



Epsilon Project

**A VIEW INTO ADVANCED LOUDSPEAKER DESIGN
AND TECHNOLOGY**

by Cary Christie, Christie Designs, Inc.

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INTRODUCTION

Why Epsilon?

Advancements in loudspeaker design are the natural consequence of a basic trait of human nature: Certain people just seem to need to improve things, to make them better. Loudspeaker designers and engineers generally are these kinds of people, ones who are professionally discontented. They rarely are satisfied with the state of development of any product that moves out of the R&D lab and into production. There is always something more they want to improve, or refine, or redesign; some new material or process to be tried, some new technology to be explored. It is inevitable that this unfinished work finds its way into succeeding projects.

So it is with Infinity's newest high performance loudspeaker, the Epsilon. The design goal for Epsilon was to make improvements in Infinity's planar driver technology and in overall system design that would yield higher levels of acoustic performance from a single pair of loudspeakers — that is, two enclosures — than that afforded by any existing pair of loudspeakers; performance that would approach that of the four-enclosure Infinity IRS V system, but at significantly lower cost and in a more space-efficient and decor-friendly form.

The starting point for the development of Epsilon was Infinity's outstanding planar drivers, drivers that have been acknowledged as being among the world's best sounding and most accurate. Even so, more could be achieved with this remarkable driver technology. Furthermore, the acoustic effects of the enclosure system bear strongly on overall sound quality. Designing an integrated system offering very high sound quality in an enclosure of a size suitable for the home is a real challenge to acoustical engineering skill. That the goal for Epsilon was achieved is a testament both to perseverance and to the wonderful "Aha!" of sudden inspiration.

This paper presents some of the important details of the design and technology of the Infinity Epsilon loudspeaker.

An Epsilon System Overview

The Epsilon loudspeaker is a four-way design that employs planar drivers to cover the frequency range above 150Hz, and a servo-controlled woofer for low frequencies below 150Hz. Each Epsilon loudspeaker contains a pair of Infinity Electro Magnetic Induction Tweeters (EMIT™), one front-facing and one rear-facing; an Infinity Electro Magnetic Induction

Midrange (EMIM™); an Infinity Lower-Electro Magnetic Induction Midrange (L-EMIM™); and an Infinity Servo-controlled Injection Molded Graphite (IMG™) Woofer. The Servo Woofer effectively functions as a “subwoofer,” since its operating frequency range extends from 150Hz down to 25Hz and below. The L-EMIM driver covers the range from 150Hz to 500Hz, the EMIM driver from 500Hz to 3kHz, and the EMIT drivers from 3kHz to well beyond 20kHz — on-axis, to an amazing 45kHz.

The drivers are mounted in a vertical array in a large, gently curved panel whose side “wings” form an acoustic baffle and “launching pad” for the output of the EMIT, EMIM and L-EMIM drivers. The forward-firing woofer is in a sealed enclosure that is integrated with the vertical panel and forms its supporting base. The rear of the vertical panel is covered by a special housing, whose design and function will be discussed in a following section on Enclosure Technology.

A Servo Control Unit contains the servo electronics and equalization circuitry; controls for the fine adjustment of the relative balances of the planar drivers are located on the rear of the loudspeaker enclosure. In a significant departure from other active subwoofer systems, the Epsilon woofer does not have its own built-in amplifier; rather, the customer has the choice of which woofer amplifier will be used. The SCU has connections and controls which place the selected woofer amplifier within the servo-system's overall feedback control loop. While there are substantial minimum requirements for the power output and current delivery of the woofer amplifier, many excellent amplifiers qualify. The L-EMIM, EMIM and EMIT drivers, together with their precision passive crossover networks, are powered by a second power amplifier, meaning that the Epsilon is bi-amplified.

Epsilon Driver Technology

The Attraction of Planar Drivers

Planar drivers are attractive to loudspeaker designers because they potentially offer the closest approach to Lord Rayleigh's theoretical ideal of a perfect acoustical piston. The practical difficulty in any driver is getting the diaphragm surface to move absolutely uniformly, so that all parts move linearly, in the same direction, by the same amount, at the same time.

Limitations of Electrostatic Designs

Electrostatic designs offer good low-amplitude performance but have restricted output because of limits on the achievable electrostatic field strength — due, in these speakers, to the high-voltage breakdown of air. To gain adequate field strength, the diaphragm-to-static-screen spacing must be kept small. This in turn limits diaphragm excursion. Limited excursion means that even high frequency drivers must be relatively large to achieve only moderate output, making them highly directional, or

“beamy.” Meanwhile, lower frequency drivers just don’t have enough excursion, period. In addition to the drawbacks of limited dynamic range and inefficiency, electrostatic designs also employ high-voltage audio step-up transformers, which are difficult loads for amplifiers to deal with, and also require bulky and troublesome high-voltage polarizing power supplies.

Limitations of Conventional Electromagnetic Designs

Electromagnetic designs potentially solve many of these problems, but come with difficulties of their own. The most important have to do with the asymmetry of the magnetic fields in conventional panel speaker designs.

FIGURE 1

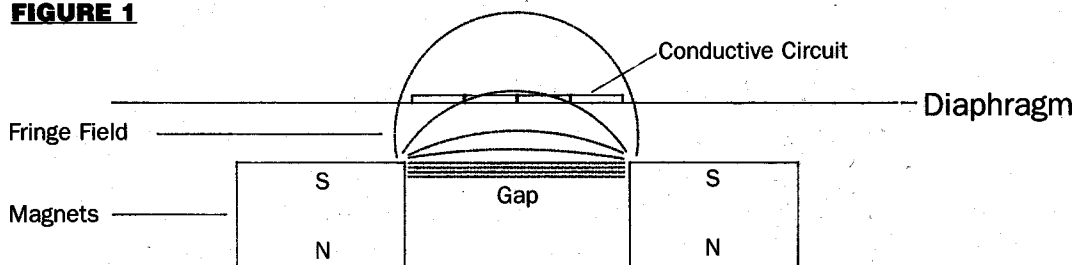


Figure 1 shows the problem of poor magnetic field strength that results from the field geometry of a set of magnets located on one side of the diaphragm only, which is the typical form of construction. As can be seen, the diaphragm with its voice coil rides above the main magnetic gap, which is between the magnets, in the magnetic fringe field (represented by the curved lines of force). This means that the field strength is low, causing poor motor strength.

Unfortunately, magnets strong enough to raise the strength of the fringe field to acceptable levels are prohibitively expensive for large, lower frequency drivers. This means that even high frequency drivers must be large to achieve reasonable output. As a result, most planar magnetic designs suffer from the same too-narrow dispersion and “beaming” found in electrostatic designs.

FIGURE 2

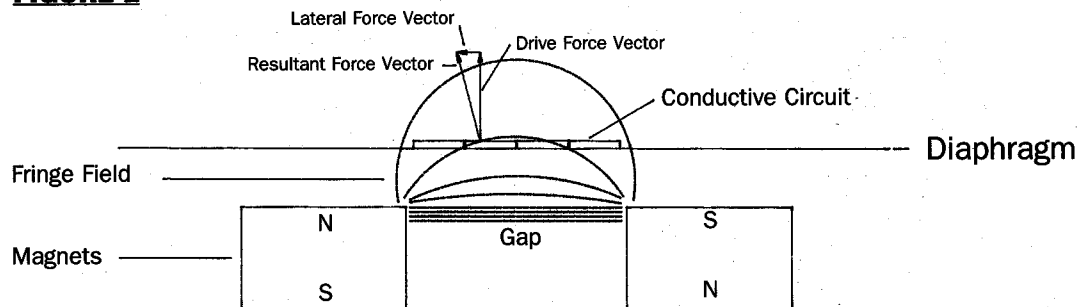


Figure 2 shows the second problem of poor field geometry. The voice coil, and the diaphragm it is attached to, attempt to move at right angles to the direction of the lines of the magnetic fringe field, meaning that they are trying to move sideways as well as in-and-out. This leads to diaphragm “buckling” and considerable acoustic distortion.

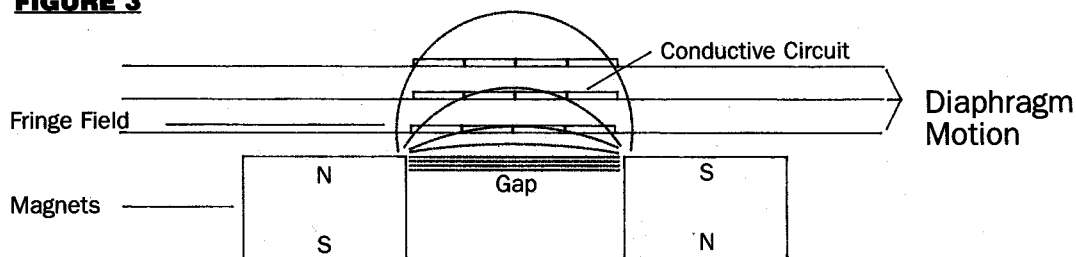
FIGURE 3

Figure 3 shows a third problem, that of poor field linearity. As the voice coil and diaphragm move in and out, they move from weaker to stronger portions of the fringe field. The result is highly non-linear movement that produces significant audible distortion, especially at realistic volume levels.

