COMPETENT THIRD PERSON REPORT

ELECTROSTATIC LOUDSPEAKERS

Report to:
Craig Evans
Immersion Technology International plc

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Gregory Keith Cambrell, B.E.(Hons), B.Sc.(Hons), Ph.D.

EXECUTIVE SUMMARY

Immersion Technology International plc (‘Immersion’) has developed an alternative electrostatic type of loudspeaker to compete directly with the existing dominant magnetostatic (more commonly called moving-coil electrodynamic) type of loudspeaker. Amongst other significant advantages that an electrostatic loudspeaker has over a conventional magnetostatic loudspeaker, the most distinguishing and noteworthy feature for the loudspeaker market is that the structure of an electrostatic panel is inherently thin, typically 10 mm or less.

There are several significant theoretical advantages to electrostatic loudspeakers compared to magnetostatic loudspeakers but in the past most of the advantages could not be fully realised until certain physical constraints were overcome [1, 2]. Immersion has successfully realised these advantages and is now poised to challenge the loudspeaker market.

In simple terms, Immersion has now attained what was previously regarded as nearly impossible to attain for an electrostatic loudspeaker because of numerous improvements in the materials of construction and the techniques of manufacture. Until now electrostatic loudspeakers have enjoyed limited acceptance in the marketplace; however, once properly commercialised, Immersion will be a viable competitor against not only existing electrostatic loudspeakers but also conventional magnetostatic loudspeakers.

Immersion has patented a number of electronic and construction techniques for improving the performance of electrostatic loudspeakers and facilitating their manufacture. They have reached the point of development where electrostatic loudspeakers of various sizes can be a superior yet cheaper alternative to the existing magnetostatic loudspeakers of comparable size for many applications.

By comparison with magnetostatic loudspeakers, the theoretical advantages of electrostatic loudspeakers include

- linear (distortionless) transduction principle
- uniform force per unit area of diaphragm
- low-mass diaphragm allowing superior high-frequency performance
- radiation characteristics (including low-frequency acoustical resistance) controlled by the extent and shape of diaphragm area
- baffles (as with conventional loudspeakers) of various sizes and shapes (possibly adjustable) may be incorporated to further control the low-frequency performance
- inherently thin construction
- relatively low cost of required materials

Immersion has developed several prototype electrostatic loudspeaker models. Immersion’s larger models have been evaluated and compared to three commercially-available electrostatic loudspeakers of similar size yet costing up to double the estimated recommended retail price of Immersion’s models. Measurements and listening tests have shown that not only have the theoretical advantages of electrostatic loudspeakers been achieved in Immersion’s new models but also their performance exceeds that of the three commercially-available products. Furthermore, Immersion’s smaller models have shown outstanding performance against conventional loudspeakers of similar size.

Mass production of Immersion’s prototype models with their patented improvements in construction techniques is expected to produce reliable high-performance products with major cost benefits compared to conventional loudspeaker products in many areas of application.

Independent market appraisals have shown the enormous potential for Immersion’s thin electrostatic loudspeaker technology to compete with conventional loudspeakers in market areas ranging from high-end audio to home and car entertainment.

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COMPETENCY STATEMENT

Dr Gregory Keith Cambrell was until March 2006 a Senior Lecturer with the Department of Electrical and Computer Systems Engineering, Monash University, Clayton Campus, Victoria, Australia. He has a Bachelor of Engineering with first class honours in electrical engineering and a Bachelor of Science with first class honours in mathematical physics both from the University of Adelaide, South Australia. He received a Ph.D. in electrical engineering from Monash University in 1973. He has had extensive experience teaching and researching in the areas of electromagnetic and circuit theory, electroacoustics, electronics and applied mathematics. He has an ongoing professional interest in sound reproduction and, in particular, has been involved over many years in designing and constructing both electrostatic loudspeakers and conventional loudspeakers. Some of his subwoofer designs have won international recognition and various awards.

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1. Electrostatic Loudspeakers

1.1 Introduction to electrostatic loudspeakers

The electrostatic loudspeaker was devised over 80 years ago yet commercial exploitation of electrostatic loudspeakers continues to be confined to a small niche portion of the marketplace. In fact, an electrostatic transducer was demonstrated as early as 1881 [1]. In order to understand how market acceptance of electrostatic loudspeakers might be overturned, it is necessary to go back to the physical principles of both the electrostatic loudspeaker and the conventional moving-coil electrodynamic loudspeaker (which, for ease of comparison, will be referred to as the "magnetostatic loudspeaker" in this report).

The word "loudspeaker" itself is used in many senses but in this report its use will be confined to describe a driver or transducer from the electrical domain to the acoustical domain via the mechanical domain. When modelling with two-terminal lumped components in each domain, the time-varying physical variables involved occur in pairs such that their product is the instantaneous power delivered to a lumped component. One of the physical variables is called a "through variable" while the other is called an "across variable". In the electrical domain the through variable is the electrical current (symbol i, unit ampere [A]) and the across variable is the voltage difference (symbol v, unit volt [V]). In the mechanical domain the through variable is the force (symbol f, unit newton [N]) and the across variable is the velocity difference (symbol u, unit metres per second [m/s]). In the acoustical domain the through variable is the volume velocity (symbol U, unit cubic metres per second [m^3/s]) and the across variable is the pressure difference (symbol p, unit newtons per square metre or pascal [Pa]). A summary of the lumped components analogous to the resistor, the inductor and the capacitor in the mechanical and the acoustical domains is given in Appendix A [3, 4].

The electrostatic loudspeaker contains one or more panels each of which is comprised of an electrically-charged flexible diaphragm insulated from and suspended between two acoustically-transparent electrically-conducting rigid stators to which the audio signal voltage is applied. Electrostatic loudspeakers require a source of electrical charge for the diaphragm, usually obtained from a low-power high-voltage source, and an audio signal of relatively high voltage, usually obtained from a conventional electronic amplifier in conjunction with an iron-cored step-up transformer [2]. The force per unit area experienced by the charged diaphragm is simply the product of the electrical charge per unit area and the electric field intensity between the stators caused by the audio signal voltage. As long as the charge per unit area (the surface charge density, symbol ρ_S, unit coulombs per square metre [C/m^2]) is held constant, the force per unit area is directly proportional to the audio signal voltage (a linear transduction principle) since the electric field intensity (symbol E, unit volts per meter [V/m]) between the stators is the voltage difference divided by the stator separation ($2d$ [m] where d is the nominal separation between the diaphragm and either stator). If the active area of the diaphragm is S_D [m^2], the linear transduction principle can be summarised as:

$$f = \frac{\rho_S S_D}{2d} v \quad \text{[N]}$$

where f is the total force on the diaphragm and v is the applied audio signal voltage.

As stated above the formula for total force on the charged diaphragm is correct only when the diaphragm is centrally located between the stators. A more detailed derivation, given in

Appendix A, shows that when the diaphragm is displaced by a distance x [m] from its central location, there is a further force term proportional to x which represents negative mechanical compliance. In short, the diaphragm is attracted to the nearer stator whenever the diaphragm is displaced from its central location. The effect is to increase the initial mechanical compliance of the diaphragm, which, for an elastic diaphragm, is usually set by prestretching the diaphragm. With enough charge on the diaphragm it is possible to completely cancel the initial mechanical compliance so that the diaphragm location is unstable; the diaphragm tends to cling to either stator and electrical breakdown will occur if there is insufficient insulation around the stator conductors.

The complete lumped equivalent circuit of an electrostatic loudspeaker panel is derived in Appendix A. It shows how the electrical variables (the applied audio voltage and current) are transformed into mechanical variables by means of an ideal gyrator, which, in turn, are transformed into acoustical variables (the sound pressure and volume velocity) by means of a second ideal gyrator. The equations defining an ideal gyrator and an ideal transformer are also given in Appendix A. In older literature the gyrator was not used in the equivalent lumped circuits of electroacoustic devices. It was then necessary to use a dual analogy in the mechanical domain whereby the through and across variables were interchanged, impedance was interchanged with its reciprocal (admittance) and series-connected circuits became parallel-connected circuits, etc.

The acoustical loading on the moving diaphragm, and the resulting radiation, has been the subject of much research and analysis. Closed expressions for the radiation characteristics of diaphragms are only available for simple shapes such as circular and rectangular. General trends are well known, however. They include the fact that a large area of diaphragm is required for good low-frequency response but a narrow area is necessary for good dispersion at high frequencies (in the plane containing the narrow dimension but normal to the longer dimension). Hence rectangular panels in the shape of strips are commonly used.

There are two conditions which limit the maximum sound pressure from an electrostatic panel. At higher frequencies, where the diaphragm excursion is small, the possible electrical breakdown of the air between the diaphragm and stators limits the maximum audio signal voltage that can be applied between the stators. At lower frequencies, usually near the mechanical resonant frequency of the diaphragm, the diaphragm can excurse so far that it may reach the stators at an audio signal voltage less than the high-frequency limit. Hence panels designed for low-frequency reproduction are given a larger separation between diaphragm and stators and consequently require higher audio signal voltages.

As it is important to appreciate the fundamental (high-frequency) limit due to possible electrical breakdown of air, a derivation of the formula for maximum achievable sound pressure level (SPL) from an electrostatic panel will be given here.

Let E_a [V/m] be the electrical field intensity (field strength) at which air tends to ionise and break down. The value of E_a depends on many factors including atmospheric pressure, humidity and the uniformity of the electric field. Between plane electrodes (hence uniform electric field) a typical value of E_a is 3×10^6 V/m. The optimum value of surface charge density ρ_S [C/m^2] on the diaphragm is such that it causes an electric field intensity between the diaphragm and stators of $0.5E_a$ [V/m]. Then an application of Gauss' flux law gives $\rho_{S\,\max} = \varepsilon_0 E_a$ [C/m^2] which is independent of the nominal diaphragm-stator separation d [m]. Here $\varepsilon_0 \approx 8.854\times10^{-12}$ [F/m] is the permittivity of free space, a fundamental physical constant.

