Mechanical and Acoustic Frequency Responses in Flat Hot-Compacted Polyethylene and Polypropylene Panels

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ABSTRACT: A range of flat hot-compacted single-polymer composite panels made from oriented polypropylene and polyethylene with differing dynamic modulus and damping capacity were freely suspended and subjected to mechanical excitation, allowing their acoustic frequency response over the audio bandwidth to be measured. The audio response over selected bands was correlated with the dynamic modulus and damping capacity measured in bending in these materials and compared with the response of a traditional composite material, namely, carbon-fiber-reinforced epoxy resin. Low damping and high dynamic modulus were found to result in relatively high output levels from the hot-compacted flat panels, which contrasted with the results previously measured on a traditional cone-shaped speaker made from a hot-compacted polypropylene material, which found high damping to be advantageous. The results of the current study on flat panels are explained in terms of mechanical impedance of the panels and their corresponding efficiency. It was concluded that the best flat-panel audio response came from compacted polyethylene sheets, which combined high stiffness, low density, and a low level of damping. © 2005 Wiley Periodicals, Inc. J Appl Polym Sci 99: 2789–2796, 2006

Key words: self-reinforced composites; audio; mechanical properties

INTRODUCTION

It is well recognized that there are two important physical properties a potential loudspeaker material should have. The first is stiffness, because for a specific loudspeaker design this determines the frequency of undesirable resonance; the second is mechanical damping, which determines the amplitude of the frequency responses and can help control unwanted resonance. In general, the designing of a conventional loudspeaker has focused on having a high-stiffness, low-mass diaphragm that operates as a piston when driven by electromagnetic, electrostatic, or piezoelectric means. The overall design principle has remained largely unchanged for decades, but a wide range of new materials have been used in the production of diaphragms. Use of such materials as low-density metals and fiber-reinforced polymers has resulted in increased stiffness and reduction in unwanted resonance in a traditional cone-shaped diaphragm,[1] said to cause tonal variation (coloration) and a blurring of the stereo image (smear). High specific stiffness and high damping are believed to be important as ideal material properties for the construction of a conventional loudspeaker diaphragm.

In a previous study[1] a cone-shaped diaphragm was used to assess the performance of a new class of polymer composite material developed at the University of Leeds. This material was manufactured by a process termed hot compaction. In this process,[2–5] an array of oriented polymer fibers or tapes is heated to a temperature at which a thin skin of material on the surface of each oriented element is melted. On cooling, this molten material recrystallizes to form the matrix of a self-reinforced polymer/polymer composite, whereas the remaining oriented fraction (~80%) acts as the reinforcing phase. By retaining such a high proportion of the original oriented elements, a material is achieved that has excellent mechanical properties of stiffness and strength, yet, because it is all polymeric, it also is low density. In addition, hot-compacted sheets are postformable, so that shapes, such as a traditional loudspeaker cone, can be readily produced.

In previous work we concentrated exclusively on cone diaphragms made from hot-compacted polypropylene sheets. Experiments demonstrated that these cones showed excellent audio characteristics because of a combination of good specific stiffness and high damping. The preferred molecular orientation in the compacted sheet (from the oriented fraction of the

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composite) provided enhanced stiffness, whereas the molecular relaxation in the polypropylene provided the damping.

Although the design of conventionally shaped loudspeakers has not changed significantly, the performance of loudspeakers with this design is still not ideal. At relatively high frequencies the sound produced by a diaphragm becomes highly directional (beaming), and the reflected sound in the listening room becomes subject to increased levels of tonal variation, which affects the fidelity of the sound perceived by the listener. The frequency range over which the sound becomes directional is determined by the area of the diaphragm, and in order to span the audio frequency range, a series of loudspeakers with diaphragms decreasing in area are included in the speaker cabinet. A crossover network separates the audio signal into frequency bands that correspond to the operating ranges of each loudspeaker. A common crossover frequency is between 3 and 4 kHz, and the slight phase distortions and tonal variations that result from the use of a crossover often can be detected by the listener because the human ear is most sensitive in this range.