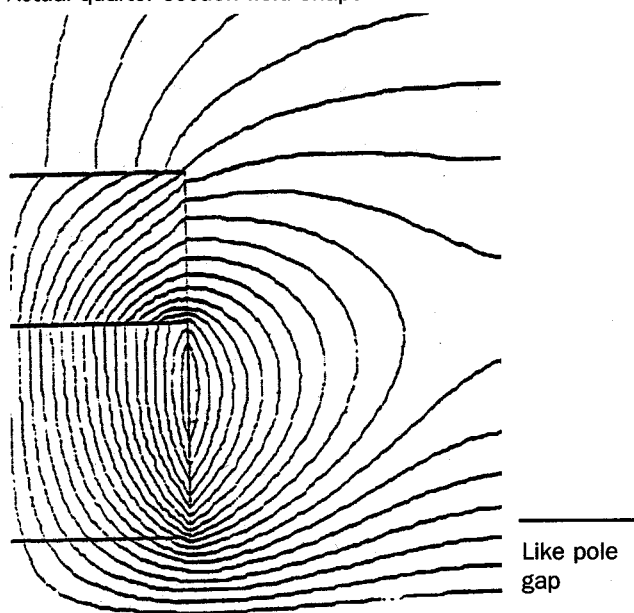
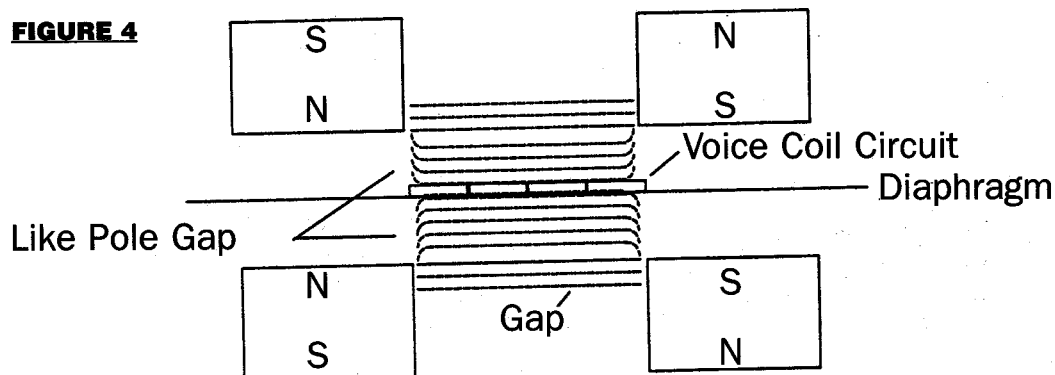
The Infinity EMIT, EMIM and L-EMIM Drivers: Magnetic Circuitry

Infinity's breakthrough solution, shown in *Figure 4*, is to use two arrays of magnets, one on each side of the diaphragm, which have "like" poles facing each other. Because like poles repel, the opposing fringe fields are strongly compressed into a powerful, uniform and linear field. To wring maximum performance from this unique design, we optimized the magnetic circuit and its field geometry using advanced computer modeling techniques.

The advantages are plain: The magnetic field in which the voice coil and diaphragm move is both strong and uniform, yielding higher efficiency and much lower distortion. The high field strength and the resulting high motor strength mean that the diaphragm-to-magnet spacing can be large enough for the excursions needed to generate very high acoustic outputs. Finally, the drivers can be physically small enough to yield wide dispersion and outstanding overall acoustic power response.

EMIM

Actual quarter section field shape

**FIGURE 4**

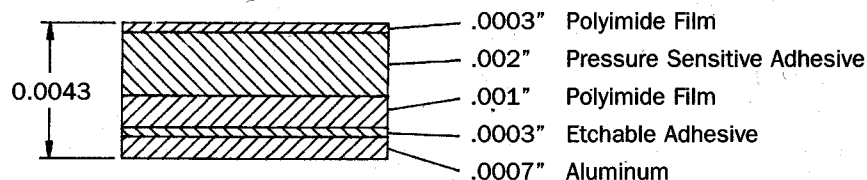
The Infinity EMIM and L-EMIM Midrange Drivers: Diaphragm Construction

While the solutions to the problems of the magnetic circuitry resulted in considerable performance gains, additional attention was paid to the construction of the laminated diaphragm/voice coil assembly. A planar diaphragm (and its voice coil) has to be under tension in order for it to have a zero-signal resting point at the exact center of the magnetic field — this assures full excursion capability in both directions of movement and fast restoration to center when driving signals cease. However, even relatively inert substances become resonant when under tension. This means that the diaphragm/voice coil assembly must include damping material to suppress resonant action.

Diaphragms of mid- and high-frequency drivers also must have extremely low mass in order to have high efficiency and quick acceleration under the drive of fast transient signals. For years, Infinity has employed a polyimide film for the diaphragm base material of our planar driver designs. The polyimide film offers excellent strength, very low mass, and extremely high dimensional and thermal stability when laminated to the voice coil (which becomes hot under high power drive conditions). Its strength makes it easy to work with in assembly operations and it also offers superb production consistency.

FIGURE 5

EMIM Laminate Structure



We have developed exclusive laminating techniques and procedures to work with extremely thin films of polyimide, aluminum and adhesives. *Figure 5* shows the lamination structure, to scale, of the new EMIM and L-EMIM drivers. The intricate voice coil shape is etched from a full-surface aluminum film after its lamination to the other components. The adhesive layer which bonds the voice coil also is etchable. After etching, the adhesive remains only under the actual aluminum voice coil trace, which helps to reduce total mass. As can be seen, the voice coil trace and the adhesive together are only one-thousandth of an inch thick — and most of this thickness is in the aluminum trace to give the voice coil high current handling capability.

However, the issue that most concerned us was that of damping the laminate diaphragm structure to eliminate the standing waves that develop when the wavelength of reproduced sound is smaller than the dimensions of the diaphragm surface. This phenomenon, known as modal break-up, is found in diaphragms of any shape. It is most audible in the diaphragms of large drivers such as midranges and woofers, because the frequencies of break-up in these drivers are in the most sensitive range of human hearing. The challenge was to find an adhesive damping material which would suppress the break-up without adding excessively to the mass of the diaphragm. It would make no sense to develop ultra-thin, light diaphragms only to give up the low-mass benefits by using a heavy damping material that would result in a diaphragm with the mass of a conventional material.

After much searching, we found an isothermic damping material which meets the design objectives of low mass and high damping. In the final design, the damping layer, which is a pressure-sensitive adhesive, is layered between the 0.001" thick polyimide base film and a second, much thinner layer of polyimide which provides both a smooth outer working surface and additional strength to the final diaphragm. The complete laminate assembly, including the voice coil, is only 0.0043" thick, approximately one and a half times the thickness of a typical human hair.