The maximum peak audio signal voltage which may then be applied between the stators must produce the remaining value of $0.5E_a$ [V/m]. By superposition of electric fields, the full value of E_a is produced on one side of the diaphragm while zero electric field intensity appears on the other side. The maximum peak audio signal voltage is therefore $v_{\text{peak max}} = 0.5E_a \times 2d = E_a d$ [V]. The corresponding peak force on the diaphragm of area S_D [m^2] is then

$$f_{\text{peak max}} = \frac{\rho_{S\ \max} S_D}{2d} v_{\text{peak max}} = 0.5\varepsilon_0 E_a^2 S_D \quad \text{[N]}$$

Assuming that the air loading on the diaphragm is the same on both sides, the peak sound pressure on either side of the diaphragm is therefore

$$p_{\text{peak max}} = \frac{f_{\text{peak max}}}{2S_D} = 0.25\varepsilon_0 E_a^2 \quad \text{[Pa]}$$

If the audio signal is sinusoidal, the rms (root mean square) value of the sound pressure is

$$p_{\text{rms max}} = \frac{p_{\text{peak max}}}{\sqrt{2}} = \frac{\varepsilon_0 E_a^2}{4\sqrt{2}} \quad \text{[Pa]}$$

which corresponds to an SPL of

$$\text{SPL}_{\max} = 20\log_{10}\left(\frac{p_{\text{rms max}}}{p_{\text{ref}}}\right) = 20\log_{10}\left(\frac{\varepsilon_0 E_a^2}{4\sqrt{2}\, p_{\text{ref}}}\right) \quad \text{[dB]}$$

where $p_{\text{ref}} = 2\times 10^{-5}$ [Pa].

Thus $\text{SPL}_{\max}$ is typically 117.0 dB at the surface of an electrostatic panel.

The question of how to achieve appropriate levels of audio signal voltage from conventional amplifiers will be addressed later in the report.

1.2 Comparison with conventional loudspeakers

The conventional magnetostatic loudspeaker consists of a coiled conductor of length ℓ [m] placed in a permanent magnetic field of flux density B (unit tesla [T]) and attached to a stiff piston or cone which is mechanically suspended at its centre and edges. As long as the magnetic flux density is constant over the extent of the allowed excursion of the moving coil, the force experienced by the coil is directly proportional to the audio signal current i [A] applied to the coil (a linear transduction principle):

$$f = B\ell i \quad \text{[N]}$$

Conventional amplifiers are designed to produce an audio voltage rather than a current (they have a low output impedance) so it is important to know the input impedance of the loudspeaker presented to the amplifier.

The complete lumped equivalent circuit of a magnetostatic loudspeaker is derived in Appendix A. It shows how the electrical variables are transformed into mechanical variables by means of an ideal transformer, which, in turn, are transformed into acoustical variables by means of an ideal gyrator.

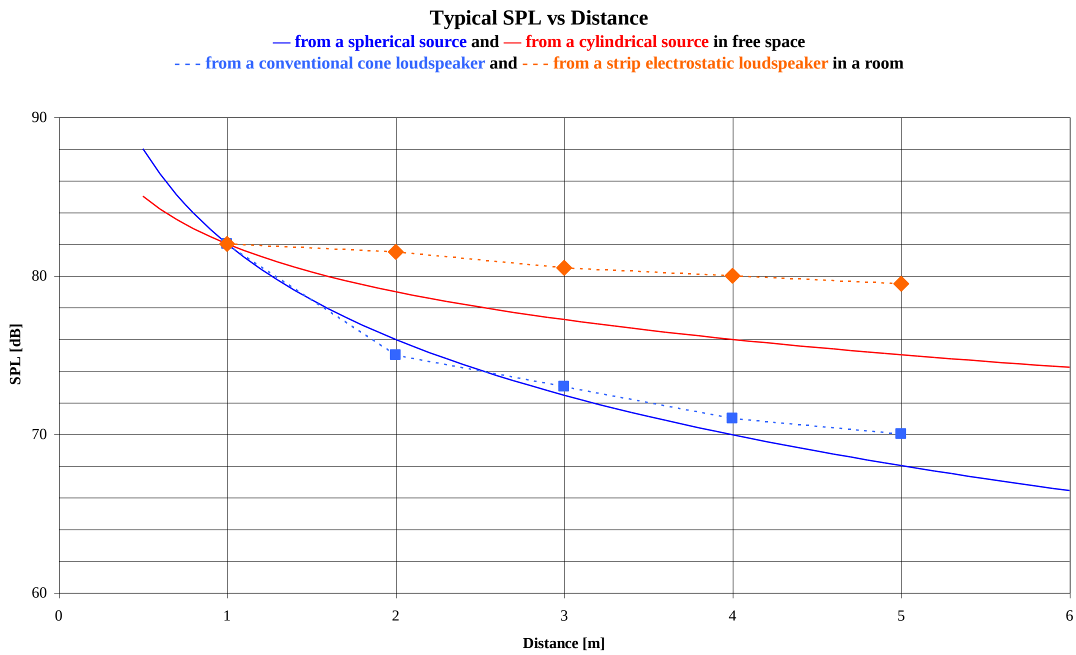
There are well known difficulties and compromises in manufacturing conventional loudspeakers but mentioned here will be only those relevant to a comparison with electrostatic loudspeakers.

The transduction principle becomes nonlinear when any of the turns of the coil move into regions where the magnetic flux is no longer uniform. An alternative to creating a long region of constant flux density is to have a long coil which is only partly immersed in the permanent magnetic field such that the effective $B\ell$ product (called the force factor) is reasonably constant as the coil moves. By contrast, the linearity of the electrostatic transduction principle is not compromised by diaphragm excursion.

The force experienced by the coil (commonly called the "voice coil") is communicated to the cone at its apex. At higher frequencies the cone does not excurse as a rigid member and the cone and suspension may resonate at critical modal frequencies, a phenomenon known as cone break-up. The resulting frequency response is uneven with many peaks and dips. By contrast, the force on the electrostatic diaphragm is evenly distributed so there is no need for it to be rigid. On the other hand it must be said that the electrostatic diaphragm is still subject to modes of resonance that require some damping in order to achieve a level (flat) frequency response.

The chief limitation to high-frequency response from a conventional loudspeaker is the mechanical mass of the coil and cone. Much effort has gone into producing cones having both low mass and high rigidity. By contrast, the mass of typical electrostatic diaphragms is so low that its effect does not appear at audible frequencies.

Conventional loudspeakers employ circular cones of diameters up to around 0.4 m. At low frequencies the moving cone behaves as a point source of volume velocity (producing spherical waves in the far field) and the radiation resistance is negligible since the wavelengths are large compared to the size of the cone. The cone must have large excursions to produce significant acoustic output. Furthermore, the SPL from a point source in free space reduces by a factor of 2 (or 6 dB) for every doubling of the distance from the source. By contrast, for a strip electrostatic panel, the diaphragm behaves as a line source (producing cylindrical waves in the far field) and the radiation resistance is significant down to frequencies where the wavelength is comparable to the longer dimension. The diaphragm need not excurse as much to produce significant acoustic



output. Moreover, the SPL from a line source in free space reduces by a factor of $\sqrt{2}$ (or 3 dB) for every doubling of distance from the source. The effect on the listener is that a strip electrostatic panel appears to have a more even sound level as he/she moves around a listening area compared to the sound level from a conventional speaker, and the panel is not deafening when approached. The graph illustrates the different behaviour of the two ideal sources in free space (thus only direct sound) assuming equal SPLs at a distance of 1 m [5, 6]. Also shown are measurements taken of an actual strip electrostatic loudspeaker panel and a conventional loudspeaker in a listening room rather than in free space. The measurements clearly indicate that reflected sound from the walls of the room add more and more to the direct sound as the distance from the loudspeakers increases. There is more reflected sound from an electrostatic panel compared to the conventional loudspeaker because, in common with all dipole sources, both its rear radiation and its front radiation are reflected around the room. Thus a strip electrostatic panel sounds remarkably constant in volume level throughout a listening room.

Low frequency output from a conventional speaker is controlled by placing it in an enclosure with various chambers and vents and designing the electroacoustic equivalent circuit to have a desired alignment curve (frequency response). Radiation from the rear side of a conventional loudspeaker is thereby “baffled" or modified to combine in a satisfactory phase relationship with radiation from the front side [7, 8]. Similar enclosures can be designed for electrostatic panels but must usually be larger. However, partial baffling of strip panels by means of obstructing the antiphase rear radiation from combining directly with the front radiation has been shown to be a successful compromise. Such partial baffles can be made adjustable by the listener.

Conventional loudspeaker enclosures are best made in a near cubic shape for controlling internal box resonances. Even so, if an enclosure is desired that is thin in one dimension, it is not possible for that dimension to be less than the depth of the conventional driver including its bulky permanent magnet. On the other hand electrostatic panels are inherently thin structures which have appreciable cosmetic appeal. Such thin panels can be flush-mounted into a wall or ceiling cavity, or be freely placed against a wall provided sufficient space is allowed for the rear radiation to escape.

Finally the cost of materials for constructing an electrostatic panel is relatively lower than a conventional loudspeaker of comparable size mainly because of the expensive permanent magnet material required. However, the cost of a high-voltage supply and step-up transformer for the electrostatic panel must be included.

