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Speaker Builder

THE LOUDSPEAKER JOURNAL

SANDERS' COMPACT ESL / TL

Speaker Builder

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About This Issue

If you have wondered how to get your speaker into the distortion cancelling feedback mode, **Hans Mortensen** has also. His suggested pathways into this relatively uncharted territory begin on p. 10. All you guitar players who've been asking for a speaker voice for your instrument are about to be gratified. Using paper drums and tubes **Glenn DeMichele** has built a beauty. The specifics begin on p. 22.

Roger Sanders, surely one of the world's leading authorities on electrostatics graces our pages again with a brand-new bass recipe in the spectacular package pictured on our cover. Our four-part series on this handsome realization of ESL/TL coordination begins on page 30.

Those nifty little Radio Shack speakers are just too tempting to let alone. **Angel Luis Rivera** suggests a new configuration for the popular pair of poppets (p. 42). **Dick Pierce** not only clarifies Richard Heyser's "time delay spectrometry" concept and such wonders as FFTs—Fast Fourier Transforms to the uninitiated—in his *Ask Speaker Builder* treatise (p. 46), but also he introduces readers to George Augspurger's mordant wit on the topic of speaker patents on p. 78.

To underline the importance of your responses to *Speaker Builder* we've moved a couple of features in this first 1990 issue. *Letters* will lead off our pages in future, but you will find the *Good News* about new vendor offerings beginning on page 73.

Next time you'll be seeing Bruce Edgar's *Show Horn* and how to fix the Klipsch Heresy plus a nifty little two-way design.

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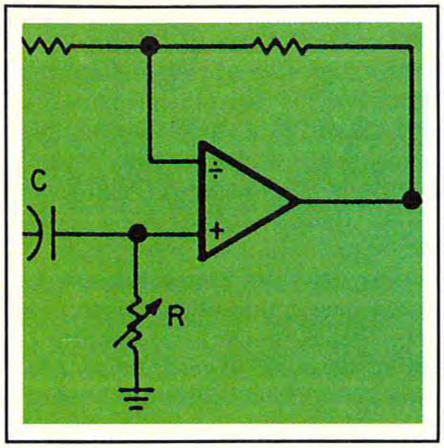

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FEATURES

DEPARTMENTS

On our cover: **Roger Sanders'** compact electrostatic/transmission line speakers without the electrostatic panels. Photo by the author.

A COMPACT INTEGRATED ELECTROSTATIC/ TRANSMISSION LINE

BY ROGER R. SANDERS

The sonic advantages of electrostatic loudspeakers (ESLs) have been well recognized for over forty years. Anyone who has ever heard one is forced to agree that magnetic speakers are still a long way from being able to match the detail, smoothness, and delicacy of electrostatics in the critical midrange. The reasons for this superior performance are quite clear: First, ESLs have essentially no mass. They will therefore respond to the audio drive signal instantaneously. Equally important is the fact that they will stop instantly.

By comparison, magnetic speakers are more massive, making them hard to start and stop. Powerful magnetic motors have managed to greatly reduce the start time, but do not stop the cone. The unavoidable result is overshoot and ringing with distressing effects on sound quality. The massless nature of an ESL means the mass of the air in the room damps any potential speaker resonances, so extremely smooth frequency response is automatically achieved.

Unlike the cone of a magnetic speaker which is driven only at its center, causing cone flexure, ESLs are driven uniformly over their entire surface. Distortion is therefore negligible. In an attempt to improve magnetic speaker performance, ribbon and planar magnetic types have been built. In many ways these are superior to the cone drive, but have numerous problems which have prevented their widespread acceptance. Furthermore, they are still far from matching electrostatic performance because they remain much more massive and are not driven uniformly over their entire surface. If one desires the finest in sound reproduction, I believe there is no choice but to use the electrostatic format.

DRAWBACKS. While difficult for commercial manufacturers to build, ESLs are simple, easy, and cheap for the home constructor. They virtually guarantee magnificent performance. Yet, they have drawbacks that have severely limited their widespread use. Ask most audiophiles why they don't own ESLs, and one of the most common reasons is the typical ESL's large size and ugliness is incompatible with their wives' living room decor. My design is aimed squarely at this problem. It is the latest in a long series of extremely high performance speaker designs that began in 1972.

Over this 17 year period, I have learned much about the construction and operation of ESLs. Some of this work has been published (*TAA* 4/75, *SB* 2, 3, 4/80) resulting in communication with engineers, amateurs and others who had many good ideas which I incorporated into later versions. The design I present here utilizes all I have learned over this period and is well proven. One of the things I learned is there is no magic. ESLs are simple, predictable, and offer superb detail. There are often many ways to accomplish the same goal. I will outline a variety of options you may choose.

My goal is to achieve the highest performance possible, considering the aesthetic restrictions of a quality living room environment. Previous designs are no-compromise performance devices consisting of floor-to-ceiling ESLs up to two feet wide which must stand away from the walls. These are combined with large transmission line woofer systems in boxes at least 4 feet tall and 1.5 feet deep. While the resulting sound is spectacular, their large size, multiple sections, and free standing requirements make them unacceptable in most homes. Clearly the challenge now is to build that kind of performance into a small, pleasingly shaped speaker that can be placed against a wall.