Conventional loudspeakers also have disadvantages in the aesthetics of the design. Because a series of loudspeaker diaphragms are required to span the audio frequency range, the cabinet needed to contain these often is correspondingly large, making positioning in a domestic environment difficult. A recent innovation in the design of loudspeakers is the production of a relatively thin and flat panel loudspeaker. It has been proposed[6] that this type of loudspeaker has a range of technical advantages over conventional loudspeakers that include insensitivity to room conditions, good linearity, and a less pronounced problem with beaming at high frequencies. As a result, the need for complex crossover circuits is bypassed.

The principle of operation of a flat-panel speaker is quite different from that of a conventional cone loudspeaker. Instead of the minimization of flexural resonance in the panel being an aim, it is actively encouraged because it is interaction of the panel resonance with air that results in radiation of sound from the panel. The performance of flat-panel speakers has several key factors.[7]

The panel will not radiate sound below the fundamental resonance of the panel, which for an isotropic vibrating plate was approximated by Leissa[8] to

$$f_0 \approx \frac{\pi}{A}\sqrt{\frac{D}{\mu}} \tag{1}$$

where f_0 is the fundamental resonant frequency, A is the area of the panel, D is the bending stiffness per unit width, and μ is the mass per unit surface area. The bending stiffness per unit width of the panel is given by

$$D = \frac{Eh^3}{12(1 - v^2)} \tag{2}$$

where E is Young's modulus, h is the thickness, and ν is the Poisson ratio.

The performance of the panel is also determined by the coincidence frequency below which a flexible infinite panel has no acoustic output. At this frequency the speed of sound becomes equal to the speed of the bending waves in the panel. In practice, it has been observed that for a finite panel, an acoustic output is produced,[9] although the panel efficiency at these frequencies is significantly reduced.

Above the coincidence frequency the efficiency of the panel is determined by the level of damping in the materials used in the construction of the panel. The efficiency is also determined by the mechanical impedance of the panel, which is given by

$$Z_m = 8\sqrt{D\mu} \tag{3}$$

To maximize the efficiency of the flat-panel loudspeakers, the material selection criteria that should therefore be applied—high stiffness, low damping, and low density—are somewhat different than those of the traditional cone diaphragm, for which a combination of high stiffness, low density, but high damping are considered optimum. Although an obvious choice of material would be carbon-fiber-reinforced polymer composites, the successful results of previous work on the audio capabilities of hot-compacted polypropylene suggested that this new class of all-polymeric composite material is a contender to be a material for flat-panel loudspeakers, albeit using a different base polymer. Polyethylene appeared to be an ideal candidate for at least three reasons: the density of polyethylene is low, at 970 kg/m^3, so low density is maintained; polyethylene can be oriented to give substantially higher stiffness than PP; and, finally, PE has lower damping than does PP over certain frequencies and temperatures. It was therefore decided to undertake a scientific study of the acoustic properties of flat hot-compacted sheets manufactured from a range of differently oriented fibers (both PP and PE) with particular attention to changing the stiffness and dynamic loss factor (tan δ) in an attempt to identify the key factors involved in producing excellent flat-panel acoustic performance. The main methods of evaluation were measurement of the mechanical and acoustic frequency response functions over the audio bandwidth and correlation of this response (over selected bands) with the dynamic modulus and

TABLE I
Details about Flat-Panel Materials

Type	Material	Code	Reinforcement modulus (GPa)
Hot-compacted sheet	Polypropylene	HS	11
Hot-compacted sheet	Polypropylene	MS	7
Isotropic sheet	Polypropylene	ISO	1.2
Hot-compacted sheet	Polyethylene	Certran PE	42
Hot-compacted sheet	Polyethylene	HSPE	88
Composite	Carbon fibers/ epoxy resin	CF	240

damping capacity of the hot-compacted composite materials.

EXPERIMENTAL

Material details

The details of the six materials used in this study are given in Table I. The first three materials form a group made from the same polypropylene polymer, differing only in the level of the preferred molecular orientation. The first two materials were hot-compacted polypropylene sheets made from layers of woven oriented PP tapes. For the first material (HS) the oriented tapes were highly drawn, with a modulus of 11 GPa; in the second material (MS) the tapes were a medium draw ratio with a stiffness of 7 GPa. The third polypropylene material was an isotropic sheet of the same PP polymer.