There are also two conditions which limit the maximum sound pressure from a magnetostatic loudspeaker. At higher frequencies, where the cone excursion is small, the maximum audio signal voltage that can be applied is limited by the maximum allowable temperature rise of the voice coil. This thermal limit is usually stated by the manufacturer as a continuous or long-term power limit (for steady sine waves) and as a short-term power limit for signal bursts. At lower frequencies the cone excursion can reach a mechanical limit where the suspension compliance rapidly becomes non-linear and/or the air-gap in the magnet finishes. Depending on the design of the enclosure, the excursion limit is usually reached before the thermal limit.

Based on the manufacturer’s thermal limit, a formula can be derived for the maximum achievable SPL from a magnetostatic loudspeaker mounted in an infinite baffle and radiating into half-space (2π steradians). Let $P_{\max}$ be the stated nominal power limit in watts [W]. If the nominal voice-coil impedance is R_{nom} ohms [Ω], the rms voltage limit is $V_{\text{rms}\max} = \sqrt{P_{\max} R_{\text{nom}}}$ [V]. From the electroacoustical equivalent circuit in Appendix A, the corresponding sound pressure at a distance r [m] from the cone at mid-frequencies (such that the mass of the cone and coil dominates but not so high that the piston radiation becomes directional) is

$$p_{\mathrm{rms\,max}} = \frac{\rho_0 B\ell S_D}{2\pi r R_E M_{MS}} V_{\mathrm{rms\,max}}$$

which corresponds to an SPL of

$$\mathrm{SPL_{max}} = 20\log_{10}\left(\frac{p_{\mathrm{rms\,max}}}{p_{\mathrm{ref}}}\right) = 20\log_{10}\left(\frac{\rho_0 B\ell S_D}{2\pi r R_E M_{MS} p_{\mathrm{ref}}} V_{\mathrm{rms\,max}}\right) \quad \text{[dB]}$$

where $\rho_0 = 1.20408$ kg/m^3 is the density of air at the standard atmospheric pressure of 101325 Pa and temperature of 20°C, R_E [Ω] is the dc resistance of the voice coil and M_{MS} [kg] is the mechanical mass of the cone and coil including the air load on both sides of the cone.

For a good-quality 300 mm diameter, 200 W (continuous), 8 Ω driver having $B\ell = 18$ Tm, $S_D = 0.050$ m^2, $R_E = 6.0$ Ω, $M_{MS} = 0.064$ kg, $V_{\mathrm{rms\,max}} = 40$ V, at 1 m distance $\mathrm{SPL_{max}}$ is 119.1 dB.

The formula for $\mathrm{SPL_{max}}$ cannot be extrapolated to very small distances from the cone but a rough estimate of the SPL at the surface of the cone is obtained by setting $r = a_D = \sqrt{S_D/\pi}$, the effective cone radius, in the formula [6]. Thus the driver above would produce a deafening 137 dB at its surface.

1.3 Realisation of theoretical advantages

Practical problems have hindered the wider acceptance of electrostatic loudspeakers ever since they first appeared commercially. Such problems have included poor insulation between the diaphragm and stators, difficulty of achieving an optimum and stable surface conductivity of the diaphragm coating, large tolerances on the critical mechanical dimensions, effects of dust and humidity, large tolerances on the diaphragm tension, electrical breakdown of the step-up transformer and high-voltage power supply, unnecessarily thick and bulky panels and expensive construction techniques.

Immersion has overcome each of the above problems. Better materials for insulation have been developed, a superior surface coating for the diaphragm has been found and a whole range of novel and improved construction techniques have been developed. Immersion asserts that its mass production techniques can achieve very small mechanical tolerances, particularly on the critical separation between diaphragm and stators. Consistent diaphragm tension would also be attainable as the entire panel assembly would be performed by automation. Complete structural integrity would result avoiding any likelihood of voids or airgaps which might cause partial discharges and eventual electrical breakdown.

Immersion has also researched electrically-conductive plastics with a view to replacing the metal rods or grids of the stators. Insulating plastic can be fashioned around the conducting plastic so that the stators could be fully moulded to great accuracy. Attention has been paid to the optimum shape of the openings in the stators for minimising turbulence of the air flow.

Insulation techniques for the step-up transformer windings and high-voltage supply have also been investigated and improved. The high-voltage supply and transformer can be housed separately from each panel and then connected to the panel with a bundle of three high-voltage cables. Alternatively the high-voltage supply and transformer can be incorporated into the base of each panel so that the connections to the panel are short and invisible. Immersion is also exploring alternative techniques for obtaining the high-voltage for charging the diaphragm, including rectification and boosting of the audio signal itself and rechargeable battery sources.

When marketing an electrostatic loudspeaker without an accompanying audio amplifier, it is important to provide audio signal voltage-overload protection in case a customer connects an amplifier of greater-than-rated output. Commercial electrostatic speakers in the past have incorporated some dramatic protection techniques including crowbar circuits which nearly short-circuit the amplifier when a voltage overload is detected. The panels might be protected from arcing but the amplifier may be damaged by the protection circuit. Immersion have perfected a more gentle solid-state protection circuit on the secondary side of the step-up transformer which eliminates amplifier damage. They also use a series capacitor to eliminate dc currents through the primary side of the transformer. Furthermore, great attention has been paid to winding techniques that minimise the leakage inductance of the step-up transformer so that the inevitable series resonance (input impedance minimum) between the leakage inductance and the static capacitance between the stators is pushed to a frequency beyond audibility. Generally it becomes more difficult to reduce leakage inductance as the required turns ratio increases. Typically a turns ratio of around 1:100 is required to raise an amplifier voltage of 40 V_{rms} to 4 kV_{rms} for the stators.

With many of the practical problems of manufacturing electrostatic panels now overcome, the theoretical advantages of electrostatic loudspeakers can now be realised for a wider market. Once individual panel construction has been perfected, loudspeaker systems with multiple panels can also be manufactured. Each of the constituent panels would cover a specialised range of frequencies and would be fed from a crossover network so as to integrate the total response. The crossover network could also incorporate extra frequency compensation for individual panels if required. The levels of audio signal voltage and high-voltage can be different for individual panels.

2. Comparison of Company Prototype Models with Commercial Electrostatic Loudspeakers

2.1 Measurements

One high-end company prototype model (known as the Immersion 880) was evaluated against three commercially-available electrostatic loudspeakers of a similar category (but costing up to twice as much as the projected retail price of the 880). Also several smaller company prototype models were evaluated. Both measurements and listening tests were performed over several days.

The Immersion 880 has a rectangular radiating area of height 1600 mm and width 462 mm divided into three sections: a narrow high-frequency vertical strip offset from the middle, a mid-frequency strip on the narrower side of the high-frequency strip and a low-frequency strip on the wider side. The stator separations are optimised for the frequency bands, the high-frequency panel having the smallest. The three panels are fed from a step-up crossover network and high-voltage supplies housed in a separate box that also includes some frequency compensation. The structure includes adjustable baffles on each side of the radiating area.

The three commercial electrostatic loudspeakers (each in pairs) were

- The Quad ESL-989 – a multi-section electrostatic panel with concentric annular segments incorporating delay lines to simulate a spherical source

- The Sound Science (Alan Gregory) Electrosignature 2 – a single full-range slightly-curved electrostatic panel

- The Martin Logan Summit – a hybrid combination of a slightly-curved electrostatic panel and a magnetostatic subwoofer at the base crossing over at 270 Hz

Measurements of the SPL at various distances from the panels were performed with automated software in a large listening room and later in an even larger reverberant factory floor area. Standard techniques were used to overcome the limitations of the testing environments (such as reflections from the walls and furniture). These include time gating and close microphone spacings. Time gating to discriminate against early reflections was more successful at higher frequencies. In some cases averaging over frequency was performed to smooth the response curves which is also standard practice for loudspeaker measurements.

Sample curves with the conditions of measurement are shown in the figures below.

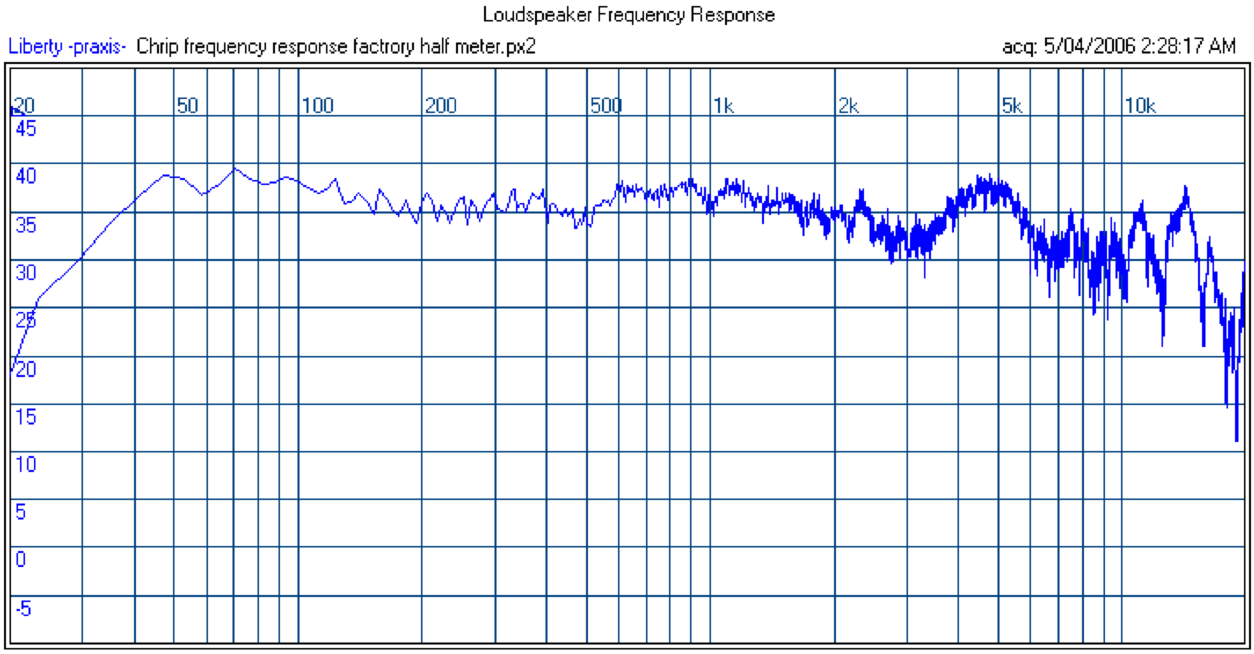


Figure 1: Frequency response of Quad ESL-989 at 0.5 m in room.