Building a small, attractive, full-range, flat frequency response ESL is a piece of cake. All you have to do is pick a convenient size, determine the phase cancellation and fundamental resonance frequencies and magnitudes, build a mirror image equalizer, hook it up and you're in business. They would be cheap (surely less than $100 for the pair) and you could build them in an evening. They would have marvelous detail, perfect frequency response, great imaging, and if done right, you could even hang them on the wall to make them virtually disappear.

If you suspect I'm deliberately overlooking something, you're right. The above speaker has one small problem: You could barely hear it. Obtaining high sound pressure levels (SPLs), particularly in the deep bass, is a serious problem and must be compromised against all other design parameters. This need for high output is *the* challenge for ESL designers. It is important to realistic sound reproduction and is the main failing of most ESL designs.

HIGH OUTPUT. To give you some idea of the output required, if you measure the SPLs of commercial source material (virtually all of which is heavily compressed), you will discover "ear shattering" levels (which I define as uncomfortably loud with loss of hearing sensitivity for a while after exposure) are about 95dB.

ABOUT THE AUTHOR

Roger Sanders is a 41-year-old inventor/designer. His interests and designs span all types of mechanical and electrical products. He maintains a particularly keen interest in electrostatic transducers and will be publishing a book on the subject this year.

Because commercial source material is generally of poor quality, I make my own recordings.

I have been fortunate enough to record live performances of good symphony orchestras and pipe organs for more than 20 years. Measuring "Row A" sound levels while recording these, the highest level I encountered was the finale of Mahler's "Resurrection Symphony" with full orchestra, pipe organ, brass choirs, extra percussion, 500 voice chorus, and soloists. I saw momentary peaks of 105dB, although I am sure some were very short peaks which the meter wasn't quick enough to display.

The ability to reproduce "Row A" SPLs in my home is a fundamental requirement of any audiophile quality speaker. To realistically reproduce such uncompressed material requires prodigious amounts of speaker output. My no-compromise system will do that. No full-range ESL can even come close. But can levels of that magnitude be accomplished in a small ESL system? Let's have a look at how it might be done.

The ESL's operating principle is the attraction of an electrically charged object. You experience this when you comb your hair on a dry day and feel the electrostatic charge on the comb pull gently on the hair on your arm or attract bits of paper. Our speaker operates by placing an electrostatic charge on a diaphragm which is suspended between two electrically conductive grids, perforated so air may pass through them. The audio amplifier drives alternating high voltage onto these grids so the diaphragm feels a net force, moves, and drives the air producing sound.

High SPLs are difficult to achieve with electrostatic designs since, unlike magnetically driven speakers, electrostatic forces are weak and travel only short distances. Speaker output is the product of driven area times excursion. Either one may be increased to increase SPLs. Large excursions in ESLs are difficult to obtain because they require very high operating voltages. Not only is it difficult to supply the speaker with such voltages, but if you do, it is difficult to prevent the speaker from arcing internally and destroying itself.