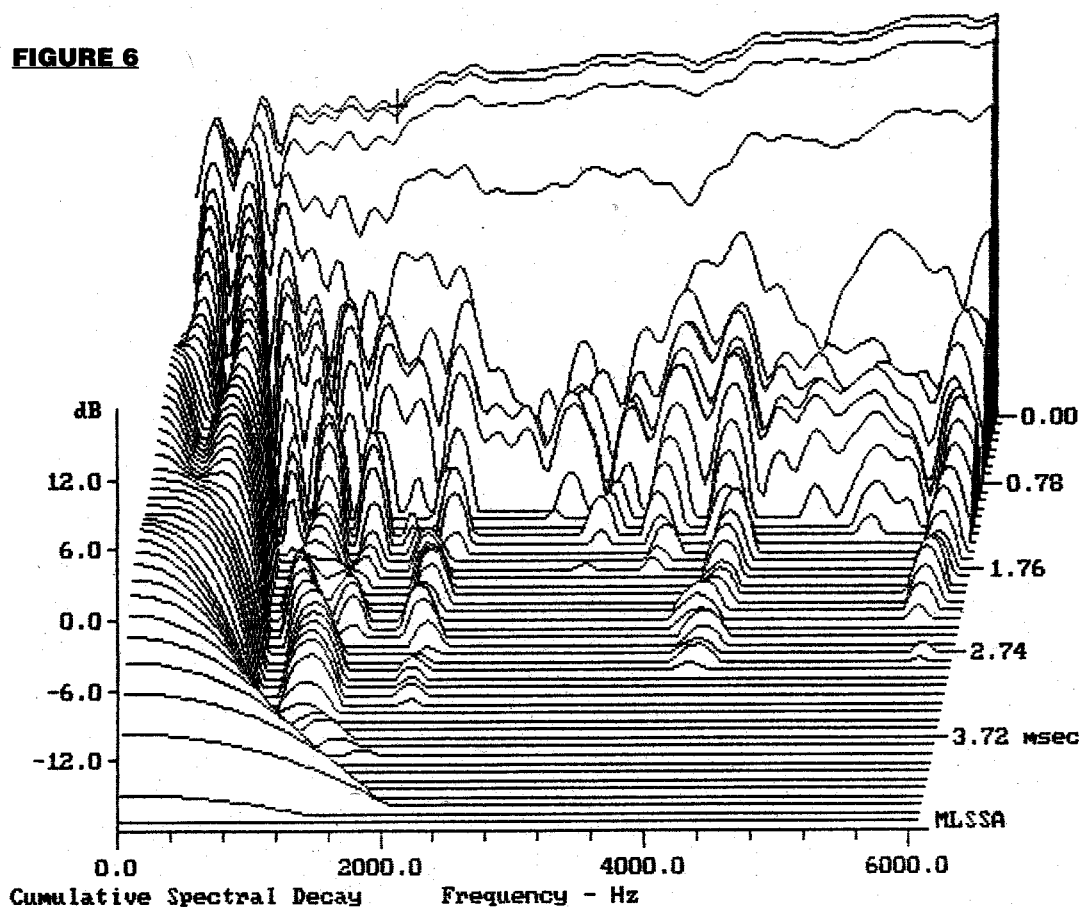
A natural question would be, "Did all this work pay off?" The answer, and the success of the new laminate diaphragm, can be seen in *Figure 6*. This is a MLSSA "waterfall" plot of the frequency response and energy storage (in this case, lack of energy storage) of the new EMIM midrange driver. The MLSSA instrument is a computer-based acoustic analysis system that not only duplicates the measurements of conventional instruments, but also provides additional analysis through powerful digital signal processing techniques. In the plot, the x-axis, horizontal scale is linear frequency, the y-axis, vertical scale is amplitude in dB, and the z-axis, front-to-back scale is time in milliseconds.

All diaphragm resonances and break-up modes act to store energy and then radiate it later in time. The audible effects of this energy storage are those of "smearing" and "ringing." When these resonances are present, the waterfall plot shows them as peaks which persist through time. The uppermost, "zero-time" trace corresponds to the familiar plot of a steady-state, swept-frequency response. I think this trace alone is remarkable for its smooth, flat characteristic. The succeeding traces down the waterfall, toward the front, indicate the decay of acoustic energy radiated from the driver after the driving signal stops. Note that the EMIM driver has large empty spaces between the successive time plots as the acoustic energy rapidly decays, indicating remarkable freedom from resonances and break-up modes. This exceptional freedom from energy storage means that the new EMIM and L-EMIM drivers sound clean and clear, free from the sonic effects of unwanted energy storage.

Together with the improvements in the magnetic circuit, this advanced diaphragm construction gives the new EMIM driver more than 12dB

greater dynamic range than the previous Infinity EMIM design, as well as smoother response and wider bandwidth. These performance gains extend to the L-EMIM and EMIT drivers as well.

FIGURE 6



8.5 dB, 1.475 kHz (37), 0.000 msec (0)

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MLSSA: Waterfall

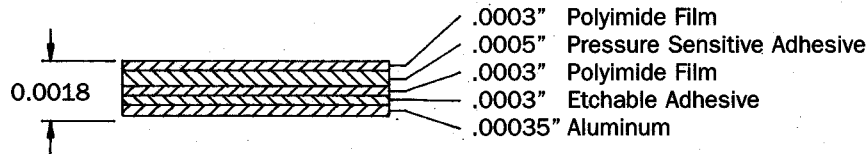
The Infinity EMIT Tweeter Driver: Diaphragm Construction

The construction of the new EMIT tweeter diaphragm is like that of the new EMIM driver and shares all of its sonic benefits. As can be seen in *Figure 7*, the primary difference is in thickness — the complete EMIT diaphragm is a mere 0.0018" thick, less than half the thickness of the EMIM construction. This means that it also has less than half the mass, an element critical to the upper bandwidth of a tweeter's response.

The low mass diaphragm and powerful motor combine to give the EMIT on-axis frequency response to 45kHz and outstanding power response to well beyond 20kHz, which is remarkable performance by any standard. As can be seen, all of the magnetic circuit refinements and diaphragm quality found in the EMIM are present in the EMIT, making it one of the world's finest high-frequency reproducers.

FIGURE 7

EMIT Laminate Structure



The Infinity IMG™ Servo Woofer: Servo System Benefits

Infinity's first commercial product was the famous Servo Statik I, a high performance loudspeaker that first brought servo system control to woofer design. Reproducing low frequencies at high sound levels requires moving an enormous amount of air, more even than the best planar drivers — Infinity's — can achieve. This means that a high output woofer must employ another design. A standard shape for low frequency driver diaphragms is the cone. It is a mechanically strong shape, one that can be made adequately large and that is easily formed from a wide variety of materials. It is also well-suited to being driven from its apex, making it ideal for attaching a compact, powerful motor. In short, the cone is a good shape to use for woofer diaphragms.

Eliminating Woofer Phase Cancellation

It is a commonplace that because the positive and negative pressures of a woofer cone's motion cancel where they meet equally, the two sides of a diaphragm must be separated from each other to achieve high output at wavelengths that are long compared to the dimensions of the diaphragm. Even partial cancellations reduce efficiency and output level.

There are many ways to accomplish this separation. For example, mounting the woofer in a baffle that is large enough, compared to the wavelength of sound at the frequency of interest, will prevent the cancellation. This type of woofer design, in the form of an open-back box, was used in nearly all radios up until the advent of modern high fidelity systems. At 1kHz, where the wavelength is a little over one foot, the baffle doesn't have to be very large to work well. In fact, the baffle principle is used in the Epsilon's midranges and tweeters to improve performance. However, at 20Hz, where the wavelength is about 57 feet, an adequate baffle design becomes a real problem. Room walls can be, and are, used as "infinite baffles," but this technique eliminates speaker placement flexibility and means that the listening position is unchangeably fixed in relation to the permanently mounted speakers.

An obvious solution is to enclose one side of a diaphragm in a closed box, preventing the radiation of the enclosed side from reaching the side which radiates into the room. If not too large, the box can be put where it looks and/or sounds best. With the success of modern speaker designs, this straightforward solution is now taken for granted, but it does have some important limitations.

A major limitation to closed-box woofer systems is that the air trapped in the box acts as a spring, equivalent to an electrical capacitor, while the mass of the woofer cone is the equivalent of an electrical inductor. These two elements make a resonant circuit in the form of an acoustic high-pass filter. Below the system resonance frequency f_c , the output of the system falls off at a rate of -12dB per octave (an octave change doubles or halves the frequency). The smaller the box or the lower the moving mass of the woofer, the higher the resonant frequency of the system and the less deep bass output. Similarly, the bigger the box or the higher the mass of the woofer cone and voice coil, the lower the resonant frequency and the more deep bass output there is.

As you can see, an excellent combination for high-level, deep bass output is one or more big (high mass) woofers in one or more very big boxes. In contrast, smaller woofer enclosures, which are more practical in every way, have less deep bass output. Using the example of the Epsilon woofer system, a 12" woofer in a two cubic foot box has a system resonance in the neighborhood of 60Hz. This means that the output at 30Hz will be nearly 12dB less. While this may be adequate for casual listening, it absolutely is not sufficient for true high fidelity music reproduction.