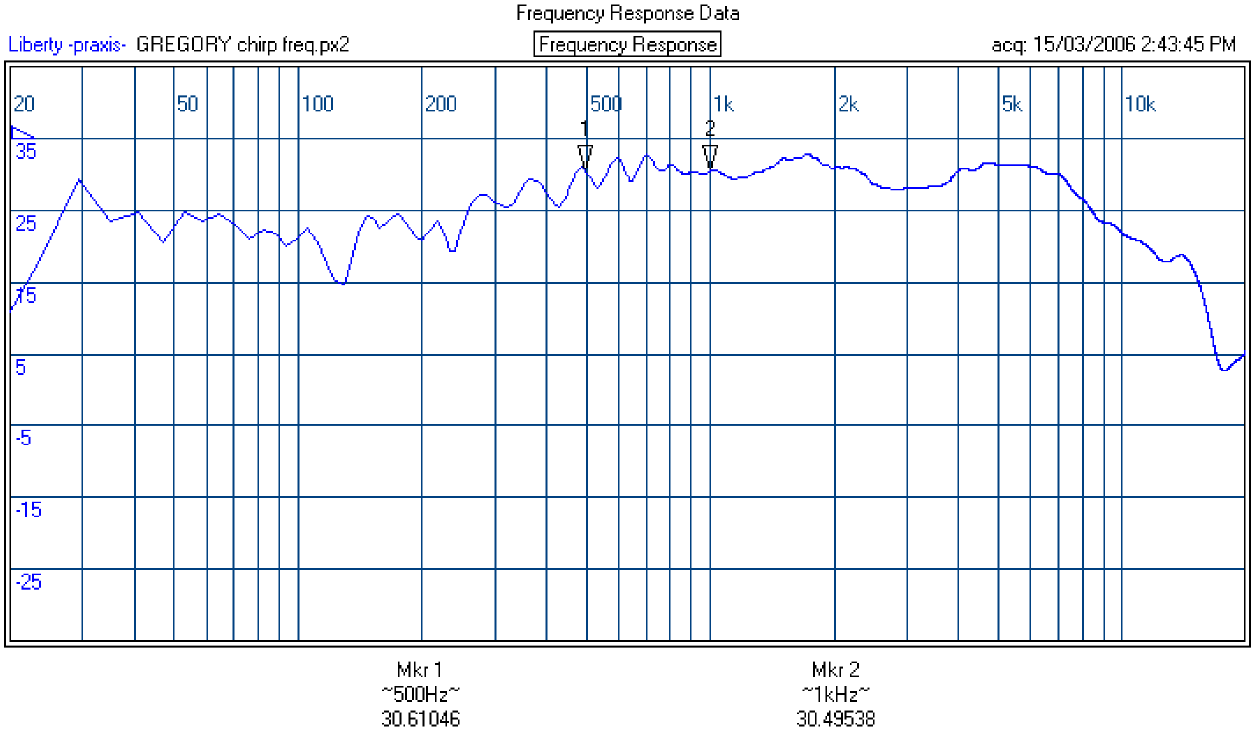
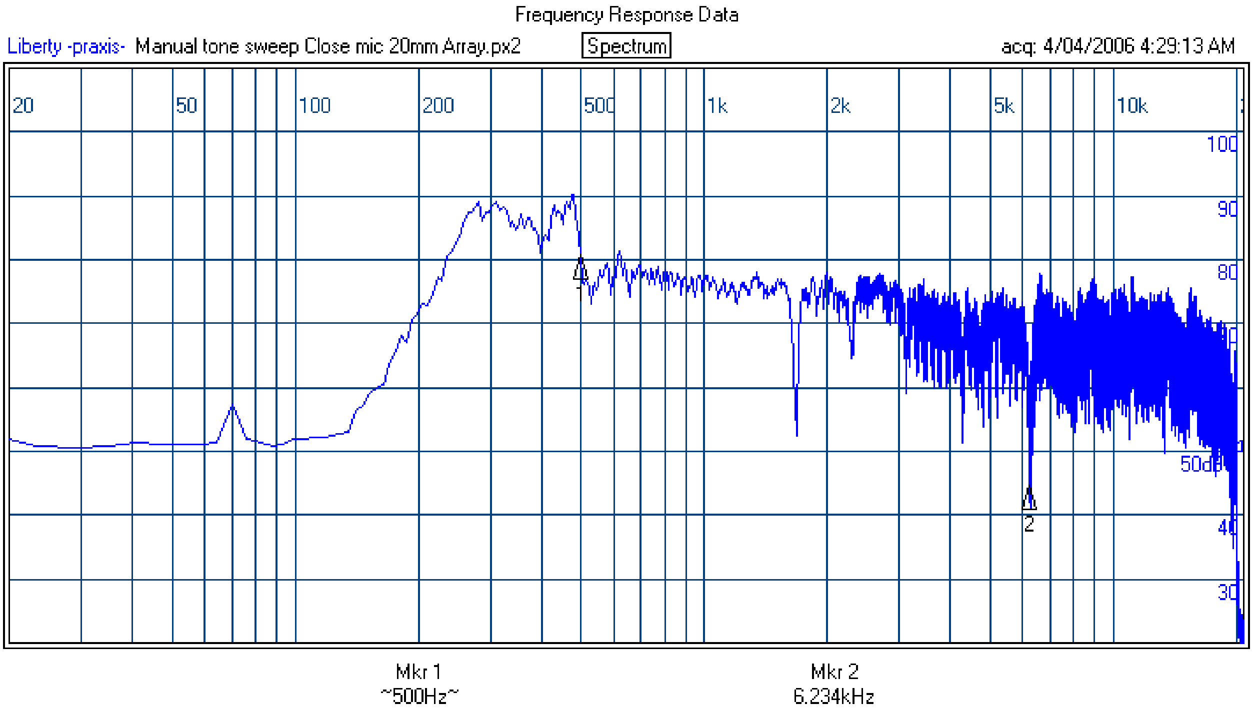


Figure 2: Frequency response of Sound Science Electrosignature 2 at 0.5 m in room (averaged).



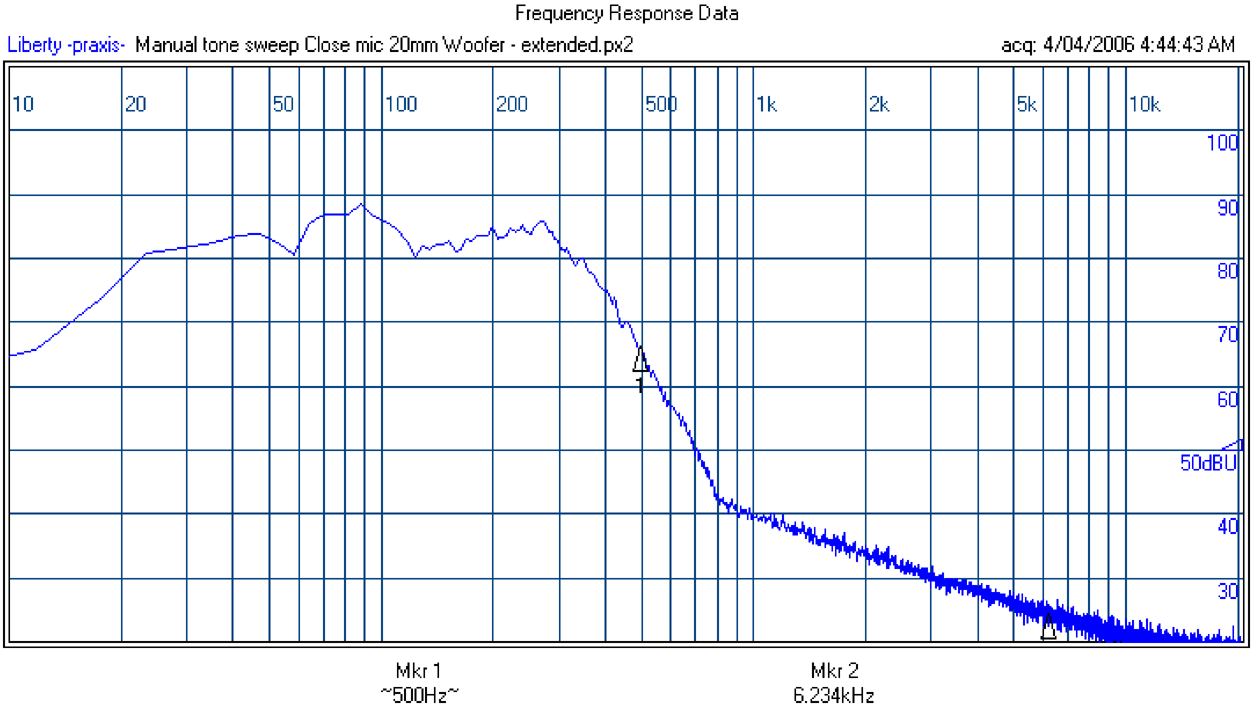


Figure 3: Frequency response of Martin Logan Summit at 0.02 m in room: (above) electrostatic panel alone, (below) woofer alone. The two are combined via a crossover network at 270 Hz.