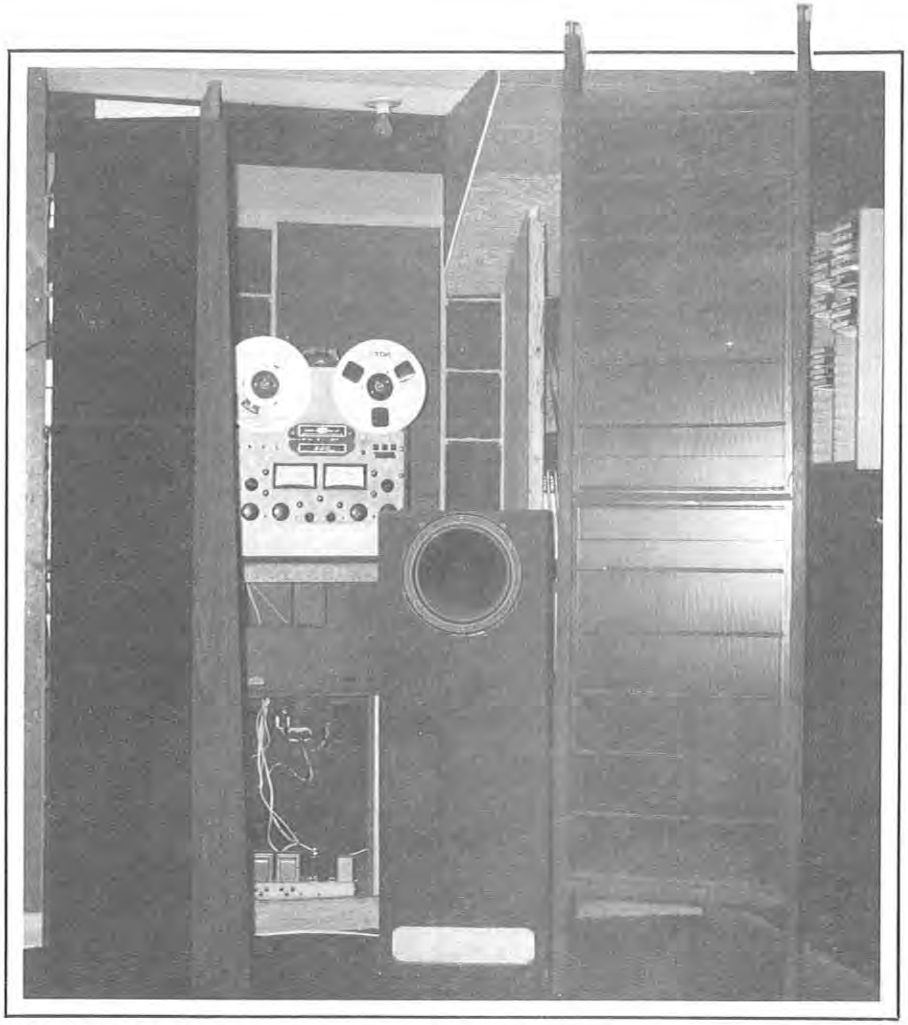

PHOTO 1: The original speaker, right, compared to the new, compact version.

DRIVE VOLTAGE. Electrostatic forces in speakers require several thousand volts to be effective. This requirement rises as the distance between the moving diaphragm and the stationary conductive grid (stator) is increased. To further complicate matters, the voltage required is squared as the distance is doubled. I use a relatively small diaphragm-to-stator spacing of around one sixteenth of an inch (often referred to as 63 thousandths of an inch or 63 mils in the literature). Even so, a total of around 7,000V is required to drive them to SPLs I consider adequate. Obviously, larger spacing requires higher voltages. Where does one get 7kV of audio drive voltage? The typical 100W amplifier is capable of an output voltage of only around 100V, and we need about 100 times that amount. This problem may be solved by either using a high voltage step-up transformer between the speaker and the amplifier, or by designing an amplifier which will deliver several thousand volts directly to the speaker.

High voltage amplifier designs are available ("An Electrostatic Speaker System," by David Hermeyer, *TAA* 4/72, p. 9 and "The Sanders Electrostatic Speaker," by Roger Sanders, *TAA* 4/75, p. 18) as well as commercial amplifiers used by Beveridge and Acoustat. However, they are expensive, parts are hard to find, tend to be unstable, radiate RF, generate large amounts of heat, use vacuum tubes, and still don't deliver as much voltage as a good hybrid system (conventional amp with transformers). Their greatest asset is that they usually will measure better into an electrostatic load, but even if this is audible (it isn't in my experience), a good transformer system will produce much higher SPLs which makes it audibly far superior. Furthermore, a transformer/conventional solid-state amplifier is cheaper than a high-voltage amplifier, easier to assemble, is stable, and runs cool.

Amplifier sound is a controversial subject. I have done a considerable amount of double blind "A-B" amplifier testing and have come to the conclusion if two properly operating high quality amplifiers sound different, the difference is always due to different distortion products produced during some type of overload condition. Amplifiers are usually driven into at least modest clipping at SPLs most audiophiles enjoy. "Tube sound" for example, may possibly be explained by the fact that few odd-order harmonics are generated by a clipping tube amp, while a solid-state one produces an edginess or harshness due to a high percentage of odd-order harmonics when clipped.

SURPRISE. When clipped subtly so the ear does not perceive gross distortion, the two amplifiers do in fact sound different. It is truly amazing how much power and headroom is needed to avoid clipping an amplifier in most listening situations. However, if you set up double blind tests which require that neither amp under test be allowed to overload at any time, you will be surprised by two things: 1) You will be unable to play your speakers as loudly as you thought you could, and 2) both amplifiers sound the same.

I realize many audiophiles simply do not believe this. However, even skeptics will agree that if such differences exist, they are subtle. If not, then there would be no controversy about it. One issue is *not* subtle: Inadequate power is extremely obvious. In short, the most important amplifier parameter, particularly when driving ESLs, is adequate amplifier power. Don't sacrifice power for some subtle (or imagined) sonic difference between amplifiers.

I have abandoned the direct drive types for the conventional amplifier/transformer setup. I can hear no reduction in sound quality between the two in a double blind test, but the hybrid system will play much louder resulting in a system which seems much more "at ease" and is far superior for meeting my goal of high output.

VOLTAGE. Transformers have their problems which I will not discuss here except to say that from a practical standpoint, the highest feasible step-up ratio ("turns ratio" in engineering jargon) in the wide bandwidth transformer my design requires is about 1:50, or about 5kV from our 100V conventional amplifier. While this voltage is quite usable, it isn't quite enough.

