A Three-cabinet suspended design | All about electrostatics

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SPEAKER BUILDER

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SPEAKER BUILDER

An Electrostatic Speaker System

Part 1

by Roger R. Sanders

Since the publication of my speaker design in *The Audio Amateur* (Issue #4, 1975, p.18), hundreds of readers have contacted me and scores have built speakers. From this and from continued investigation on my part several new designs have been built and tested and many small bits of worthwhile information have been learned. The purpose of this series of articles is to make it possible for the average audiophile to construct his own speaker that will exceed the performance of the finest commercial systems.

I shall discuss theory, construction, and custom tailoring. If you build the proven design without modification, I can virtually guarantee you superb results. I'll present various modifications to allow for individual preferences, but all modifications have been tried and studied and I have chosen the best combination of compromises for the "ultimate" system; modifications will degrade performance in one area or another.

Electrostatic loudspeakers (henceforth called ESL's) offer improved detail and clarity compared to conventional dynamic loudspeakers. The reasons for this are clear. Essentially, the dynamic loudspeaker has a great deal of mass compared to the air it is driving, while the ESL has essentially no mass compared to the air it is driving. This offers much better transient response; more important, no resonances are present above the ESL's fundamental resonance because the speaker is air damped.

Sonically this means the sound is very smooth as well as detailed. The ESL is driven over its entire surface, rather than at just one point as in a dynamic speaker; therefore the driving surface is scarcely distorted. Because of the lack of moving mass, the driven surface response is exceedingly linear and therefore essentially perfect frequency response should be available from the system.

DRAWBACKS

Well, it certainly sounds good; there must be a catch or else everybody would be using it. There is a catch—in fact several. To understand one must understand the speaker's working principle. Unlike the magnetic forces that drive a dynamic speaker, the ESL is driven with electrostatic attraction. This is the force you feel when you run a comb through your hair on a dry day and feel the comb attract the hair on your arm or have little bits of paper stick to it.

The force is developed by high voltages (problem #1), and it is very weak (problem #2), it is only available across very short distances (problem #3), and tends to migrate across the surface of the charged object (problem #4). Electrostatic force decreases with the square of the distance which causes non-linear motion (problem #5).

We can take a thin piece of non-conductive film such as the cellophane found around cigarette packs, and place several thousand volts on it. It will have an electrostatic force if placed within a few thousandths of an inch (hereafter called "mils") of another object. If that other object is conductive, like a perforated metal plate, a voltage (hereafter called "charge") can be easily placed on it or removed from it by an audio amplifier. If the non-conductive film (hereafter called diaphragm) has 2000 volts (2kV) positive on it and the amplifier is causing the perforated metal plate (hereafter called "stator") to have 3kV negative charge, then the diaphragm is going to be strongly attracted to the stator. It will be more attracted to a 3kV negative stator than to a zero volt one. If our stator is changing voltage as directed by our audio system amplifier, then the diaphragm will move back and forth and you will hear music as the air moves through the holes in the stator.

HIGH VOLTAGE

The principle is simple, but the solution to the problems are not. Let's examine the problems and possible solutions.

The first problem is that we need high voltages. This means the speakers have to be built with insulation in mind and some safety precautions are needed. Conventional audio amplifiers generate only approximately 100 volts of output swing (peak to peak), and we need several thousand volts. The diaphragm voltage is reasonably easy to develop: we used about 2kV and essentially no current is required. An easy way to get this voltage is to connect a surplus copy machine power supply to the diaphragm.

The amplifier voltage problem is usually solved by driving the speaker through a transformer with a high turns ratio in order to step up the voltage. Transformers don't really like this because the speaker does not draw current: electrically the transformer sees the speaker as a capacitor. This makes for problems with transformer resonances, goofed-up frequency response, and instability in some amplifiers. Good transformers of this type are also rather expensive.

Several people have tried to build a high voltage amplifier directly connected to the ESL stator. These are not without problems, the biggest one being instability (see my article in *The Audio Amateur*, issue #1, 1976, p. 12, and David Hermeyer's articles in the same publication, issues 2 and 3 of the 1977 series). They are also costly to operate because they are generally class A devices, and they are quite an undertaking to build. With the correct transformer, I believe a transformer coupled system with a conventional amplifier is still the best compromise. More discussion of this later will make my reasoning clear.

SHORT FORCES

The second problem: the forces are small; the third: they are available only across very small distances. It therefore becomes impractical to drive the diaphragm over large excursions, which severely limits how loudly the speakers will play. The frequency spectrum of music is such that a great deal of energy is needed in the midbass and lower midrange (100-500Hz by my definition). This is particularly unfortunate because also in the lower frequencies we run into problem #6, phase cancellation or the tendency for the sound pressure levels (hereafter called SPL's) to decrease even though the diaphragm motion is linear. This is caused by "leakage" of the pressure waves from one side of the speaker to the other.

To demonstrate, pretend a canoe paddle is the diaphragm and put it into a tub of water and pretend that it is air. Move the paddle rapidly back and forth in the water and you get big waves (loud high frequency sound). Now move it very slowly the same distance back and forth: you get little waves or none (weak bass). You can see the water has more time to move around to the other side of the paddle and cancel out the pressure waves at low frequencies. The same is true of an ESL and air.

PHOTO BY REG WILLIAMSON.

Photo A. The author's system including two transmission line woofers with KEF drivers and four 2'x3' electrostatic panels. The speakers are driven by two stereo amplifiers with electronic crossovers and equalizers.