For comparison, Immersion's 880 SPL response is shown below. The adjustable baffles were fully extended for this test. The frequency response extends from below 40 Hz to beyond 20 kHz with notable flatness. Only the Martin Logan model extends lower but only because of its conventional subwoofer. The commercial loudspeakers all had falling response at 20 kHz. With approximately 30 V_{rms} sustained from the amplifier at 1 kHz, the SPL from the 880 was recorded as 105 dB at 1 m distance. With a more powerful amplifier, the 880 is capable of higher output. Thus the sensitivity of the 880 is about 85 dB SPL at 1 m from 2.83 V_{rms} input (1 W into 8 Ω nominal).

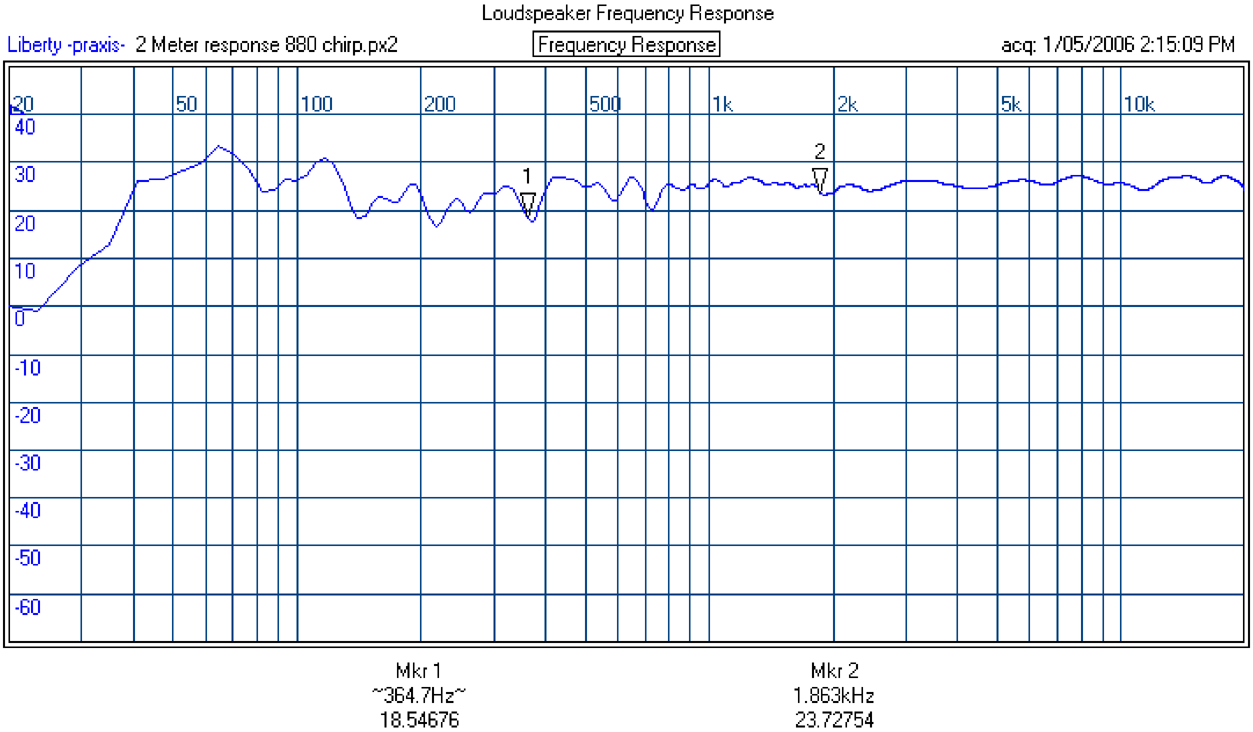


Figure 4: Frequency response of Immersion 880 at 2 m in room (averaged).

Polar response patterns were also compiled. Sample patterns are shown below. It is noted that an ideal dipole source (such as a strip panel) produces a “figure 8” polar pattern in the far field with full response on axis in front (0°) and behind (180°) and zero response at 90 and 270 degrees (either side view of the panel). The polar response is particularly affected by room reflections so that the hardly any of the measured patterns showed the expected nulls at 90 and 270 degrees.

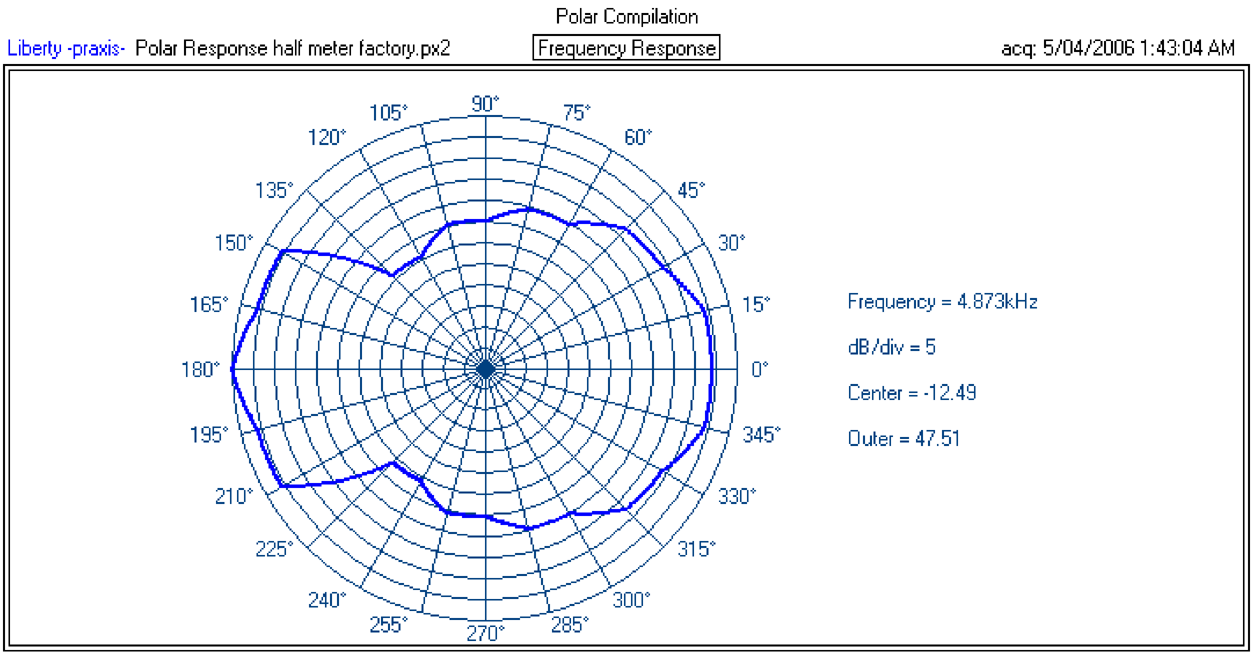


Figure 5: Polar response of Martin Logan Summit at 4.873 kHz in room.

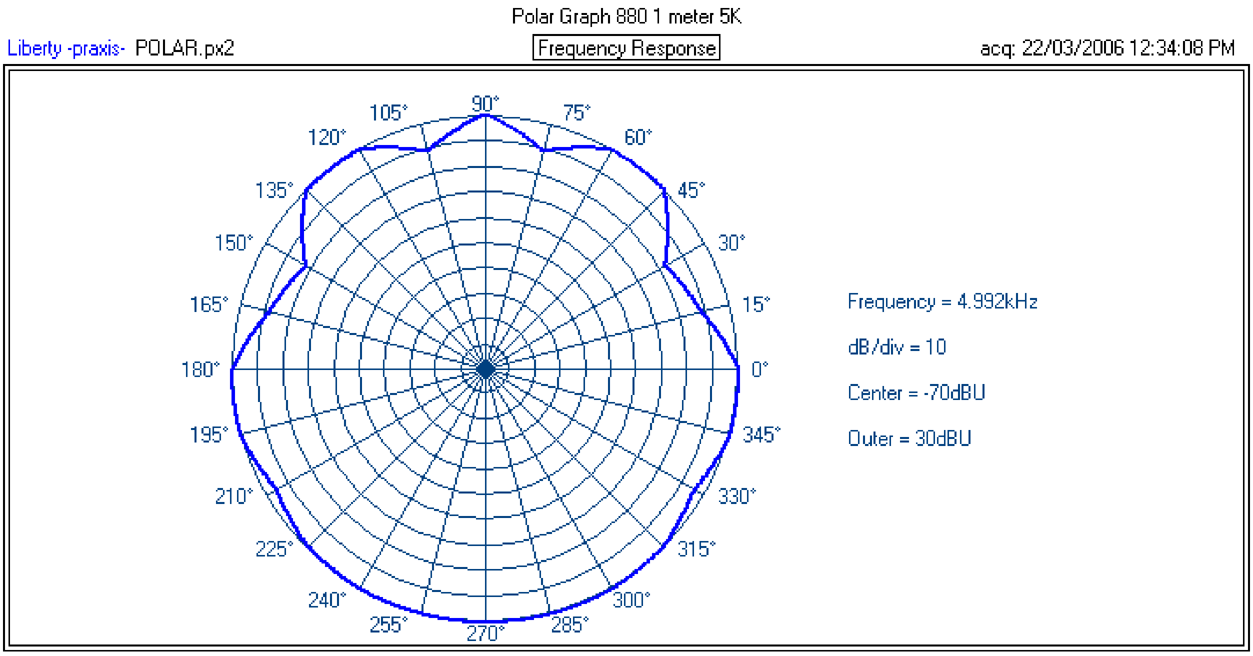


Figure 6: Polar response of Immersion 880 at 4.992 kHz in room.