A larger amplifier is one answer. Personally, I use the Hafler 500 which will swing nearly 180V with plenty of amperage, for a drive voltage of around 7kV. Add a diaphragm polarizing voltage of around 3kV for a total voltage of around 10kV. This level drives an ESL with a diaphragm-to-stator spacing of around 60 mils extremely well. But to double the excursion to 120 mils you would have to square the voltage. It is difficult enough to develop the 10kV. How would you generate several times that amount?

Furthermore, even if it were practical, preventing arcing within the speaker would be difficult. Dayton-Wright even replaced the air between the stator and diaphragm with sulfur hexafluoride gas which has six times air's insulating qualities. Thus, increasing diaphragm excursion is impractical.

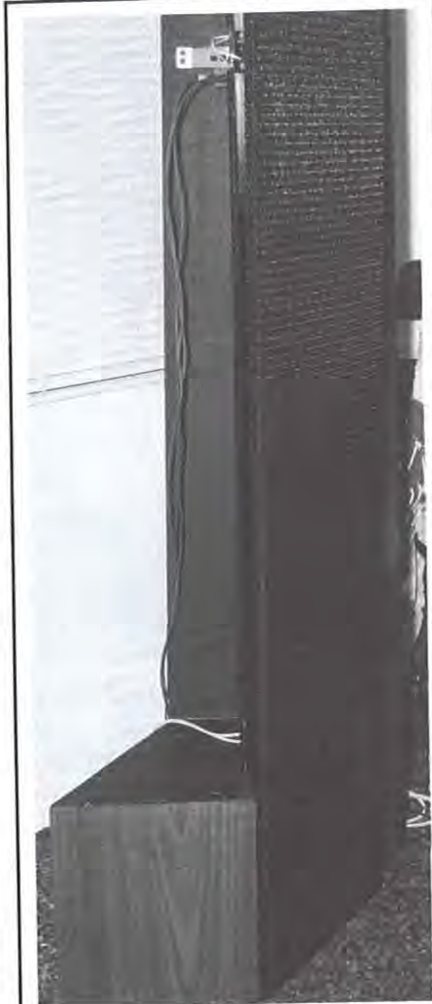

PHOTO 2: A peek around the inside edge of the speaker.

PHASE CANCELLATION. Phase cancellation at low frequencies is the biggest problem with obtaining high output from ESLs. ESLs are usually used as dipoles, i.e., they are free to radiate in both directions. The speaker's pressure waves leak around its edge to the other side. When this occurs, the pressure wave magnitude is reduced, thereby reducing output.

The "leak's" seriousness is determined by how far the air must travel and how much time it has to get there. Distance is reduced as the driver gets smaller, and time is increased as the frequency is reduced. Hence, small speakers suffer severe low frequency losses. These losses start when the sound's wavelength is about twice the minimum dimension of the speaker and the output falls quite dramatically with lower frequency.

Imagine that the ESL is a canoe paddle and the air in the room is a bathtub full of water. If you put the paddle in the water and move it rapidly back and forth (high frequency sound in the ESL), you get big waves (high output in the ESL). But if you move the paddle very slowly (bass frequencies in the ESL), the water has time to travel around the side of the paddle and cancel most of the wave energy, hence there are almost no waves in the water (low bass output from the ESL).

CONTROL. We can control phase cancellation in many ways. Most magnetic drivers are simply placed in some type of enclosure which effectively isolates the frontwave from the rear. This causes all sorts of problems with resonances and diffraction effects. One of the reasons ESLs sound so clear is they avoid the problems associated with enclosures. Placing the ESL in an enclosure does not solve the problem because its low mass results in a high fundamental resonance with rapid output loss below that.

Other solutions are to increase driver size, increase excursion at low frequencies, or increase radiating area at low frequencies. Since one of my goals is to keep the size small, increasing it is unacceptable. Increasing the radiating area at low frequencies again requires us to increase the size or give up SPLs, both of which are unacceptable. Increasing excursion at low frequencies gets us back to the problem of needing very high drive voltages.

There is no magic, the laws of physics cannot be circumvented. There is simply no known way to make a small full-range ESL with flat frequency response *and* high output. Some compromises are possible. I have a reputation as a designer of ESLs but, in fact, that's the easy part. Any *real* success of my designs is based on carefully selecting the best compromises to achieve my goals of electrostatic detail coupled with very high output. That and the difficulties in developing adequate woofer systems have occupied most of my design efforts. The importance of working out the compromises cannot be overestimated.

BASS SOLUTIONS. The first of several compromises required for high output is to avoid ESLs for producing bass. Conventional magnetic drivers are quite capable in the bass, and are much smaller. The trick is to mate them to an enclosure that does not color the sound and blends well with an ESL. High quality magnetic drivers mated to transmission line (TL) enclosures are quite satisfactory for this purpose. Such enclosures are typically rather large and difficult to build, but are more resonance free and have deeper frequency response than other enclosure designs.

TRANSMISSION LINE THEORY. A TL is a long tapered tube ("line") into which the woofer's rearwave is directed. Tapering the tube results in an infinite number of insignificant resonances rather than the two or three large ones typical of most box enclosures. Stuffing the line with damping material absorbs most of the sound energy except for the deep bass.