The next two materials were also hot-compacted panels but were based on highly drawn polyethylene. One panel was made from woven melt-spun polyethylene filaments (Certran® made by Hoechst Celanese, Charlotte, NC); these fibers have a tensile modulus of 42 GPa and are made from a polymer with a weight-average molecular weight of 150 g/mol. The second polyethylene hot-compacted panel was made from woven layers of a very highly drawn melt-spun tape, trade name Tensylon (Integrated Textile Systems Inc., Monroe, NC); the modulus of this tape was 88 GPa. For comparison, the final material chosen for testing was a carbon-fiber-reinforced epoxy resin composite.

The codes for the six materials are:

Polypropylene
High-stiffness hot-compacted woven PP tapes (HS)
Medium-stiffness hot-compacted woven PP tapes (MS)
Isotropic PP (ISO)
Polyethylene
High-stiffness hot-compacted Certran woven PE fibers (Certran PE)
Ultra-high-stiffness hot-compacted Tensylon woven PE tapes (HSPE)
Other composite system
Carbon-fiber epoxy resin (CF)

Production of the panels

Flat square panels 30 × 30 cm in size were fabricated from the six materials for evaluation of the mechanical and acoustic frequency response functions. For the manufacture of the hot-compacted panels, a similar procedure was used for all the material types. The oriented fibers or tapes were either woven into cloth or supplied by the manufacturers as woven cloth. From these cloths 300-mm squares were cut and assembled between thin, polished soft aluminum sheets and placed into a matched metal mold of internal dimensions 300 mm square: the number of layers were chosen so as to give a compacted sheet thickness of approximately 1 mm. The mold assembly was placed into a heated compression press set at the appropriate optimum compaction temperature established from previous studies of polypropylene[4] and polyethylene[3], and a pressure of 400 psi was applied. Once the assembly reached the appropriate compaction temperature, it was left for 5 min, during which time it cooled rapidly while under pressure to a temperature below the crystallization temperature of the material. To make the isotropic PP sheet, a temperature above the melting point of the oriented tapes was used.

The carbon-fiber composite panel comprised a four-layer plain-weave 3K high-strength fiber and a 737 epoxy resin (supplied by Cytec Engineered Materials, Ltd., Wrexham, UK). The composite panel was fabricated using an autoclave to minimize the level of voids in the sample.

Frequency response measurements

For the frequency response measurements, the panels were all freely suspended. An electromagnetic shaker (4810) and a force sensor (8200) were mounted 11.0 and 8.0 cm, respectively, from two adjacent edges of each square panel. A low-mass accelerometer (Endevco Isotron 25B) was attached to the center of the panel with accelerometer mounting wax supplied by Endevco. Acoustic measurements were made using a linear response microphone (MBC 550) at the center of the panel 15 cm from the flat surface.

The electromagnetic shaker and a constant current power amplifier (2706) were used to drive the panels with random noise over the bandwidth from 100 Hz to 15 kHz. The force sensor measured the applied force, and the accelerometer measured the vibrational response of the panel. The response functions were averaged using 500 response spectra.

A Bruel and Kjaer PULSE analysis system was used to measure the magnitude of the frequency response functions of the panels. The frequency response function (transfer function), $H(f)$, for a linear system is defined as

$$H(f) = \frac{Y(f)}{X(f)} \quad (4)$$

where $Y(f)$ is the Fourier spectrum of the output signal and $X(f)$ is the Fourier spectrum of the force input signal.

The frequency response functions were smoothed using an adjacent average routine in Origin 6.0 (supplied by MicroCal) and then analyzed in two ways. With the first method the prominent peaks in the response over selected frequency bands were identified, and with the second method an average value of the response was calculated, again over the selected bands. The bands were selected according to the sensitivity of the human ear; the bands identified as key frequency bands were 0.1–0.3, 1–2, 3–4, 8–10, and 14–15 kHz.