The Servo Feedback Woofer

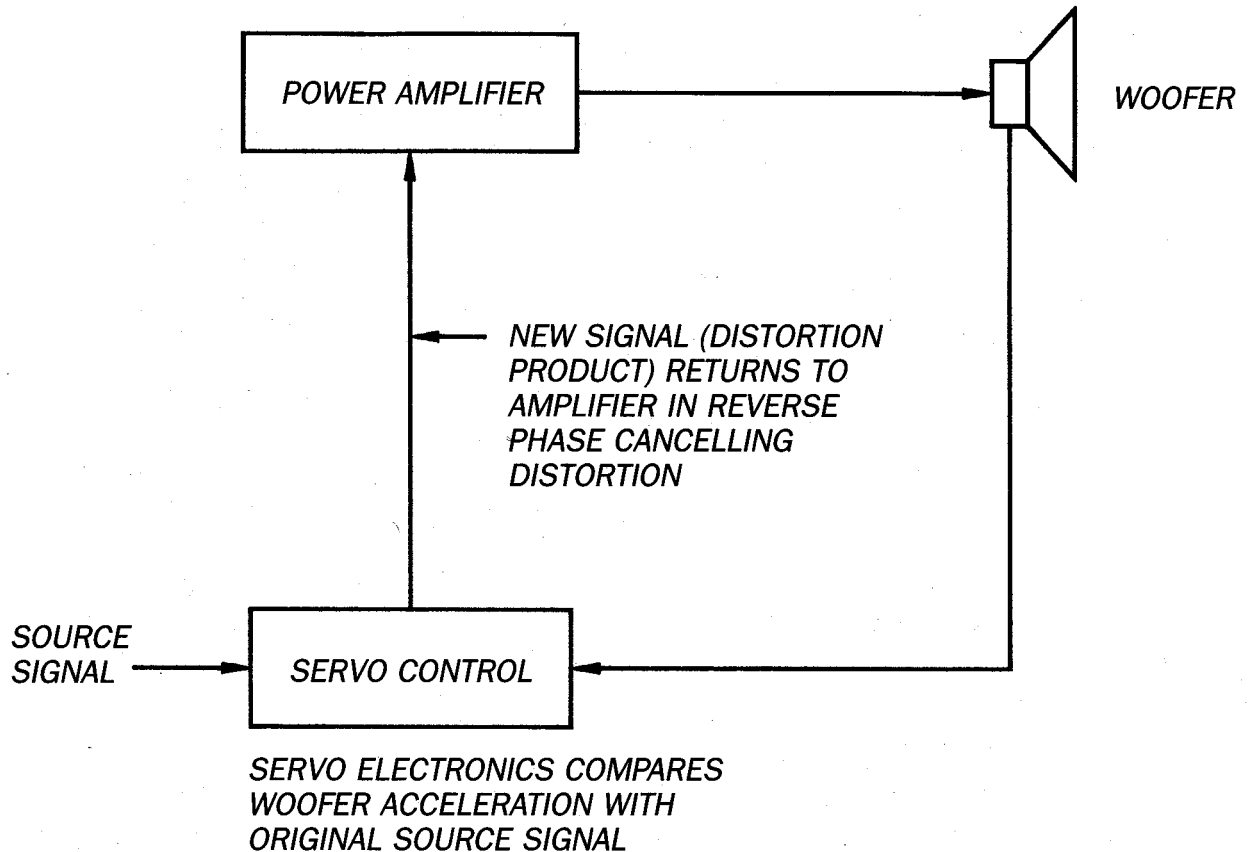
The partners who founded Infinity realized that a woofer and its enclosing box could be made to act much "bigger" than it actually is by putting the woofer in an electronic feedback loop with the driving amplifier. This would let compact woofers perform like big, room-filling systems, making high performance bass reproduction available from practical size enclosures.

In the servo feedback system design, the feedback action of the loop effectively controls the excursion of the woofer cone to produce the level of output called for by the driving signal — no more, and no less. *Figure 8* shows the basic arrangement of the system. Cone motion feedback control offers the huge and immediate benefit of reducing both linear and non-linear distortions.

Linear distortion occurs because the woofer's moving parts have inertia due to their mass. If they are at rest, they want to stay at rest; if they're moving, they want to keep moving — regardless of the requirements of the driving signal.

Non-linear distortion is the result of variations in cone motion caused by variations in the stiffness of the suspension system and variations in the strength of the motor circuit.

FIGURE 8



If the inertial effects or the non-linearities of the voice coil/cone motion produce too much or too little output, the feedback system detects the difference and corrects the drive signal to make it right. This feedback-controlled operation is what defines a “servo system” and it was the foundation of the runaway success of the Infinity Servo Statik loudspeakers. By using servo feedback, a relatively small active woofer system like that of the Epsilon can actually far outperform much larger passive designs in accuracy and clarity of reproduction.

The Feedback Sensor

The means used to detect the woofer’s motion is important. There are a variety of ways to detect cone motion and/or position, and some of them work much better than others. We, the partners who founded Infinity, were aerospace engineers who were intimately familiar with the accelerometer servo systems used in aircraft and spaceflight applications. The availability of relatively inexpensive and light-weight solid-state acceleration sensors made it practical to attach the servo feedback sensor directly to the woofer cone, near the voice coil. In this arrangement, special circuitry scales and converts the sensor output to match the signal requirements of the amplifier. This accelerometer feedback system is still the single most effective way to control the motion of a woofer cone to get extended, highly linear bass output.

The Infinity IMG™ Servo Woofer: Driver Design

To take full advantage of the active servo woofer system's potential, the woofer driver itself has to be exceptionally good. Because the servo system overcomes the limitations of the small enclosure by increasing the electrical drive to the woofer, the woofer driver must be able to handle large low-frequency signals from the amplifier without excursion restrictions or excessive distortion. Furthermore, the cone must behave like a perfect acoustic piston, because, while the servo system assures accurate motion of the cone at the point where the accelerometer is attached, it cannot control erratic, distortion-producing motions resulting from resonances or modal break-up. Like excellent midranges, the woofer cone must be light, strong and well-damped. As mentioned before, woofer break-up modes are potentially serious because of the highly audible middle frequencies at which they occur.

The Infinity IMG™ Cone

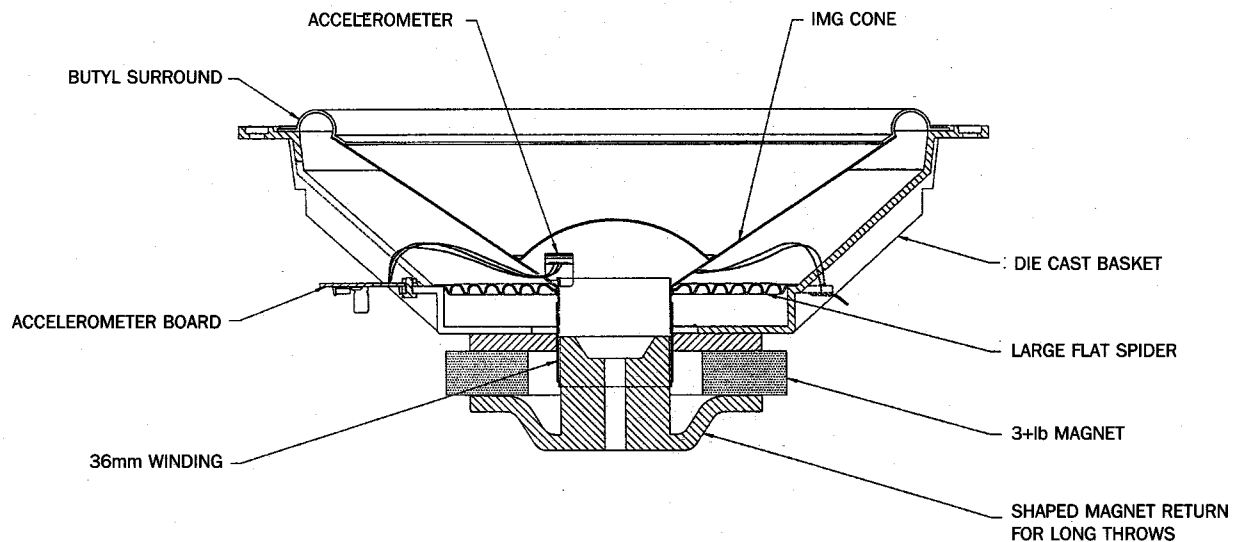
Infinity's Injection Molded Graphite woofer cone neatly overcomes difficulties encountered in many previous designs. It is formed from a combination of polypropylene and carbon-graphite fibers. Graphite fibers have the highest strength for their weight of any material. Woven into a fabric and bonded with resin, graphite fibers make extremely strong molded shapes. However, this material by itself is too resonant, or "ringy," for loudspeaker diaphragms. Polypropylene, on the other hand, is a soft plastic that has extremely high damping — acoustically, it is quite inert. Unfortunately, by itself, polypropylene tends to be "floppy" and weak. To make an acceptable woofer cone, polypropylene must be thick, making it heavy and "slow."

The IMG woofer's unique combination of graphite fiber and polypropylene results in a cone that has the highly desirable properties of each material, yet is free from either material's defects. In the IMG cone, the graphite fibers are oriented radially out from the neck, where the voice-coil attaches, so that the force of the coil's motion is transmitted along each fiber's long axis, the direction of greatest strength. The motion of the voice-coil is smoothly transmitted through the whole cone surface, while the high damping of the polypropylene keeps the cone free from resonances and break-up distortion.

Long-Excursion Suspension Design

To assure the linearity of coil and cone motion and to prevent catastrophic failure, a woofer's suspension system has to maintain perfect alignment of the voice-coil in the magnetic gap over a large excursion range. At the same time, the suspension system must prevent cone motion from exceeding the woofer's safe limits.