Impulse and waterfall transient responses were examined for speed of attack and for lack of sharp (high-Q) resonances that hold energy and linger excessively. Waterfall plots are more properly called cumulative spectral decay (CSD) plots [11]. Sample results are shown below. The unmarked nearly horizontal axis is frequency on a linear scale up to 20 kHz. The vertical axis is the remaining sound pressure magnitude (SPL in dB) at the time indicated on the third axis (in milliseconds) after the initial impulse. Background noise in the room is also picked up by this test so that the vertical scale needs to be read carefully in order to obtain a fair comparison. It is noted that Immersion's 880 is quicker to decay at all frequencies than the others.

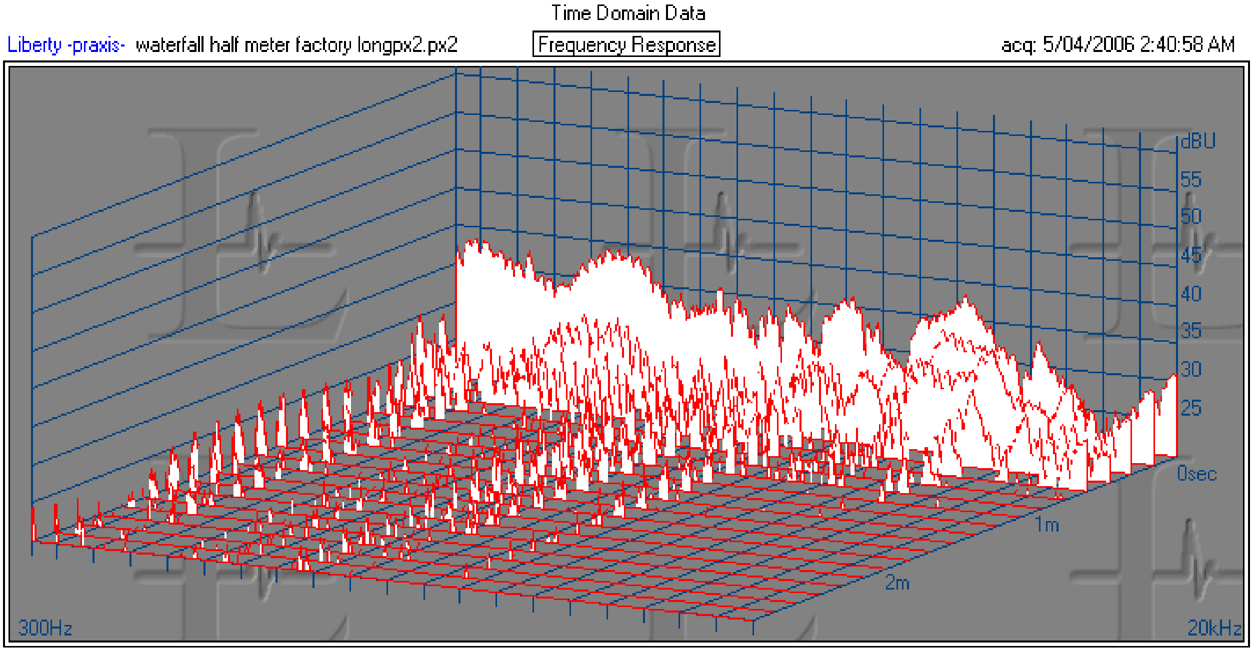


Figure 7: Waterfall (CSD) response of Quad ESL-989 at 0.5 m in factory.

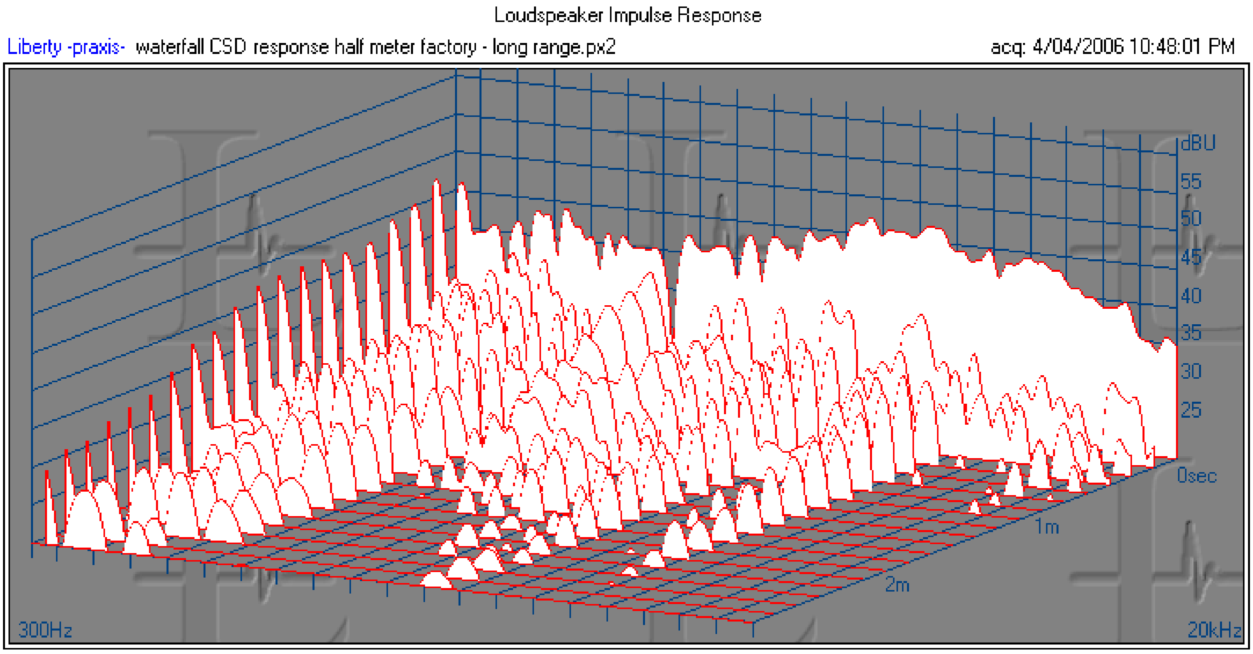


Figure 8: Waterfall (CSD) response of Martin Logan Summit at 0.5 m in factory.

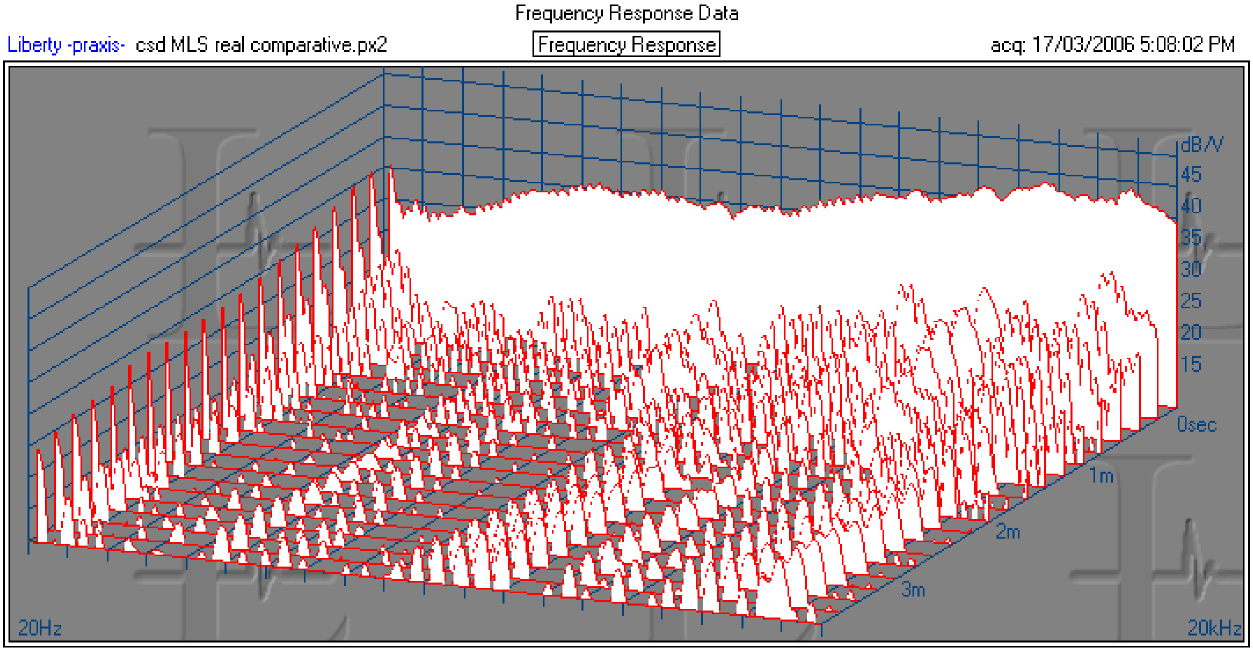


Figure 9: Waterfall (CSD) response of Immersion 880 at 0.5 m in noisy room.

Some distortion measurements were taken with the automated software. Total harmonic distortion (THD) above 200 Hz was generally well below 1% on all models and therefore THD is unlikely to be an important discriminating factor in listening tests. Some intermodulation distortion (IMD) tests were also performed but showed no anomalies.

Impedance measurements were also performed on all models. Some results are shown below in Figures 10, 11 and 12. All of the models have frequencies where the impedance falls to a low value, considerably below the nominal impedance. Thus electrostatic loudspeakers tend to have the reputation for being difficult to drive. Some commercial models (those having sharp impedance dips and consequent large phase angles) have caused various amplifiers to become unstable and oscillate. Immersion has paid attention to the design of its models to ensure that the low-impedance problem is reduced so that conventional audio entertainment material can be played on the majority of mainstream amplifiers without the loudspeakers causing current overload or instability.