DYNAMIC MECHANICAL MEASUREMENT

The dynamic mechanical behavior of the hot-compacted sheets was determined by using a Rheometrics RDAII. The tests were carried out in three-point bending operating at a frequency of 1 Hz, for both a single measurement at room temperature (20°C) and over the temperature range from −50°C to +50°C. Results for the dynamic modulus, E', and the loss factor, tan δ, were obtained using a testing span of 48 mm, a prestrain of 0.1%, and a dynamic strain of ±0.05%.

RESULTS

Dynamic mechanical properties

The DMTA temperature scans (at a frequency of 1 Hz) for the six materials are shown in Figure 1(a,b), and representative single-point values of E′ and tan δ are shown in Table II. The DMTA results shown in Figure 1(a,b) are most instructive. First, it is clear that the storage moduli of the Tensylon PE and carbon-fiber epoxy sheets were much greater than those of the polypropylene materials, with the Certran PE having an intermediate value. Second, Tensylon PE and carbon-fiber epoxy showed low tan δ values at room temperature, with the values of Tensylon PE increasing as the α process region was reached. The α process in PE involves large-scale chain motion and leads to inter- and intralamellar relaxation processes. Mechanical damping caused by these relaxation processes will

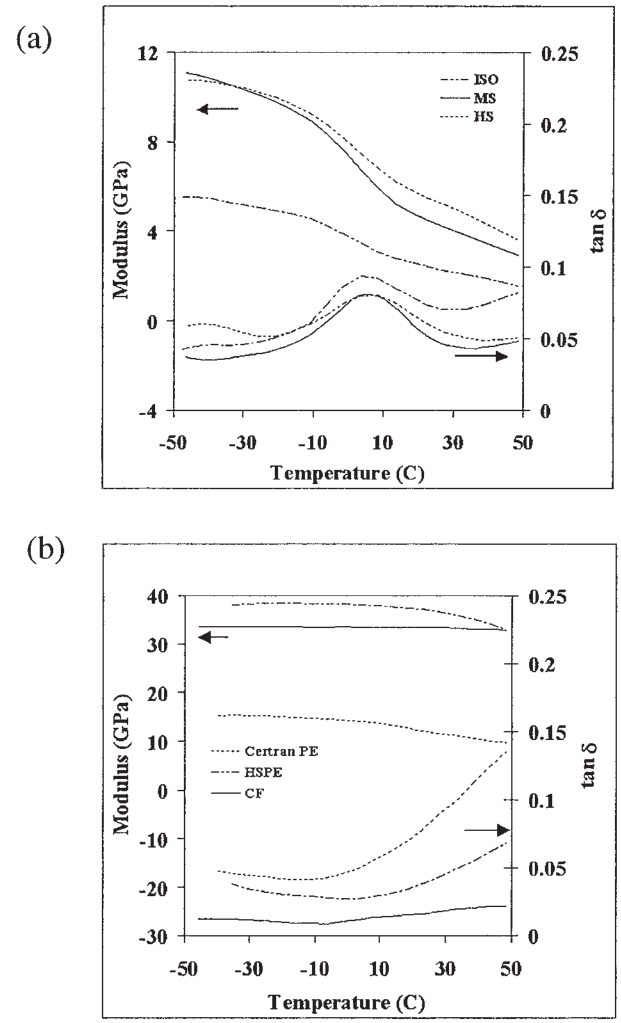

Figure 1 DMTA results for loudspeaker panel materials: (a) polypropylene-based materials (ISO, MS, and HS), (b) polyethylene materials and the carbon fiber/epoxy composite (Certran PE, HSPE, and CF).

only be large at temperatures approaching PE melting, that is, at temperatures greater than about 200°C in the audio frequency range.[10] Certran PE showed a similar rise in tan δ above room temperature because of the α relaxation. Bearing in mind that the frequency of measurement was 1 Hz, the value of tan δ at higher frequencies for the two PE materials would be even lower at room temperature as the α relaxation shifted to higher temperatures. For the polypropylene sheets there was a significant loss peak at 1 Hz in the room temperature range because of the β relaxation process, a process that in PP involves large-scale motion in the noncrystalline regions.[11] It is akin to a glass transition with a very high activation energy that is large compared to the α relaxation in HDPE (~500 kcal/mol compared to ~80 kcal/mol for the α process in HDPE[12]) and so will not shift appreciably to higher temperatures with increasing frequency. This suggests that for the PP materials there would be significant