By the time the deep bass exits the line, it has been considerably delayed which shifts its phase so that instead of canceling the woofer's frontwave, it augments it. This extends and supports the deep bass response which by that time is falling due to reduced radiation resistance. The resulting woofer system is essentially free of audible resonances and coloration, is reasonably efficient, has linear frequency response, and has remarkably extended deep bass performance.

TLs are capable of producing the same type of clean easy sound typical of ESLs so there is a seamless match between them. While much smaller than ESLs of similar bass capabilities, TLs are not necessarily small since they must be several feet long. The exact length is controversial; I'll not get into all the arguments here. In my experience the ideal is in the range of eight to ten feet, which I chose here.

HIDING THE TL. The challenge was to somehow stuff an eight-foot TL into a size small enough for a compact ESL/TL system. At first glance this seems impossible. Where can we hide eight feet of transmission line? As can be seen from the photographs, the solution was to run the line up the side of the ESL. I also made the line more compact than usual by making the cross-sectional area smaller than usual.

Conventional TL design says the cross-sectional area of the line immediately behind the woofer should be 125% of the woofer area. This will taper to 100% of the woofer area at the port. Some English engineers believe it unnecessary to have such large areas although unquestionably they work. Because this line needs to be crammed into the smallest space possible, I reduced the cross-sectional area to near 100% immediately behind the woofer, and tapered it to 70% at the port. I reduced the damping material density from the standard ½ pound per cubic foot to about ¼ pound to compensate for the reduced area.

If you choose a reasonably small woofer, the line can be quite narrow, and you can use it to mount the ESL which will need some kind of support in any case. Added benefits are that the rearwave of the ESL must travel around the side of the TL so the problem of phase cancellation is reduced, and you can use the TL as a beam splitter to improve casual dispersion characteristics which I will discuss shortly.

CROSSOVER LOGIC. The bass cancellation problem could be avoided if the ESL were crossed over to the woofer at a high enough frequency (several kHz, depending on size). However, crossovers are fundamentally evil devices and listening tests demonstrate that the ear can detect the effects of even the best crossovers as the crossover frequency rises above 500Hz. On the other hand, my tests produced no evidence that the ear can detect well-designed crossovers if they are used with excellent woofer systems below 500Hz.

Of course, the biggest problem with high crossover points is that magnetic drivers, particularly woofers, are simply incapable of high quality midrange sound reproduction. After all, isn't that the reason we are building ESLs? The larger the ESL, the lower it can be crossed over. This design is fairly small, but we can still cross over to the woofer as low as 550Hz if we use some modest equalization to support the midrange to that level. This crossover point is low enough, and the woofer system is good enough that audible problems with crossovers and the limitations of woofers operated into the midrange are not a problem. The crossover greatly helps the problem of phase cancellation as does using the TL as a baffle to increase the sound wave path, but neither completely resolves the issue.

EQUALIZATION. Electronic equalization is needed to boost the frequencies in the range from 500Hz to 5kHz. This equalization is on the order of 7dB, moderate enough for us to still attain very high SPLs with currently available drive voltages. Please avoid the technofreak gut reaction of omitting this small bit of electronics in the interest of purer sound.

The electronics are extremely clean, and if the ESL is not equalized it will have that thin, bright, unnatural sound so typical of most ESLs. This is because you will adjust the woofer to the ESL in such a way as to have a full sounding midrange. But if the ESL is unequalized, the low range of the ESL will be markedly attenuated due to phase cancellation. When you adjust the levels for a full midrange, the upper regions of the ESL will be exaggerated. The net result will sound much as though you had turned up the treble on a preamplifier. In short, the equalization is essential, don't omit it.

SPACING. Diaphragm-to-stator spacing is critical for high output and must be carefully selected. Larger spacing offers potentially greater output, but requires more voltage as previously discussed. Smaller spacing produces higher outputs for a given set of voltages, but arcing occurs more easily and acoustic coupling becomes a problem.

Acoustic coupling occurs when the diaphragm is driven into the stator by sound waves from the woofer and often exaggerated by room resonances. At high SPLs, you can see the ESL diaphragms move by observing your reflection in them. If you turn off the ESLs and only operate the woofers, they still move, proving that the air in the room is driving the diaphragms. If the room has large resonances, such acoustic coupling can be a major problem. I chose 68 mil spacing because it maximizes the output that can be obtained with 7kV drive systems and arcing is rare. This dimension is usually wide enough to prevent problems with acoustic coupling unless your room resonances are horrible.

PHOTO 3: Speaker with grille removed.

OUTPUT DETAILS. Finally, your careful attention to a number of little details will add up to improved output. Each individual factor may not seem important, but when combined, they make a significant difference. This reminds me of the first rule of lightweight backpacking: "Pay attention to the ounces and the pounds will take care of themselves."