FIGURE 9



To meet these requirements, we chose the suspension design shown in the woofer cross-section drawing of *Figure 9*. This design uses a large centering “spider” on the voice coil and a strong yet flexible rubber compound outer surround at the edge of the cone. This design allows long cone travel with outstanding support. While even “high-performance” woofers have spiders of only four or five inches in diameter, the spider of the Epsilon woofer has an eight-inch diameter. This large spider size assures voice coil/cone apex travel which remains radially centered in the magnetic gap throughout the excursion range, free from the voice coil “rocking” distortions common to all single-spider designs.

* Spiders are typically formed of lacquer-impregnated fabric which is pressed in a mold to form circular (annular) corrugations. The corrugations give the fabric some stretch for longitudinal (axial) motion, while the orthogonal warp and weft of the fabric inhibit lateral (radial) motion. In early woofers, the spiders were formed from flat pieces of metal or phenolic with three or four “S”-shaped arms around a central ring. The arms looked like spider legs, hence the name.

Infinity High Power Motor Design

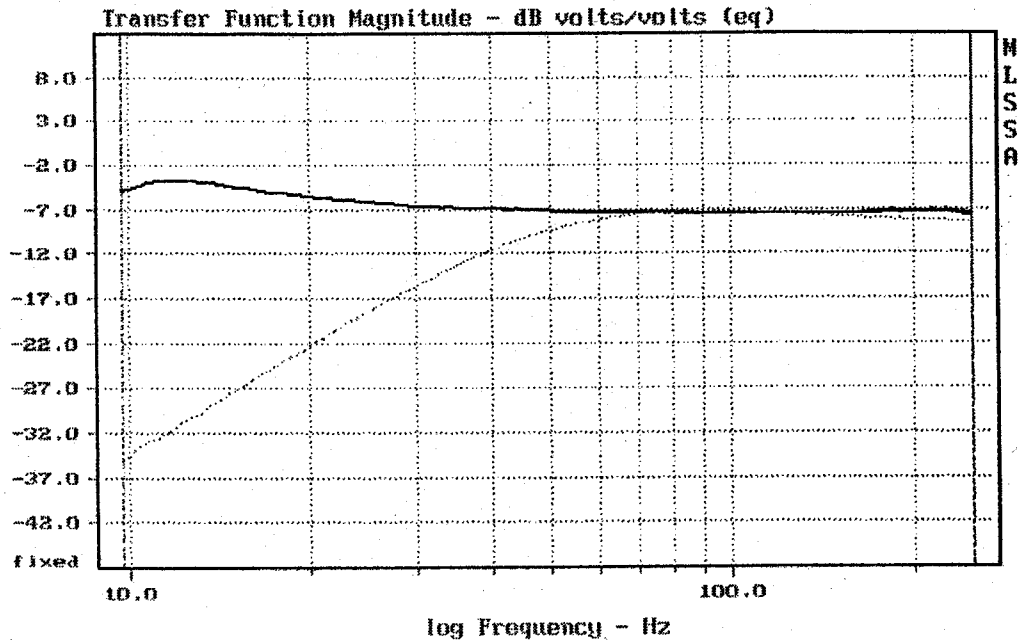
The Epsilon woofer’s massive magnet system employs a powerful ceramic magnet weighing over three pounds. This mammoth magnet is sandwiched between heavy, grain-oriented steel pole pieces shaped to carry the large magnetic flux “current” generated by the magnet. As with the EMIM driver, the woofer’s pole pieces have been designed with sophisticated computer modeling, to maximize the magnetic field strength in the gap while maintaining uniform field shape.

A large, ultra-pure copper voice coil is wound on a strong phosphor Bronze coil-former to resist bending and deformation.* The coil is 1½” long, which means that there is coil wire in the magnetic gap even at the extremes of excursion, so that the driving amplifier always has control over the voice coil.

Together with the long throw suspension, the voice coil and magnet system design allows for peak-to-peak cone excursions of greater than one inch. This ability to move a huge volume of air is critical to the woofer's mission of deep bass reproduction.

* Phosphor Bronze is much stronger than more conventional formats such as aluminum yet has very high thermal conductivity which enhances power handling and therefore reliability.

FIGURE 10 *



epsilon woofer without crossover. ____with fb. ...w/o fb.

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MLSSA: Frequency Domain

Figure 10 shows the Epsilon woofer system's output with and without the servo system control. As can be seen, the action of the servo system functions like an equalizer to boost and flatten the output of the system below resonance. However, unlike any equalizer, the feedback control of the servo system produces distortion cancelling drive needed to produce smooth, flat response and to reduce linear and non-linear distortions. The bottom line is bass output over a more than three-octave range that has unmatched accuracy, clarity and power.

* Note: Close-miked measurement of Epsilon woofer in its enclosure with and without feedback prior to insertion of hi and low pass crossover filters.

Epsilon Enclosure Technology

Enclosure and Driver Interactions

All loudspeaker drivers are affected by the enclosures in which they are mounted, whether the enclosure is a sealed box or merely an open frame. Some of an enclosure's effects are not at all obvious, while others are readily understandable and foreseeable. Different driver designs clearly are affected in different ways, requiring different enclosure solutions. The areas of an enclosure's strongest audible impact are in effects on acoustic radiation, including dispersion patterns, reflections, and diffractions, and in effects of loading and resonances.

Appearance Considerations

A non-trivial aspect of enclosure design is outward appearance. When people describe a speaker, they don't describe the actual producers of sound — the drivers — at least, not at first. Rather, they describe the enclosure: How big (or small) it is, its shape, the wood or other material it's made from and the finish it has, how it looks and feels. While no one readily admits it, most loudspeakers, like cars, are purchased primarily on the basis of appearance — the first impression — with sound quality, and engineering or design details important second factors.

To sell in quantities of more than a few, a technically superior loudspeaker must look like a superior loudspeaker. Music lovers and audiophiles who care very much about sonic quality, who in fact put it first, still care greatly about appearance and construction quality as important factors in the purchasing decision. It is much easier for an owner to be proud of the sound of a speaker when he or she is proud of its looks, as well.

Epsilon's Woofer Enclosure

In general, woofers present the fewest surprises and problems to a loudspeaker designer. A closed box woofer design primarily requires an enclosure that is acoustically rigid and inert, and that is mechanically suited to supporting a large, heavy woofer driver (and often, other system components). Woofers usually take up the largest amount of an enclosure's volume; however, thanks to the effectiveness of the servo system, the Epsilon woofer occupies a much smaller proportion of the enclosure than is usual.

The Epsilon woofer enclosure is made from High Density Fiberboard (HDF) with walls one inch thick. This pressed-wood material is substantially more dense than the MDF material commonly used in speaker enclosures. The enclosure is heavily braced and tapered toward the rear, so that it does not have parallel walls, a design that helps to suppress resonances. The front baffle, to which the woofer driver is mounted, is more than three inches thick. The stiffness and mass of this front baffle, which is partially made up from the vertical baffle that supports the planar drivers, helps to give the woofer a stable platform for generating high-acceleration (>90G) bass cone motion.

The woofer enclosure is filled with sound-absorbing material that converts the acoustic energy of the woofer's rear wave from adiabatic compression to isothermal — in other words, from sound pressure into heat. This transformation of energy makes the volume of the enclosure look “bigger” to the woofer, extending bass response. The filler also prevents the acoustic energy, particularly at frequencies above the 150Hz crossover point, from reflecting off the interior of the enclosure, passing back through the woofer cone and into the room as unwanted distortion. The resulting high-mass, high-stiffness, high-absorbency enclosure adds no audible “box sound” of its own to the powerful woofer driver.

The Disadvantages of Dipole Radiation

Epsilon's planar drivers, the L-EMIM, EMIM and EMIT, place difficult constraints on enclosure design. Planar drivers usually are operated as dipole panels that are free to radiate equally from both sides. In order to prevent the out-of-phase interference and cancellations described previously, these panels often are large, acting as their own baffles at upper midrange and tweeter frequencies.

Since dipole speakers freely radiate equal energy from both side of their diaphragms, they generate a great deal of acoustic energy that is not directed to the listener, but which instead indirectly reflects off of room surfaces, and then interferes with the direct sound.

Even more significant are the cancellation effects that occur in the near field of the loudspeaker. These near-field cancellations, which are the result of baffle-cutoff effects and of reflections and diffractions, have a powerful negative affect on the quality of the direct sound reaching the listener.