TABLE II
Dynamic Mechanical Properties and Densities of Panel Materials

Material	Code	Three-Point bend (DMTA)		Density
		E′ (GPa)	tan δ	kg/m^3
High stiffness PP	HS	5.40 ± 0.05	0.0828[a]	910
Medium stiffness PP	MS	4.39 ± 0.01	0.0854[a]	910
Isotropic PP	ISO	2.35 ± 0.01	0.098[a]	900
High-stiffness hot-compacted PE fibers	Certran PE	12.3 ± 0.1	0.0426[b] ± 0.0016	970
Ultra-high-stiffness hot-compacted Tensylon PE fibers	HSPE	34.6 ± 1.4	0.0301[b] ± 0.0026	970
Carbon fiber epoxy	CF	33.1 ± 0.1	0.0100[b] ± 0.0013	1500

[a] Peak value
[b] average value from the plateau region (−30°C to 0°C)

damping at room temperature over the whole frequency range, in contrast to PE, for which the damping would be much lower.

For these reasons the single-point values of tan δ from the DMTA test, shown in Table II, were calculated as follows. For the three PP materials the peak value of the β process was used, whereas for the two PE materials and the carbon-fiber material, an average from the plateau region was used (taken between −30°C and 0°C).

Therefore, on the basis of the DMTA results we can separate the six materials into two groups. The first group, comprising high-stiffness PP, medium-stiffness PP, and isotropic PP, was characterized by a relatively low dynamic modulus and high damping. The second group, comprising Certran PE, Tensylon PE, and carbon-fiber-reinforced epoxy, was characterized by a relatively high dynamic modulus and low damping. In the latter group, Tensylon high-stiffness PE (HSPE) had the highest specific stiffness, for even though its dynamic stiffness was similar to that of carbon-fiber-reinforced epoxy, the density of the polyethylene material was 970 kg/m^3, compared to 1500 kg/m^3 in the carbon-fiber-reinforced epoxy.

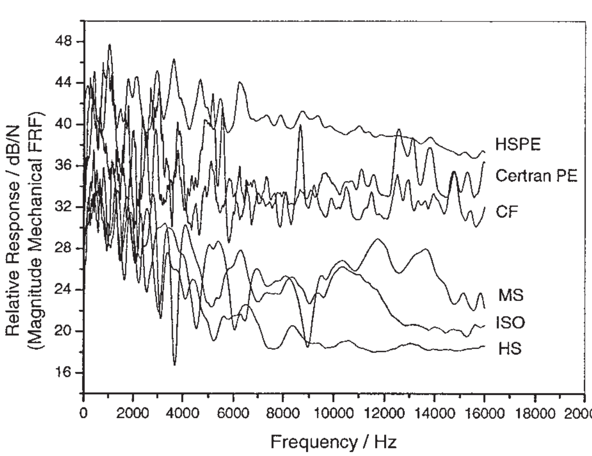

Figure 2 Mechanical frequency response functions for panel materials.

Mechanical frequency response function

The magnitudes of the mechanical frequency response functions obtained for the panels are shown in Figure 2, from which it is clear that the responses fell into two groups. The first group (the PP materials) was characterized by a relatively low response over the measured frequency range, and the second group was characterized by a relatively high response over the measured frequency range. The latter group consisted of Tensylon high-stiffness polyethylene (HSPE), Certran polyethylene (Certran PE), and carbon-fiber epoxy laminate (CF). Therefore, it was clear that there was a close correlation between the material groups identified in Table I and the responses shown in Figure 2, with high stiffness and low damping resulting in relatively high mechanical frequency response levels.

The effect of the dynamic modulus of the panel materials and damping on the magnitude of the mechanical frequency response, averaged over the selected bands, are shown in Figures 3 and 4, respectively. It is apparent that a relatively high response correlated with relatively high dynamic modulus and low damping. This trend also was observed in the peak response. Also, a trend was observed of decreasing response with increasing frequency, which was in accordance with the trends shown in Figure 2.