The small quality factors include:

- Narrow insulators since they do not produce output but take up valuable limited space
- Thin glue bonds so the diaphragm-to-stator spacing is not needlessly increased
- Closely spaced stator wires or holes to achieve high field density
- Careful diaphragm preparation to produce uniform surface conductivity to avoid output voids anywhere on the speaker's surface
- Develop the highest possible diaphragm tensions so maximum polarizing voltage can be used
- Run the polarizing voltage as high as practicable
- Use high power amplifiers and high turns ratio transformers for maximum drive voltages
- Keep interconnecting wires separated to minimize stray capacitance
- Build highly directional cells to concentrate output energy in the first arrival wave front
- Listen in a spot close to the speakers so the sound energy is not dissipated before reaching you.

ESL DIMENSIONS. The free-standing ESL's minimum size is determined by the wavelength of the lowest frequency we wish the ESL to produce. With the techniques above, we can use a minimum ESL dimension of only 12 inches and still produce SPLs in excess of 100dB. If we want to be able to hear the speaker in both standing and sitting positions, be able to produce very high SPLs, and have some place to put the TL, it must be taller than 12 inches. Fortunately, height does not take up floor space, the main problem with speaker size. A tall, thin speaker can be very attractive and also have superb sonic performance.

DIRECTIONALITY. I invented a smoothly curved free-standing wide-dispersion ESL and have done much testing and comparing of curved cells and flat (planar) cells. Despite the perfect dispersion characteristics of curved ESLs, I consider the planar cells superior. Therefore I specifically designed my system to be extremely directional. Most audiophiles seem to desire wide dispersion, because they apparently believe they must be able to listen to their system from almost anywhere in the room and have it sound wonderful. Unfortunately, the laws of physics do not allow this.

Wide dispersion speakers are unavoidably compromised in several ways, the most important of which is the ability to resolve detail. Remember your first headphone experience? There may have been faults, but you were surely impressed by how clear and detailed they were. Why are even poor headphones nearly as detailed as the best loudspeakers? This mostly has to do with room acoustics.

Consider the wide dispersion speaker. It sends sound directly to you, but simultaneously bounces sound off nearby walls and objects which then reaches you after a very slight delay. This delay is too short for the ear to separate it as an echo. The audible result is that this delay "smears" the detail and affects the frequency response by phase cancellation and augmentation.

Headphones avoid room acoustics. Highly directional speakers barely excite room acoustics. Furthermore, they get their sound to your ears *before* exciting room acoustics, and then after a considerable delay, you finally hear some room acoustics. Your ear can easily tell the difference between the direct sound and the delayed sound with the result that the sound is much more detailed than any wide dispersion speaker can be.

SPL. Sound pressure levels are subjectively much higher in directional speakers. With an SPL meter I have measured planar and curved ESLs with the same dimensions, side by side with the same drive amp. Both registered the same loudness. However, the planar sample subjectively seemed much louder and needed a higher woofer drive level for the system to have subjectively linear frequency response. I believe the meter was registering the total energy in the room, while psychoacoustically, the brain was responding to the first arrival wave front.

The wide dispersion cell was radiating only a small percentage of its energy toward the listener as a first arrival wave front, while sending the largest percentage away to produce room reflections. The directional cell was radiating virtually all of its energy as a first arrival wave front therefore seeming louder. We need more studies in this area to precisely identify this phenomenon, which doubtless exists.

Planar ESLs project a much more realistic and believable image than wide dispersion types. The image from such a speaker has often been compared to a laser holograph. When listening to this form of ESL you will be able to visualize the stage with incredible detail in three dimensions (if the recording has been done in true stereo). If you have experienced only standard wide dispersion speakers, the above statement may seem akin to advertising hype. However, once you have heard a planar ESL for comparison you will understand.

DIMENSIONS. Directional speakers are phase coherent. The sound does not seem artificial since it doesn't appear to come from the speakers, but rather floats between them. Wide dispersion speakers by contrast create an image that is diffuse and spatially ill defined. This sound seems to come *from* the speaker (although the best ones have a transparent quality that makes the sound seem to be coming *through* them). When the sound comes from the speaker, your mind seems to be able to tell that the image is artificial and two, rather than three dimensional. When further confused by all the room reflections, the image simply isn't precise enough to convey much of the third dimension.

This can be a two edged sword however. If your source material is only recorded in two dimensions, then neither type will transmit a three dimensional image. A good example of this is the typical recording studio that uses a single microphone to record a singer and then "pans" that signal to "center stage." With only one microphone, your ear lacks the clues necessary to determine the third dimension, and no amount of artificial reverberation can change that.

On the other hand, a simple concert hall recording done with just two high

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quality microphones will produce amazingly three dimensional images. The pop singer recorded with one mike and loaded with artificial reverb will sound bloated and as though she is singing inside a 30 foot pipe, while the opera singer recorded with two mikes and no artificial reverb will appear to have a voice of normal size inside a concert hall.

Should we blame a speaker that is accurately reproducing poor recording techniques for the unnatural image of the pop singer? Or should we use wide dispersion speakers that are incapable of precisely reproducing the recording so that the recording faults are not so obvious? You might want to use the wide dispersion speakers on the pop singer, but you would then sacrifice the superb realism offered by the directional ones when good source material is available.