The acoustic result of these phase cancellations is the creation of acoustic “comb” filters that cause manifold and serious deep notches in the frequency response of the speaker. The sound quality of dipole speakers is often promoted as having unusual “depth.” In our experience, however, this depth is artificial; it is actually the result of amplitude variations caused by the comb filter action of the dipole radiation and by the time-delayed reflections from room boundaries. Instruments and voices typically seem to move back and forth on the acoustic “stage” as they go up and down the scale, moving in and out of the amplitude notches of the comb filters. They literally fade in and out, creating a false sense of stage depth.

Ideally, we would like to completely absorb the rear wave of the planar drivers. Unfortunately, the low mass diaphragms of our planar designs, which are a huge benefit in generating accurate sound, also create difficulties. These ultra-thin, light diaphragms are essentially transparent to acoustic energy, which passes right through them. Even materials that are ordinarily considered absorptive can reflect considerable energy, especially at longer wavelengths. This means that any sound waves reflected from a closed rear enclosure or its filling, however weak, will enter the room as a source of phase distortion. Furthermore, a sealed enclosure can load the diaphragm, adding “stiffness” to the system which impairs its designed operation.

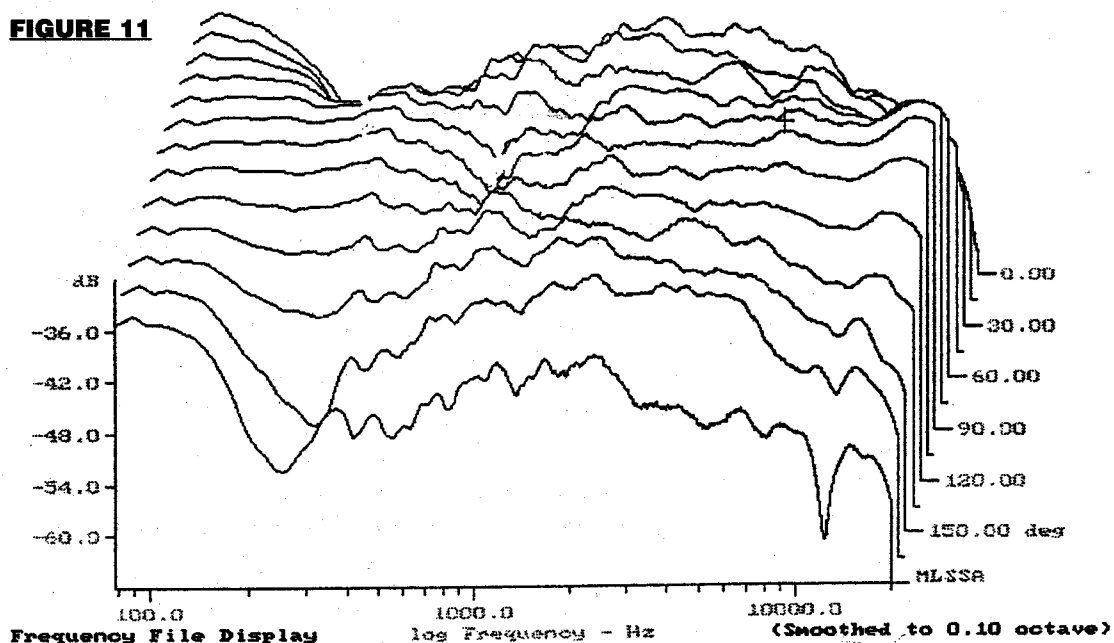
Epsilon's Radiation Pattern Control: Planar Driver Baffle and Rear Housing

Rather than suffer the "phasy" ill effects of dipole radiation, or trying unsuccessfully to completely absorb the rear wave, we experimented with reducing and controlling the rear wave energy.

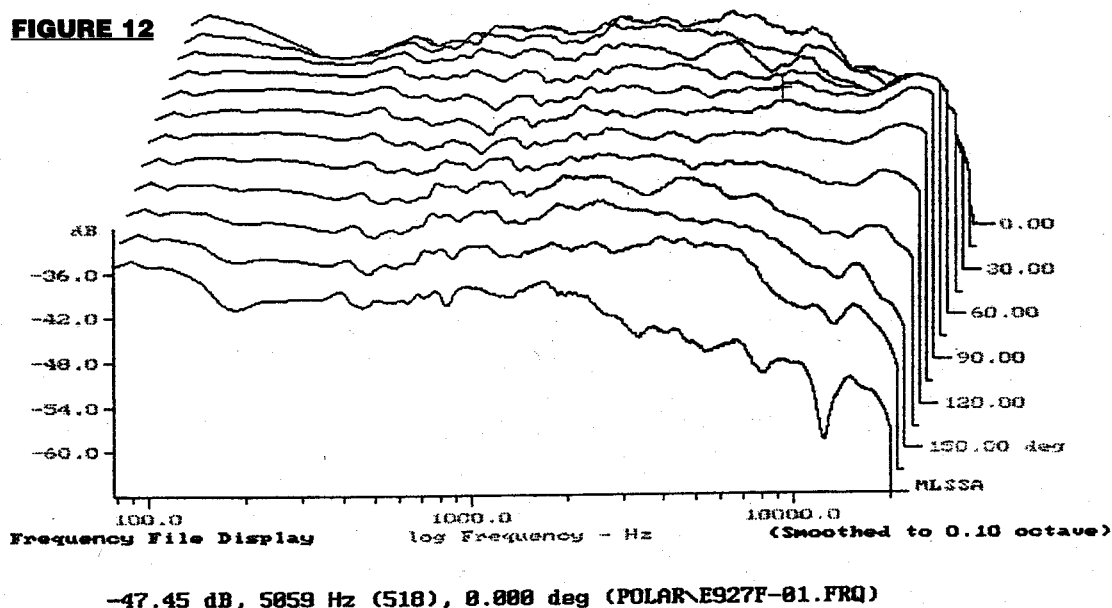
The first thing we did was to adopt a slightly rounded baffle front surface, into which the planar drivers fit flush, in cutouts. This baffle design makes the grille material and its frame an integral part of the driver's mounting frame, which then smoothly joins with the baffle opening. Furthermore, the frames and solid face surfaces of the drivers are covered with acoustic felt to prevent reflections that cause response anomalies in the upper midrange and high end. The smooth transition from driver to gently rounded baffle ensures the projection of uniform wavefronts at all radiated frequencies, free from "foldback" cancellation effects caused by the diffraction that occurs at abrupt edges of any kind. The baffle's width gives the lower frequency drivers sufficient area to ensure smooth waveform "launches."

Even with this advanced baffle design we discovered that cancellation effects were occurring in the lower midrange that adversely affected the uniformity of the total power response. *Figure 11* shows the problems we encountered. This MLSSA plot shows the response versus horizontal angle of the Epsilon system over a span of 180°. In this plot, the on-axis, front response can be seen at 90°. One problem is the deep cancellation wells, or notches, at 0° and at 180°. These wells are caused by lower midrange rear wave interference. The second problem is amplitude notching that occurs at approximately 800Hz, at 90° (the on-axis response), and is a side-effect of the baffle cutoff frequency.

FIGURE 11



-47.96 dB, 5059 Hz (518), 0.000 deg (POLAR\E927N-01.FRQ)

FIGURE 12

As mentioned, we decided to experiment with partial absorption of the rear wave. We found that by carefully sculpting a special fiberglass into a form that narrows in width and depth behind the drivers, and venting the rear of the enclosure, the dipole cancellations could be nearly eliminated in their operating band. At the same time, the front hemisphere response significantly improved in smoothness and breadth, indicating improved acoustic power response. *Figure 12* shows just how successful this approach turned out to be. This MLSSA plot shows the same angular span and frequency range as *Figure 11*, but with the rear housing in place. Note that over a wide angle, the traces are at nearly identical levels to beyond 8kHz. The lower midrange cancellations are almost completely eliminated and the on-axis notch at 800Hz has disappeared. This wide, smooth power response of Epsilon is a key to its open, smooth sound quality at nearly any listening position.

Epsilon's Radiation Pattern Control: EMIT Acoustic Filter

The new EMIT tweeter design of the Epsilon system offers improved vertical dispersion compared to the previous design. We achieved this by making the diaphragm shorter. However, in order to maintain enough diaphragm surface area for smooth response at the lower end of the new EMIT's range, the diaphragm had to be widened. So, while the vertical dispersion widened, the horizontal dispersion narrowed above 8kHz.