The response of the panel was also found to depend on the specific modulus, E/ρ, with a trend toward increasing mechanical response with increasing specific modulus, as shown in Figure 5, in which the results in the upper right of the diagram are from the Tensylon PE panel, confirmation of the previous assumption that this is the best material. This trend also was observed in the peak response.

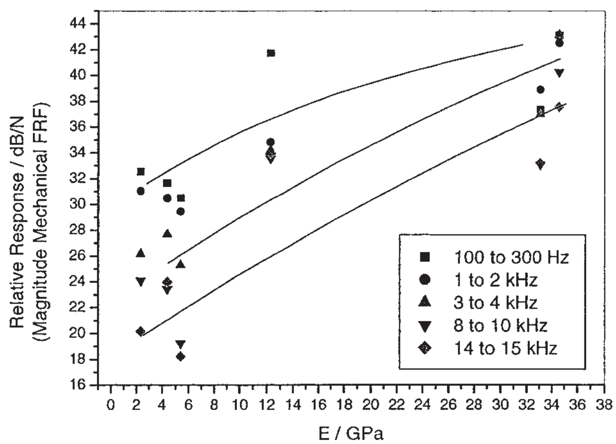

Figure 3 Variation of relative mechanical frequency response with relative dynamic modulus averaged over selected frequency bands (solid line intended to guide the eye).

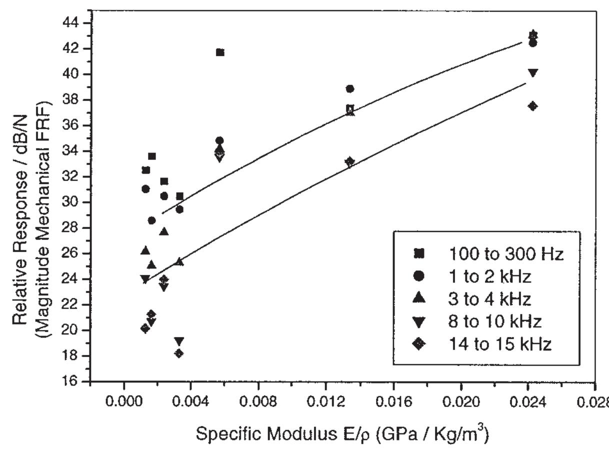

Figure 5 Variation of relative mechanical frequency response with specific dynamic modulus averaged over selected frequency bands (solid line intended to guide the eye).

Audio frequency response function

The magnitudes of the acoustic frequency response functions obtained for the panels are shown in Figure 6. In general, response decreased with increasing frequency. It was clear that the material producing the highest relative acoustic output was HSPE, which, on closer inspection, was followed by carbon-fiber laminate and Certran polyethylene. Although not as marked as the trend shown in the mechanical response (Fig. 2), the acoustic responses could be correlated with the material groups identified in Table II from the DMTA results.

The effects of the dynamic modulus and damping of the material on the magnitude of the acoustic frequency responses are shown in Figures 7 and 8, respectively. In agreement with the trends observed in the mechanical frequency response functions, the response was found to increase with increasing stiffness and decreasing damping.

The increase in the level of acoustic frequency response with increasing stiffness tended toward an almost linear dependence, whereas the dependence on damping tended toward exponential decay. As shown in Figure 6, the relative response was significantly reduced with increasing frequency. The effect of specific modulus also was in accordance with the mechanical frequency response, with the acoustic response increasing with increasing specific modulus, as shown in Figure 9. The above trends also were observed in the peak response.

