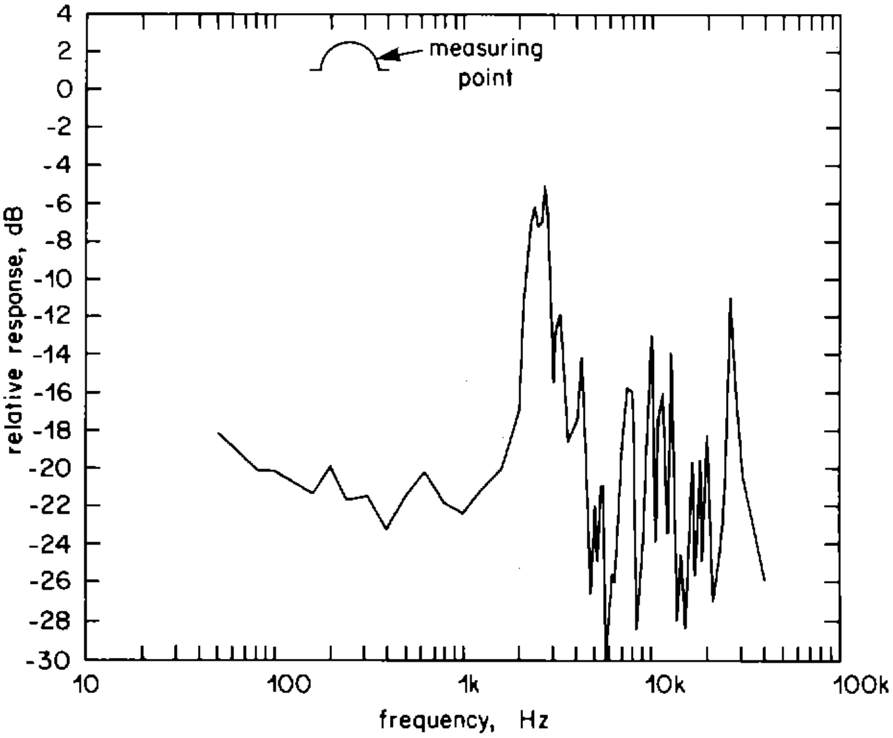

Fig. 21
67½° off axis
(for damped dome)

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