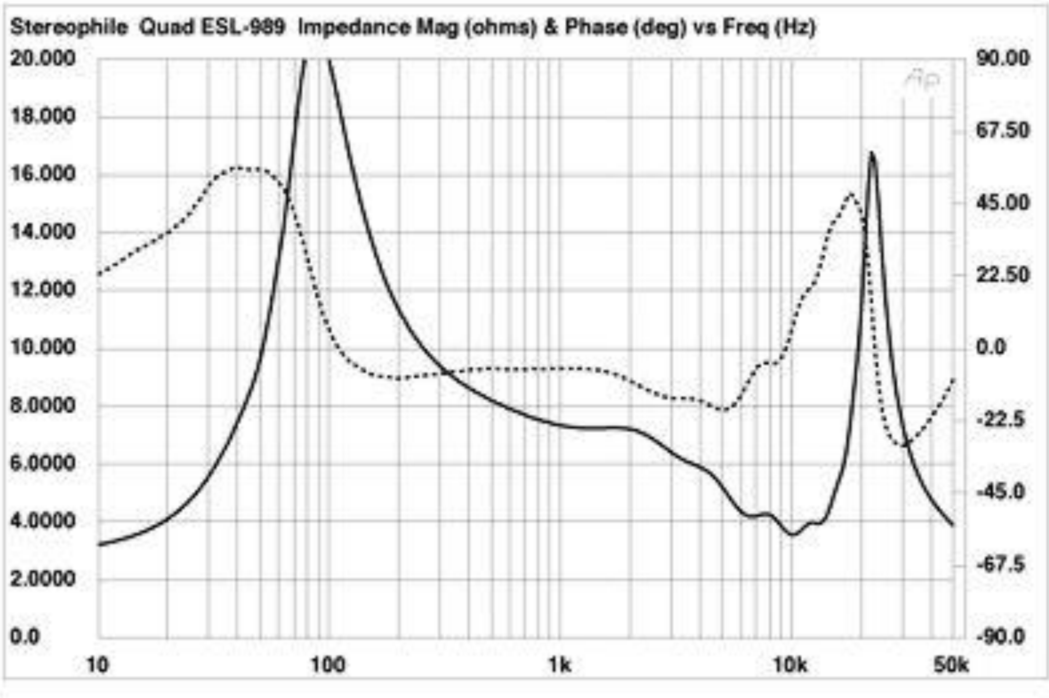


Figure 10: Input impedance of Quad ESL-989: magnitude (solid) and phase (dashed). (Reproduced from [12]).

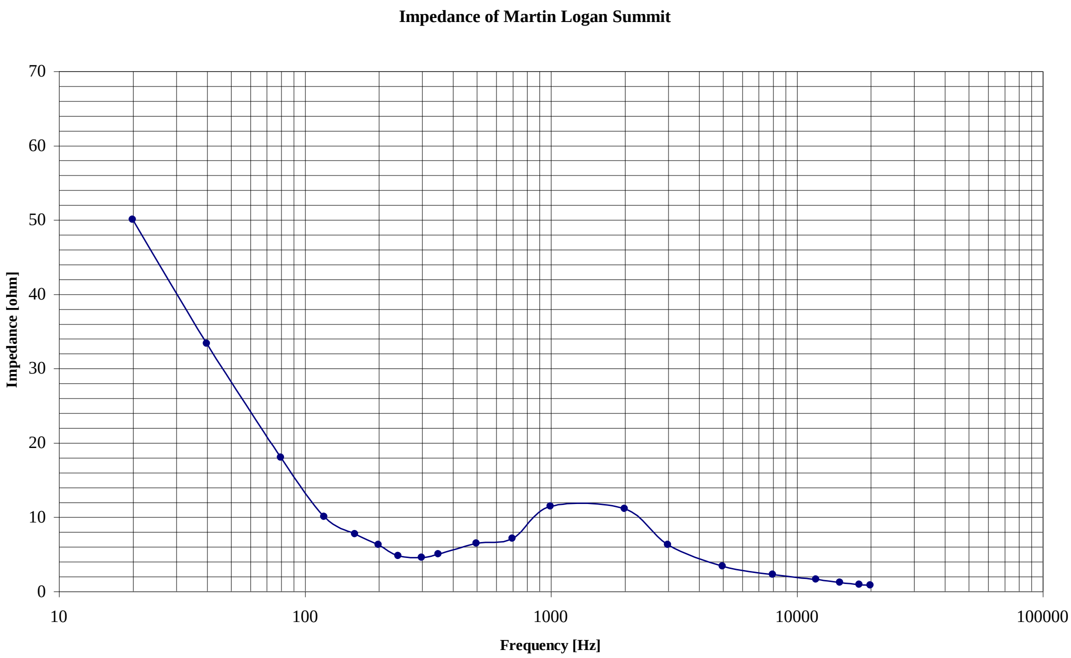


Figure 11: Input impedance of Martin Logan Summit.

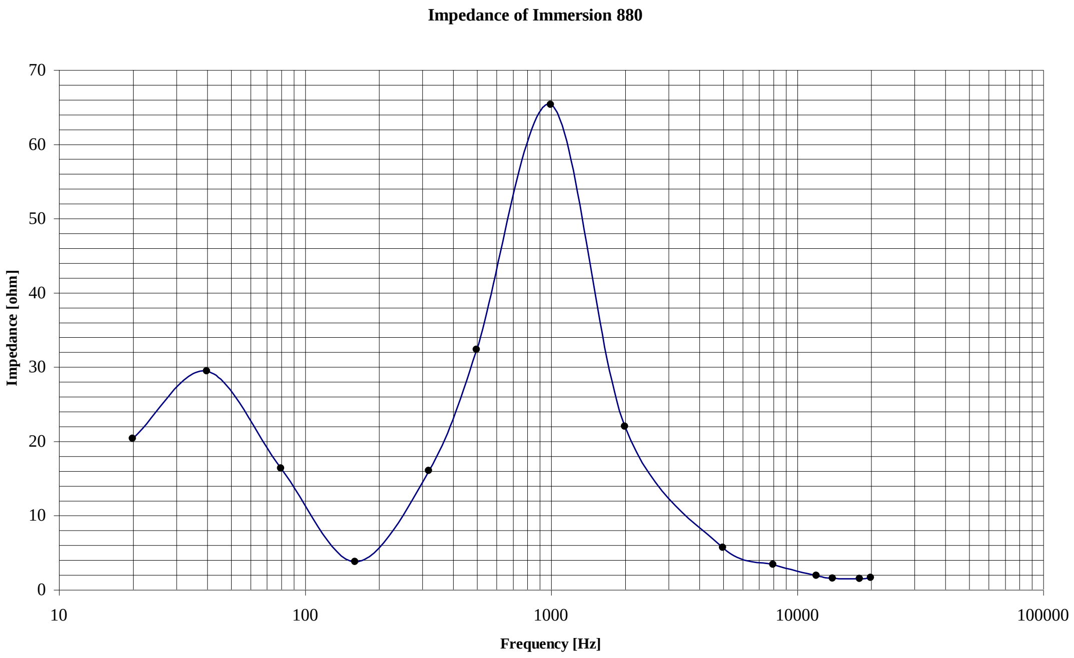


Figure 12: Input impedance of Immersion 880.

Immersion has several smaller prototype models. They are single electrostatic panels designed to reproduce all but the very lowest frequencies. The frequency response of one "midget" model (130 mm by 800 mm) when baffled is shown in Figure 13. (The indicated response below 45 Hz is not valid.) Its performance is better than a conventional loudspeaker of comparable size and far superior to a flat panel loudspeaker using NXT technology.

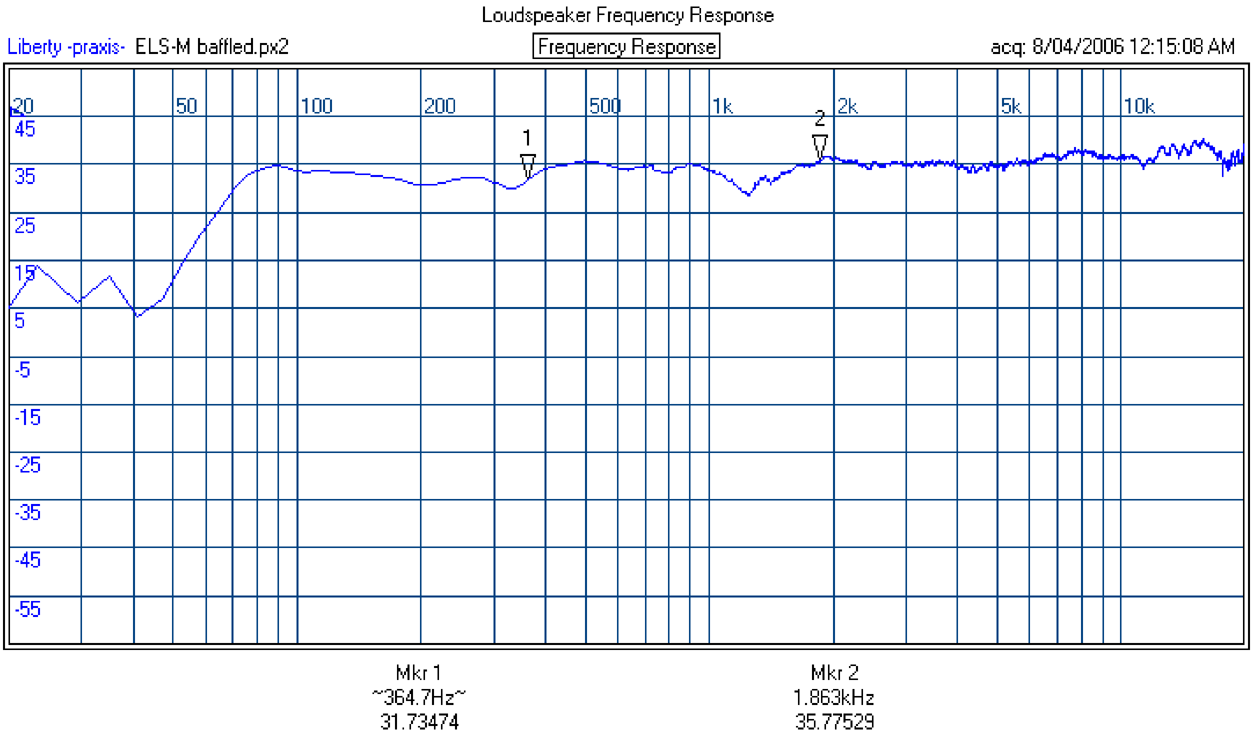


Figure 13: Frequency response of Immersion's midget model when baffled.