BEAM SPLITTER TECHNOLOGY. For casual listening and background music, superb imaging is not necessary and the compromises involved in wide dispersion speakers are not a problem. At the same time, wide dispersion is highly valued so you can use the room freely and hear the speakers acceptably everywhere. Planar dipole radiators have very poor dispersion. We need a speaker with perfect imaging for serious listening, and wide dispersion for casual listening that simultaneously does not harm the image at the focal point ("sweet spot"). The two seem mutually exclusive, but my design incorporates a novel idea to solve this dilemma.

A dipole sounds poorly off axis because the highs are lost. So long as you are in the main or rear reflected beam, the sound is acceptable, but these beams only cover very narrow areas. The rear beam from a dipole radiator does not harm the image since it has long delay times and is mostly decayed by the time it reaches the focal point. Therefore, the problem could be solved if we had a multitude of rear beams going in many directions so we would be in a beam no matter where we were in the room, while at the same time being careful to avoid directing any of the beams into the focal point.

To test this theory, this speaker uses the TL's vertical column's shape as a beam splitter to reflect the ESL's rearwave in three different directions. None of the beams intersects the focal point. This beam splitter is much like—dare I say it—a Bose speaker, except that it does not influence the focal point.

REFLECTIONS. Listening tests revealed that the three beams produced by the beam splitter produced much better tweeter beam coverage than the conventional dipole's single beam, although admittedly some voids remained. Dispersion covered a full 180 degrees. Interestingly, once you are distanced from them about four times the speaker's width, they sound about as coherent as the typical wide dispersion speaker at a similar distance.

I designed this system with only two extra reflections, yet this concept worked well. Additional work in this area utilizing curved or multiple angle reflecting surfaces could produce a speaker that has essentially perfect coverage, yet uses the highly directional beaming qualities of dipoles to *avoid* putting any of these reflections directly into the focal point which is what ruins imaging and detail for serious listening. This is an exciting development that offers a real solution to the compromises and controversy surrounding the dispersion issue. Many of you will undoubtedly expand this idea. I would appreciate hearing news of your results.

Finally, even wide dispersion speakers have only one sweet spot. It is exactly equidistant between the speakers. Anywhere else is a compromise of phase and image coherency because the sound will be arriving at your ears at different times from the different channels which is certainly not what occurs when you hear live music. You can get away with it with wide dispersion speakers because their phase coherency is so poor you can hardly tell the difference. Because I don't like to compromise performance, I chose planar cells. They are also much easier to build than curved ones.

COST CONSIDERATIONS. Cost was not a design restriction, hence this is not an inexpensive project. However, from the standpoint of quality sound versus money these speakers are a bargain. The ESLs are quite cheap; you should be able to build them for well under $100. However, you can expect to spend at least $200 for the TLs when you consider the cost of materials, drivers and fancy finish work. The added costs are in grille cloth, connectors and miscellaneous hardware. The prototypes cost around $400. Associated electronics (EQ, crossovers, power supplies, chassis and transformers) are costly and may match the cost of the speakers themselves. Also, you will probably need at least one additional amplifier.

ELECTROSTATIC CELL DESIGN. Before the development of modern plastics, reliable ESLs were difficult to build. Now we are blessed with many different ways to build them. Builders have strong and varying opinions about the best way to build ESLs. I believe all ESLs of similar dimensions sound the same. For those who disagree, I offer five different construction techniques from which you may choose. All utilize quarter or half mil polyester film (Mylar) diaphragms and acrylic (Plexiglas) or polycarbonate (Lexan) insulators. The main differences are in support structures and stator construction techniques.

The construction types are as follows: 1) Steel rod stators as designed and built by Barry Waldron for this project (to be published in *SB* 2/90). 2) Steel rod stators as designed by the author. Suitable plans can be found in *TAA* 4/75. This construction is somewhat simpler than Barry's design. I used 50 mil music wire spaced 12/inch.

Some modifications to my original design will make construction easier. First, you may prefer to use copper coated 1/16 inch welding rod spaced 10/inch. Welding rod is cheaper and more readily available than music wire. You can also omit the insulation, and use a heat gun to shrink the Mylar tight as will be outlined later in this article, rather than using the stretcher specified in the original article. It would also be a good idea to use some conductive paint to improve the diaphragm contact point. Rather than using a clock gear to space the wires, use a long piece of threaded rod as Barry outlines in his instructions.

3) Insulated tensioned wire stators called "A Sheathed Conductor ESL" by David Lang (*SB* 6/88). 4) Perforated aluminum stators similar to those originally described in my *SB* '80 articles, but modified for more reliability and easier construction. 5) Perforated plastic stators by Ronald Wagner and described in his book *Electrostatic Loudspeaker Design and Construction* (Tab Books No. 2832).