DISCUSSION

Correlation of mechanical frequency responses with dynamic modulus, damping capacity, and density

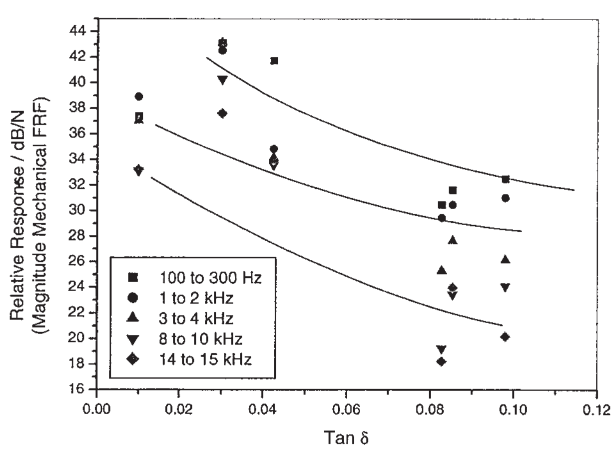

Figure 4 Variation of relative mechanical frequency response with damping averaged over selected frequency bands (solid line intended to guide the eye).

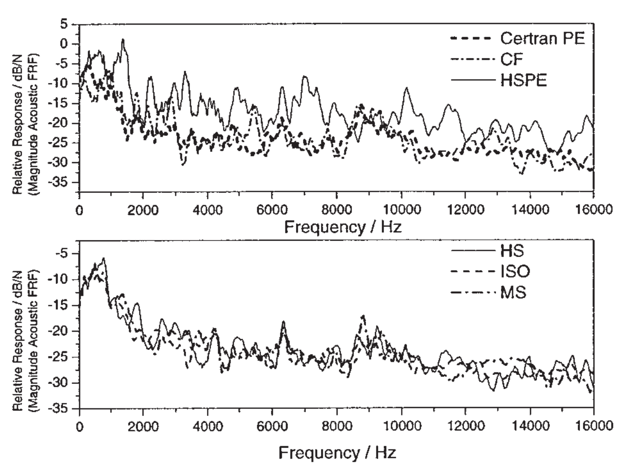

Figure 6 Acoustic frequency response functions for panel materials.

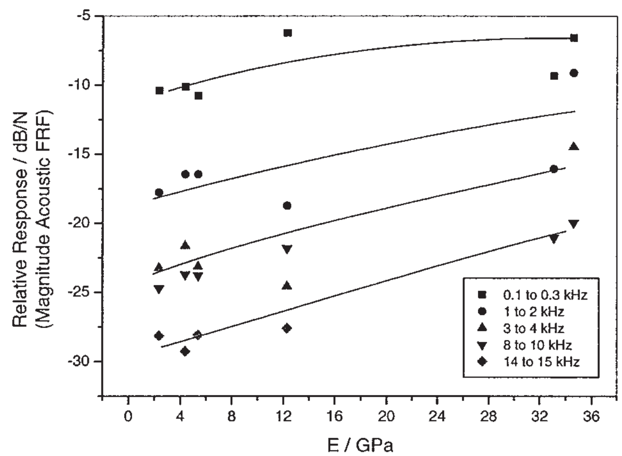

Figure 7 Variation of relative acoustic frequency response with relative dynamic modulus averaged over selected frequency bands (solid line intended to guide the eye).

clearly showed relatively high responses with relatively high dynamic modulus, low damping capacity, and high specific modulus. The explanation for these observations lies in the relationship between the efficiency of the panel and the mechanical impedance. For a point-excited infinite panel, mechanical impedance is a frequency-independent real constant[13] and is inversely proportional to E/ρ.[7] Therefore, materials with relatively high stiffness and low density will have low mechanical impedance and correspondingly high efficiency. The damping capacity of the materials also affected the efficiency of the panel in that materials with high damping reduced the amplitude of the flexural resonances in the panel and therefore reduced the resulting acoustic output.

A trend also was apparent between the mechanical and acoustic frequency responses, with a relatively high mechanical frequency response corresponding to a relatively high acoustic output. Because the level of mechanical frequency response reflects the amplitude of the flexural vibrations in the panel and the acoustic output is determined by the amplitude of the flexural resonances, the relatively high levels of acoustic output were a direct consequence of the observed mechanical response levels.

The effects of the material properties observed in the mechanical responses of the panels were also found in the acoustic responses, with relatively high output resulting from materials of relatively high stiffness, low damping, and high specific modulus. Panels produced from materials with high stiffness and low density resulted in reduced panel impedance and increased efficiency, with low damping capacity also enhancing panel efficiency.