2.2 Listening Tests

Listening tests were performed in the same large listening room on all models. The room was probably quite representative of a typical domestic environment and the reflections from various objects in the room would have served to scatter the sound randomly throughout the room. The loudspeakers were listened to at close range to better hear the direct sound and also further back in the room to hear the direct and reflected sound together.

It was noted that the perceived frequency responses were quite similar to the measurements. Distortion was not evident until amplifier overload was reached and then amplifier distortion was heard rather than loudspeaker distortion. The writer was generally impressed by the clarity of reproduction from all models but the perception of clarity was influenced by the frequency response differences. It is the writer's view that Immersion's 880 model with its extended treble response won the clarity tests.

When run in 5.1 channel mode, Immersion's models performed exceptionally well and comfortably achieved a realistically high SPL for movie presentations when supported by a high-quality conventional subwoofer.

3. Market Potential

3.1 Short term market opportunities

A recent independent and comprehensive market appraisal on the loudspeaker industry has been compiled under contract by Global Industry Analysts, Inc. [10]. The writer's comments on the market potential for Immersion's electrostatic loudspeakers have drawn heavily upon this report.

The entire global loudspeaker market, including both electrostatic and magnetostatic loudspeakers, was estimated to be worth around US$ 3,540 million in 2005 with an annual growth rate of 3.0%. In the same year the total volume sales of loudspeakers was estimated to be 13.5 million units. On the other hand the sheer number of companies involved means each company faces intense competition for a viable portion of the market.

Many loudspeaker companies, particularly the smaller ones, have resorted to finding specialised niche markets. All companies have needed to be quick to respond to the changing demands of customers, though ultimately what must influence customer preferences are the introduction by companies of new products with improved technology, better performance and/or more pleasing aesthetics. If new products are not readily accepted by customers through advertising and other promotional methods then a loudspeaker company needs to adapt rapidly.

Above all, the music and entertainment industry is the major influence on the loudspeaker industry. The introduction and ready availability of high-quality audio and video material (including games and movies) on CDs, DVDs and the internet, together with the decreasing cost of computers, players and amplifiers, has driven the demand for loudspeakers of better quality yet more affordable and more pleasing aesthetically.

Recent significant marketing trends include

- Customer preference for surround sound systems instead of stereo systems
- Customer desire for louder, more powerful loudspeakers
- Customer desire for extended and louder bass response (subwoofers)
- Increasing importance of aesthetics, particularly the appeal of flat and thin structures
- Increasing emphasis on the size and placement of free-standing loudspeakers, particularly wall placement off the floor
- Integrated video and audio panels for television, home theatre, computers, games, music players and mobile phones

The most rapidly changing market is in home entertainment where there is now a convergence of music, movies and games into one integrated entertainment platform combining television, music and video players, games machines and personal computers into one arena.

Although many customers are not immediately influenced by the quality (frequency response, distortion, clarity, etc.) of the sound reproduction from loudspeakers, it is the writer's experience that once customers have heard and listened at length to high-fidelity reproduction, as from electrostatic panels, they learn to become more discerning of the quality they expect from loudspeakers.

Immersion is planning to take up short-term (as well as long-term) market opportunities in the home entertainment arena to which the electrostatic loudspeaker is entirely suited. A number of surround sound packages are planned each of which will incorporate strip electrostatic panels of various sizes together with conventional subwoofers. Larger panels will be used for the front left and right loudspeakers, smaller ones for the rear left and right loudspeakers, and an intermediate-sized horizontally-placed panel for the centre loudspeaker.

To give an idea of the world market potential for satellite/subwoofer loudspeaker systems, Figure 14 below shows the recent past, current and future volume sales for both 3-piece and 6-piece systems for the years 2000 to 2010 [10, Table 23].

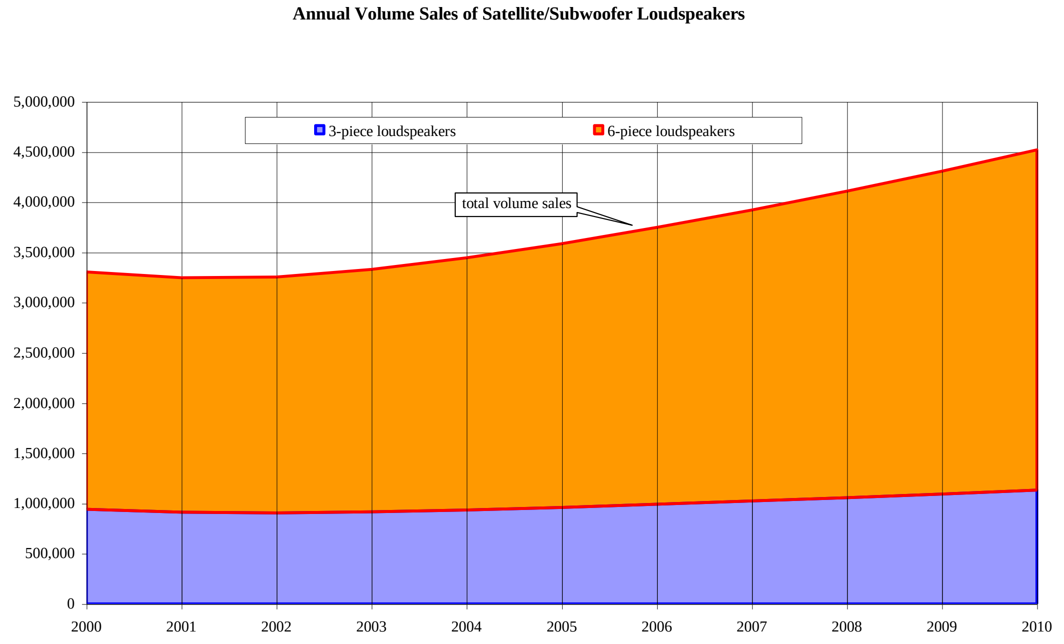


Figure 14: World annual volume sales of satellite/subwoofer loudspeaker systems.

Immersion is also planning to license OEM electrostatic loudspeaker panel products for the video panel market (plasma, LCD and others).

At this juncture it is important to emphasise the advantage of marketing conventional subwoofers in pairs, not only for stereophonic (2 channel) systems but also for 5.1 and 7.1 channel systems where the low-frequency effects (LFE or .1) channel is only monophonic. By the well-known Small efficiency trade-off formula [9], the efficiency (the ratio of acoustical power out to the electrical power in) of a conventional subwoofer is directly proportional to the total internal enclosure volume V_B [m^3] for a given alignment and cut-off frequency. Thus the efficiency is doubled either by doubling the volume of a single subwoofer or by using a second subwoofer of the original size alongside the first subwoofer. However, the advantage of using a second subwoofer is that the maximum input power handling capacity is also doubled, and the combination of doubled efficiency and doubled input power means the maximum acoustical output power is quadrupled (an increase of 6 dB in maximum SPL). But the perceived increase in SPL is even greater than 6 dB because of the Fletcher-Munson curves [4, page 399] whereby the human ear is insensitive to very low frequencies but once the SPL is above the threshold of hearing the perceived loudness (in phons) increases more rapidly than the SPL (in dB) increases. Furthermore, because the wavelengths at low frequencies are so large, it is possible to separate the pair of subwoofers without losing the efficiency gain and place the individual subwoofers in different locations in a room in order to minimise the effects of room modes (standing waves between walls). Finally, there is probably a marketing advantage in selling two smaller subwoofers that can be separated rather than one subwoofer of double the volume. Immersion is wisely planning to incorporate conventional subwoofers in pairs into most of their packages.

3.2 Long term market potential

In the longer term Immersion has plans to penetrate the vast car entertainment market as well as the games, video and music player market, including desk and portable models.

High-end products are also planned for the purist audiophile market where electrostatic loudspeakers have traditionally enjoyed the best reputation. Immersion has already demonstrated products that outperform some of the best commercially-available electrostatic models.

One of the impending challenges to be faced by Immersion is the “SurfaceSound” technology being marketed by NXT plc [13]. Their flat panel loudspeakers are essentially conventional magnetostatic loudspeakers with a miniaturised permanent magnet and voice coil attached to a reinforced flat panel instead of a conventional cone. In contrast to electrostatic panels, the force applied to the diaphragm is concentrated near the centre resulting in break-up and resonances that are difficult to control. Listening tests have confirmed that an (unbaffled) electrostatic panel of similar size clearly outperforms a currently-marketed NXT panel (130 mm by 200 mm). (In this size range both panels require a supplementary conventional subwoofer.)

The writer is completely confident that the future of the electrostatic loudspeaker, as continually improved by Immersion, is assured. As more listeners worldwide come to appreciate the inherent advantages in not only the cost but also the performance of electrostatic loudspeakers, their uptake and acceptance in the marketplace will accelerate. The appeal of their thin structure will further reinforce their popularity.

4. Conclusions

Immersion has succeeded in overcoming past limitations of electrostatic loudspeaker construction and reliable mass production and is poised to challenge the conventional magnetostatic loudspeaker in many areas of application, particularly the entertainment industry.

The challenge will take place on three fronts: the appeal of thin structures, cost competitiveness and, last but not least, outstanding performance in comparable sizes.

This report has emphasised the sound theoretical and scientific basis for all of Immersion's claims.