All the designs have various advantages and disadvantages. Remember that in the following comparisons, all critical dimensions will be the same for all cells. Specifically, the diaphragm-to-stator spacing will be about 68 mils (63 mils for the insulators and 5 mils for the glue), and the overall size of the cells will be 13 by 36 inches regardless of the construction technique used.

To aid you in choosing the construction method best suited to your needs, I offer my observations on them. Some will disagree with my comments, but they are an accurate report of my well controlled testing experiences. Briefly, the sound *quality* will be identical for all the cells. The differences are in the *quantity* of sound (cell output), ease of construction, and cost. Unquestionably, perforated aluminum cells are the cheapest and easiest to build. Mr. Wagner's perforated plastic cells are the most expensive and difficult with the lowest output. The various wire types lie somewhere in between.

STATOR INFLUENCES. Output at a given combination of voltages and diaphragm-to-stator spacing is essentially a function of electrostatic field density. Field density is directly affected by how far apart the conducting parts of the stator are. In other words, highest output will be obtained with wires that are close together in a wire stator, or tiny holes in a perforated one. The point of diminishing returns is reached when the distance between the conductors approximates the diaphragm-to-stator spacing.

Obviously then, the ideal stator for a diaphragm-to-stator spacing of 68 mils will be wires about 1/16 inch apart, or 1/16 inch holes. This specification is constrained by three factors. The optimum percentage of open area is about 42%, the thickness of the stator, and the physical strength of the cell. It is easy to see that for 1/16 inch spacing, the wires should be about half that diameter, or 1/32 inch. This would give 50% open area, a thin stator, and very high efficiency.

However such small rods are not stiff enough to avoid sagging between insulators. Tensioned wire with the recommended insulation is too thick to maintain the required 42% open area. Perforated metal with 1/16 inch holes on 3/32 staggered spacing is ideal, but is neither readily available nor inexpensive. So as usual, compromise is in order.

Stator thickness is important, particularly in perforated designs. A thick stator with small holes will be seen by the air as having "tunnels" rather than "holes." Tunnels have resonances. A thick stator causes distressing Helmholtz Resonator effects. Stator thickness should not be greater than the spacing between conductors.

IDEAL DESIGN? You can judge for yourself how closely the various designs offered approach the ideal. You may have to modify your ideal selection based on cost and construction effort. The best stator of all has not yet been built to my knowledge. If I didn't already have a fine set of speakers, I would try building a tensioned wire stator using medium-sized tined or silver coated copper wire spaced 16 to 20 per inch. This would offer excellent charge density with smooth rounded wire to reduce corona effects.

If I desired an insulated stator, I would use magnet wire which would offer a thin, but high quality film of insulation. The general design offered by David Lang would be a good starting point for such a stator design. If you build such

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represented by three different loss levels (Q_L of 3, 7, or 15). Deriving the parameters you ask for using this situation gets much more complex, and involves substituting various pole/zero coefficient sets into transfer function equations. My advice would be to rely upon one of the Thiele/Small programs currently on the market, such as Bob Bullock and Robert White's BOXRESPONSE. It is menu driven, easy to use, has graphic output, and is reasonably priced at $50 from Old Colony Sound.

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your records and turntables pour out. Some records are not playable with this system unless you include a steep LF-garbage filter. But that is a very different story.

ACKNOWLEDGMENTS. I thank *Electronics and Wireless World* for permission to quote *Figs. 1* and *8* and Philips for permission to reprint the schematic. I owe my wife, children and friends thanks for their support and patience. Continuous low-frequency sine waves at high SPL are a demanding experience.

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COMPACT ESL/TL

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a speaker, I would appreciate hearing about the results.

John Sutton has built a variation on David Lang's design. Using Lang's "egg crate" plastic stator support structures, he glued aluminum 16-wires-per-inch window screen to them rather than wrapping them with wire. It doesn't surprise me that John reports excellent results from this technique and states that the efficiency is comparable to my perforated metal designs.

John has had difficulties attaching the

screen to the egg crate with epoxy. He advises builders to lay out a length of aluminum foil on a flat surface. Fill a syringe with acrylic solvent. Place the egg crate on top of the precut screen. With a continuous motion, inject solvent across every square on the gridwork. Weight it down and wait 24 hours. This welds the screen to the plastic that was softened by the solvent. Be careful, the fumes from two ounces of solvent spread out over an area can be overwhelming.

NO MAGIC. If you are beginning to get the idea that there is no magic to ESLs, you are right. ESLs are such simple predictable devices they can be built in almost any way imaginable and still work splendidly. I have no strong personal preferences so long as the cells are highly efficient, since my main concern is high output.

Unless you are a perfectionist or just want to experiment, I recommend you build the cells of perforated metal. This method is cheap, lightweight, quick, easy, has high output, and the completed cell is only a trace over ⅛ inch thick. While not the most efficient design possible, the efficiency difference between it and the theoretical best is around 1dB and is not audible except in direct A-B tests.

If you are an absolute perfectionist, I refer you to one of the close-spaced wire construction types. The rest of us will be completely satisfied with perforated metal cells. Their construction is outlined in the next issue of *SB*.

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