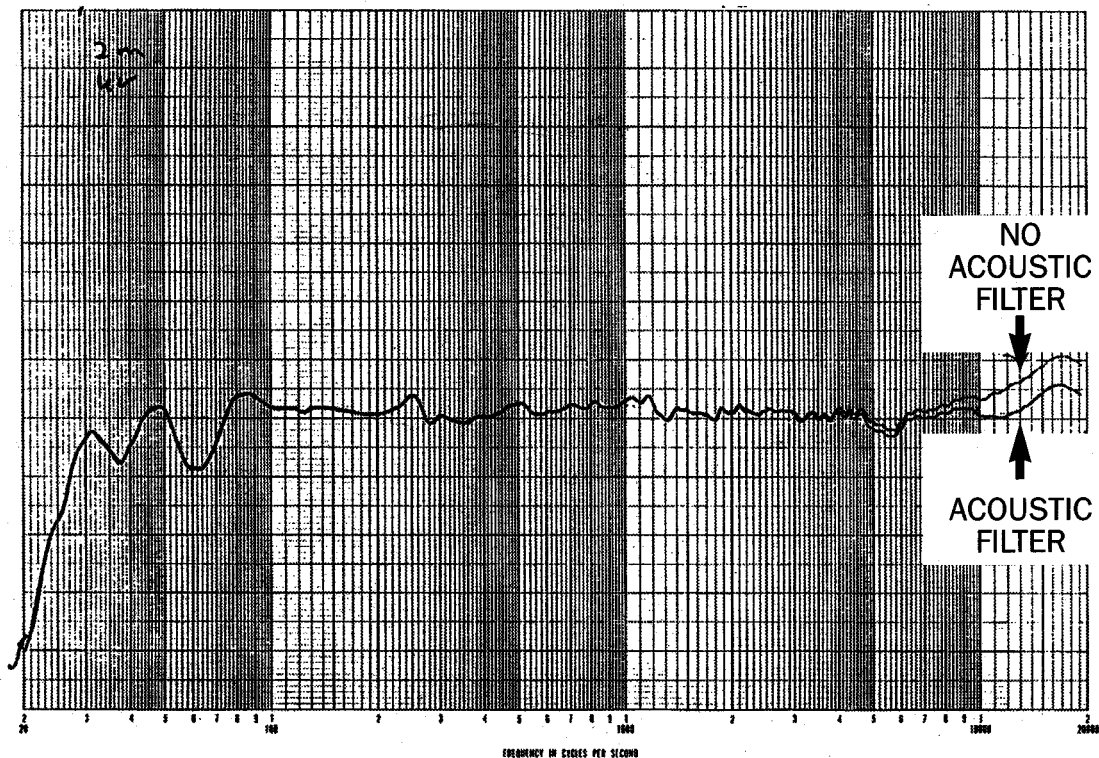
This "beamy" effect actually appears in every tweeter, regardless of the diaphragm shape. As the wavelength approaches the dimensions of the diaphragm, the waveshape begins to become planar rather than spherical. In a typical 1" dome tweeter, for example, this narrowing, or "beaming" becomes serious at about 10kHz. If the dome had flat power response, the on-axis response would actually rise, and some do, however most show a roll-off in power response due to the reactive mass of the dome. The on-axis frequency response of such a tweeter may show a "flat" characteristic out to beyond 20kHz, but this is only because the energy is concentrated in an increasingly narrower angle. The actual power response of the dome is falling off rapidly, beginning its drop-off as low as 6kHz.

As discussed previously, the EMIT diaphragm provides extremely wideband response — on-axis, to 45kHz — and it also has exceptionally good power response to well beyond 20kHz. This means that the narrowing of the horizontal dispersion actually causes a strong rise in on-axis response above 10kHz. For the new EMIT tweeter, we needed a way to narrow the horizontal opening at high frequencies, so that wide dispersion is maintained and the on-axis response flattened. At the same time, we needed to keep the opening wide at lower frequencies to assure flat response and high output.

This thorny problem in dispersion control caused a lot of thought and experimentation. In the end, we designed a multi-layer fabric acoustic filter that is relatively transparent at lower frequencies and relatively absorbent at higher frequencies. This filter gives exactly the control needed to have broad dispersion above 8kHz, both vertically and horizontally. *Figure 13* shows the on-axis frequency response of the new EMIT driver without, and with, the acoustic filter. The strong on-axis rise of the EMIT that is the result of narrowing dispersion can be seen in the trace without the filter in place. Using the filter drops the on-axis output by 2.5dB at 20kHz; this drop is the result of the widening of the horizontal dispersion due to the smaller horizontal aperture of the filter at high frequencies.

To further broaden the top two octaves of Epsilon's power response, a second EMIT was placed in the rear of the baffle, outside of the rear housing. At the high frequencies and short wavelengths that this rear EMIT reproduces, the cancellations that are so troublesome in the low and mid-frequencies become random and inaudible, so that the resulting wide overall power response gives a pair of Epsilons an exceptional quality of spaciousness and "air."

FIGURE 13



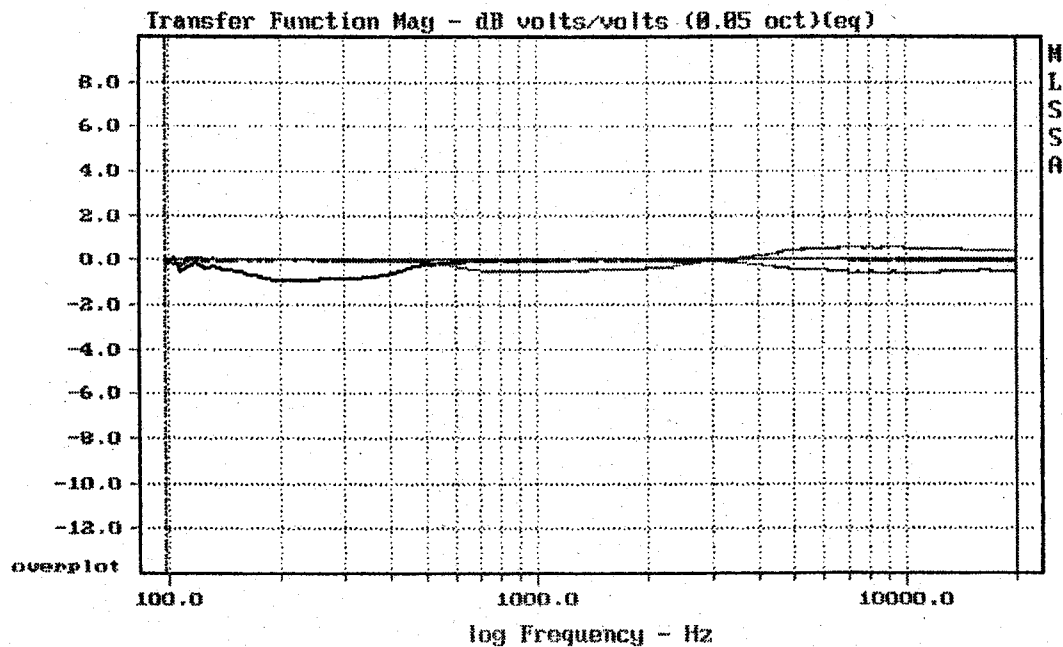
Crossover Networks and System Details

Passive Crossovers

Epsilon's four planar drivers all employ passive crossover networks that are driven from a set of input terminals separate from those for the woofer section. This bi-amplified configuration is required by the woofer servo system but beyond that, the benefits of bi-amplification are important to amplifier and wire performance. The two pairs of gold-plated input binding posts for the woofer section and for the upper end of the loudspeaker are located on a gold-plated metal connector panel. This panel also holds the "XLR" connector for the servo sensor output which goes back to the Servo Control Unit.

The passive crossovers are located within the woofer enclosure. Each planar driver section — tweeter, midrange and lower midrange — has its own separate crossover printed circuit board. The individual boards are as widely separated in the enclosure as possible in order to reduce interaction among the various components, particularly the inductors. The component parts are of very high quality, each selected to perform its task in the way that works and, most importantly, sounds best. Glass-epoxy circuit boards with heavy double copper traces, low-loss polypropylene capacitors, precision resistors, high-Q inductors optimized for each application, high-quality cabling, gold-plated connectors — all of these premium quality components affect and improve the sound of the loudspeaker.

FIGURE 14



epsilon level controls. 0 line = flat

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MLSSA: Frequency Domain

Three switches on the back of the enclosure, behind an access door, provide for small but highly significant adjustments of the relative level of each section. *Figure 14* shows the effects of the level switches on the electrical drive level to each section. As can be seen, the various level change steps amount to less than one dB each. As little as this may seem to be, their aggregate effect is sufficient to compensate for many different listening room conditions. In our experience, the smoother and flatter the response of a loudspeaker, particularly the overall power response, the more noticeable and important small level changes become.

Woofers Servo Control Unit

The Servo Control Unit (SCU) is designed to be located with the electronic components of the high fidelity system, especially the preamplifier. It contains the circuitry that amplifies the output of the accelerometer sensor attached to the woofer's cone and converts it to the form and level required for use as a feedback control signal. The input signal from the preamplifier is combined in the SCU with the accelerometer feedback signal. The woofer power amplifier, selected by the customer, is placed between the Servo Control Unit and the woofer driver input binding posts.