In terms of the relative merits of the materials evaluated, the groups identified in Table II again serve to illustrate that materials exhibiting high stiffness, low damping, and high specific modulus demonstrated relatively high mechanical frequency response and correspondingly high acoustic output. The materials that constitute the second group—high-stiffness PE, Certran PE and the carbon-fiber laminate—all clearly showed relatively high output, but the high-stiffness PE exhibited the highest stiffness and lowest damping of the hot-compacted materials tested. Although it did exhibit higher density than the PP-based materials, this appears to have been compensated for by the increased stiffness. These material properties resulted in a panel of increased efficiency through a combination of reduced impedance and reduced damping.

CONCLUSIONS

The correlation of mechanical and acoustic frequency response functions with the dynamic modulus, damp-

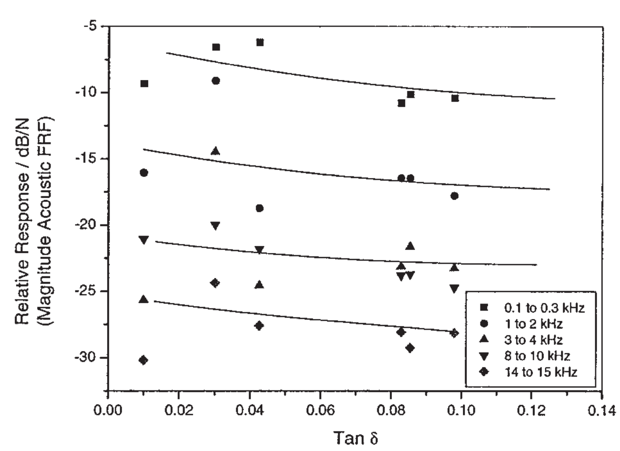

Figure 8 Variation of relative acoustic frequency response with damping averaged over selected frequency bands (solid line intended to guide the eye).

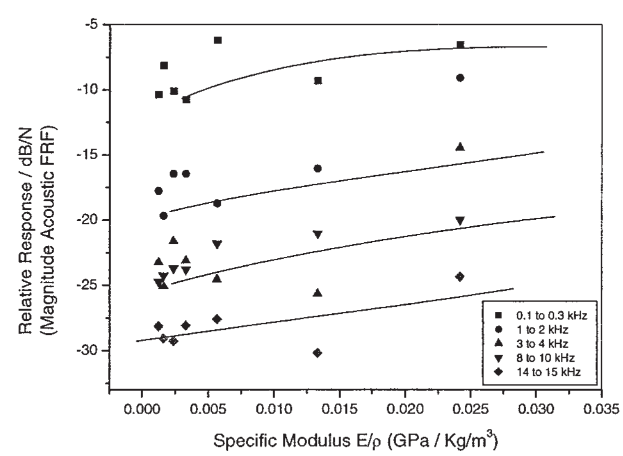

Figure 9 Variation of relative acoustic frequency response with specific dynamic modulus averaged over selected frequency bands (solid line intended to guide the eye).

ing, and specific modulus of the panel materials clearly show that the ideal combination of material properties to maximize the acoustic output of the panel is as follows: high stiffness and low density to reduce the impedance of the panel and low damping to enhance the efficiency.

However, there the material properties posed conflicting demands when they were considered for use in flat-panel and conventional loudspeaker designs. The latter require a material of high stiffness and low density to ensure rapid pistonic motion of the cone, but high damping capacity to reduce unwanted resonances. In a flat-panel loudspeaker, the requirements of high stiffness and low density are similar to those of a conventional loudspeaker, but the requirement for damping capacity is quite different. In flat-panel loudspeaker designs, low damping enhances performance through increased efficiency.

Therefore, the success with which the hot-compacted PP materials were incorporated into conventional loudspeakers[1] was in accordance with the results shown in this work. The hot-compacted PP materials exhibited levels of damping required to produce loudspeaker diaphragms that suppress any cone resonance, but the hot-compacted PE did not because of reduced damping capacity. Therefore, hot-compacted PE does exhibit the material properties required to produce highly efficient flat-panel loudspeakers.

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