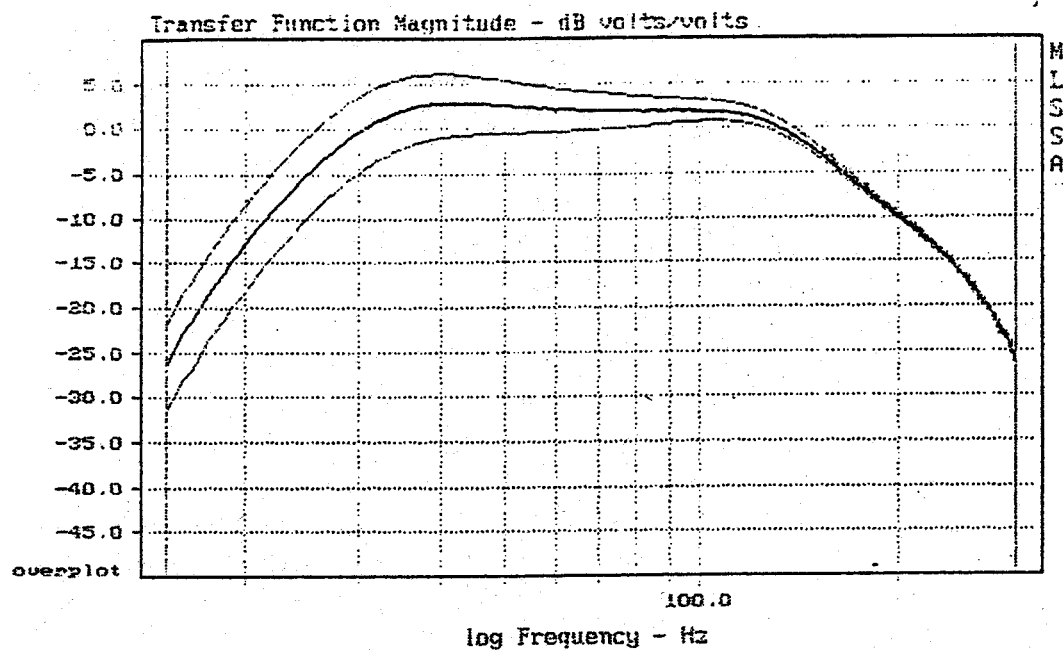
Once it is amplified, scaled and converted, the accelerometer sensor signal is compared to the incoming signal in a differential amplifier. The output of this amplifier is a signal which is the difference between the input signal and the woofer's output. When there is no difference, the input signal passes through the differential amplifier unchanged, to be amplified by the woofer power amplifier, just as it would be in any ordinary system. However, when there is a difference, the output is a signal that contains the inverse of the difference. This signal, which carries the information needed to correct the motion of the woofer, goes to the power amp and on to the woofer. This closed-loop system works to control the cone's motion in the same way that negative feedback works to make an amplifier's output signal exactly match the input signal — in the same way that a human works to steer a car precisely along a prescribed course.

The Servo Control Unit has controls for Mid-Bass Contour, Bass Contour, and Level. The action of the Bass Contour control is shown in *Figure 15*, while the action of the Mid-Bass Contour control is shown in *Figure 16*. The actions of these two controls give the user a great deal of control over the quality of bass sound in the listening room. The Mid-Bass control, in particular, provides compensation for the variations in room mid-bass response related to speaker placement. The Level control offers matching of the overall woofer level to the level of the rest of the system.

The Servo Control Unit also includes circuitry which helps to prevent woofer and amplifier overload under overdrive conditions which physically cannot be met by the capabilities of the woofer system. The connections from the loudspeaker to the SCU for the accelerometer are through balanced "XLR" type professional microphone connectors to ensure low noise and clean transmission. Because the performance of the servo system

depends in part on the voltage gain of the woofer amplifier chosen, provisions are made for matching of the Servo Control Unit and the woofer amplifier.

FIGURE 15



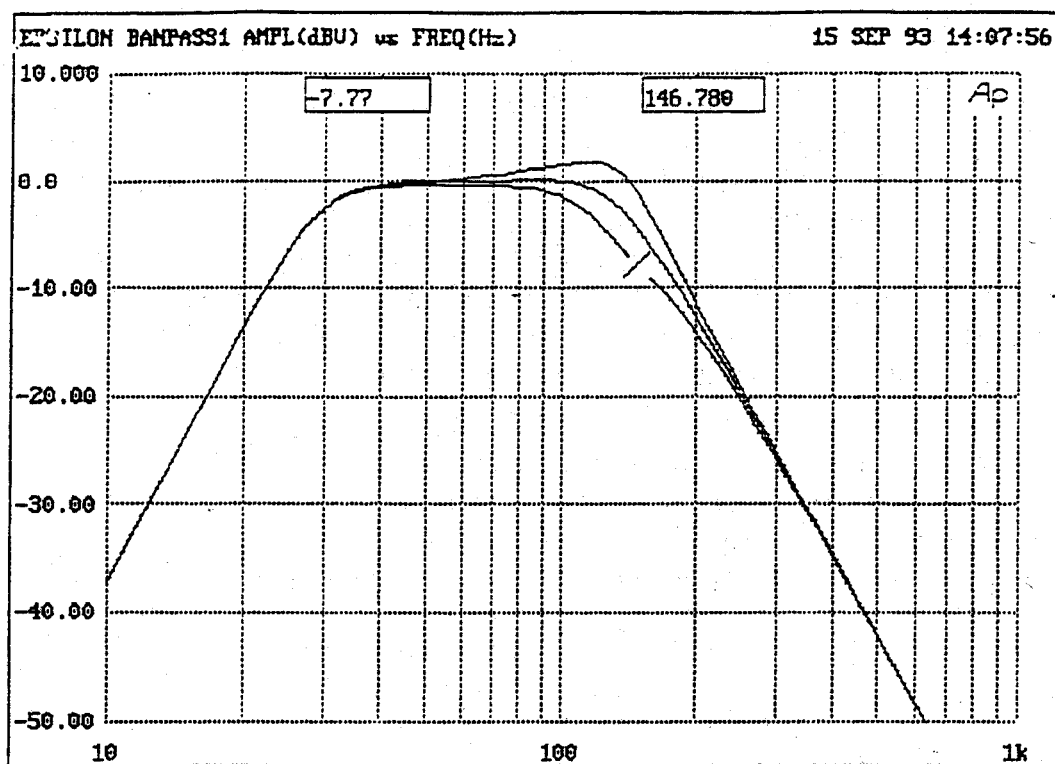
CURSOR: y = -25.6294 x = 299.8047 (614)

epsilon for japan bass contour control range + 0 -

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MLSSA: Frequency Domain

FIGURE 16



The Art of Loudspeaker Design

Although this paper has focused on the technologies of Epsilon, it would be a mistake not to acknowledge the importance of art in loudspeaker design. As audiophiles long have known, there is more to be heard in loudspeakers than we are currently able to measure and quantify. Like any enterprise where human perception, judgement and creativity are the most important components, designing loudspeakers requires fine human judgements about the quality and appropriateness of each element of a design.

A good example of this is found in the tweeter crossover circuitry of Epsilon. We discovered that if, instead of a single capacitor, we used series-parallel combinations of polypropylene capacitors in series, meaning that each is twice the final size required, and then bias the joining point between the two capacitors with a small DC voltage applied through a large-value resistor, the sound of the tweeter system improves dramatically. We have theories as to why this should be so, but cannot yet confirm our theories through measurements. Nevertheless, this serendipitous (if you will, artful) discovery is an important aspect of Epsilon's sound quality.

The access panel which conceals the three midrange and tweeter level switches also holds the two 9V batteries required for this circuitry (one for each tweeter capacitor). The +9V bias voltage is applied through a 5 Megohm resistor, meaning that the life of each battery is essentially that of its life just sitting on the shelf — for an alkaline cell, more than 2 years.

Conclusion

We sincerely believe that the infinity Epsilon establishes a new standard of excellence in high fidelity loudspeakers for use in the home. While not compact, or even moderately small, Epsilon nevertheless offers a level of performance that substantially exceeds its physical size. It has the wide bandwidth, high output, low distortion, broad power response and dynamic range to faithfully reproduce any kind of music in the home at realistic, live concert levels. Epsilon's reproduction is so clean that listeners often do not realize that the system is playing at ear-bending levels until they attempt to talk over it, and suddenly realize that not only can they not hear each other, they cannot even hear themselves.

We've done our best to give Epsilon qualities not found in any other speaker, from its precision and care in manufacturing, to its appearance and sonic stature. We hope that this look at the technology and art of Epsilon helps you to appreciate the achievement we believe it represents.



We get you back to what it's all about. Music.

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