FIG. I

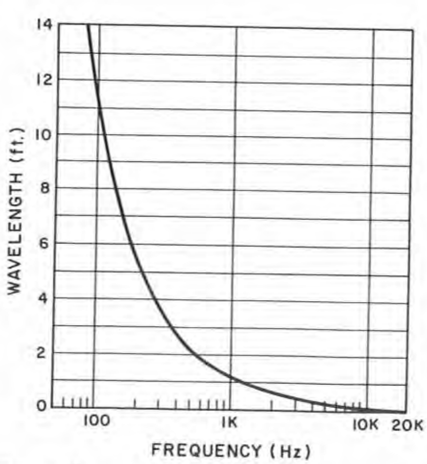

Fig. 1. The wavelength of sound versus frequency.

To compensate one can equalize the bass and make the speaker go through large excursions, which is difficult to do because of the weak forces, small distances, and large voltages required. Essentially the compromise here is that you get bass at the expense of SPL's. Alternatively, we can increase the speaker area. This works well up to a point; after all, if the speaker completely seals off the end of the room, no air can get around it. In free space, the speaker would have to be at least 30 feet across the smallest dimension to reproduce 30Hz linearly—see the sizes required in *Fig. 1*.

Not only is it impractical to make such large speakers, but they are also very difficult to drive: the load they present to the amplifier and transformers (if used) becomes unmanageable. Imaging also becomes a problem with the sound arriving from such large areas. The most practical way to get the bass response required is to use conventional dynamic woofers. A *good* woofer in a good enclosure (either a transmission line or a large horn system) can be made to sound clearly superior to a full range ESL in direct A-B tests.

WHICH IS BETTER?

Now, I realize that comment is going to make the "techno-freaks" say I am crazy: a crossoverless ESL just has to be superior to a hybrid system. Well, "techno-freaks" generally don't have hands-on experience and so aren't realists; I know, I used to be one. The point is, just because theory says something should be better doesn't mean it *is* better.

I can't tell you how much time I have spent with readers who insist on operating the ESL's full range or at least down to 100Hz because "it should sound better." It is *not* better. I have demonstrated in A-B tests on several occasions that the full range system is inferior to the hybrid system. Tests were done with the ESL equalized to achieve reasonably linear bass response to about 70Hz (one just can't get a dipole of this design to produce really *deep* bass). I used transmission line woofers rolled off at 70Hz to approximate the ESL response, alone with 18dB/octave crossovers with an effective crossover point at 400Hz. I matched levels with an SPL meter.

All listeners were clearly biased in that they expected the full range ESL to easily outperform the hybrid system, particularly with regard to mid-bass detail and clarity. At no time during the test were the ESL levels so high as to produce obvious distortion. The test results converted the listeners without question to thinking the hybrid system was clearer and more at ease than the full range system. Of particular interest was the fact that the critical mid-bass/low midrange was actually clearer with the hybrid system than with the ESL operated full range. The logical question is, "Why?"

It's difficult to be certain, but my best guess is the ESL diaphragms are being driven so far that the diaphragm is changing tension significantly and in a non-linear fashion, and also that the amplifier is being asked to deliver tremendous voltages which it cannot easily do. This is not to say the full range ESL was not good; it was very clear and detailed, considerably more so than conventional box speakers. The point is that if the woofer system is done right, you can have your cake and eat it too—you *can* have clear bass and high SPL's using a hybrid system.

BIG PICTURE

I must emphasize the term "system." I have spent nearly as much time working with woofer systems as I have with ESL's. They are equally important. Crossovers are also important. You can't take an iron core inductor, passive, high level, 12dB/octave, conventional crossover and make a clean hybrid system: you must use "electronic crossovers" at 12dB/octave or, better yet, 18dB/octave and bi-amp the system. You can't take a little, boomy, cheap "woofer in a box" and get a good hybrid system, either; it really takes transmission lines or horns to do the job.

Now, this doesn't mean that none of the above will work. I have had readers who listened only to chamber music or gentle popular music and were ecstatic over the sound of their full range systems, but they didn't need deep bass or high SPL's. Others are finding so much improvement over their conventional systems even when using poor woofer systems that they are quite satisfied to continue. But most readers are interested in the best possible reproduction, and they will get such reproduction if they are willing to listen to experience, do what has been proven to work, and not let their "techno-freak" ideas stand in their way.

My personal standards are severe: I want to be able to play my live concert recordings from uncompressed master tapes at "row A" levels, with no apparent distortion, in a system I can afford and would be able to put in my living room. I require SPL's in excess of 103dB at my listening location four meters from the speakers. Frequency response must be essentially linear from 20Hz to 20kHz. I find my system is adequate to these tasks; if you wish to make modifications, please do, but the suggested system is proven.

BOXED ESL'S?

I tried one other way to get full range from an ESL: I enlcosed it in a box to isolate the front from the back and prevent low frequency cancellation. This did not work. The enclosure produced all kinds of colorations from resonance effects, but worse still, the bass was not there. After some head scratching and measurements I realized the problem was the ESL's fundamental resonance. Because the ESL was rather small (about 18" x 34"), the resonance was at about 300Hz. Without the mass of a conventional dynamic woofer, the system was simply reaching fundamental resonance and the output was falling rapidly below that.

It appears it is not possible to achieve bass in a reasonably sized ESL with the use of an enclosure. This does not mean this is not a useful technique, and readers who wish to pursue it are referred to Peter Walker's famous articles, "Wide Range Electrostatic Loudspeakers," in *Wireless World*, May, June, August, 1955. The first article deals with the concept of constant charge operation which solves our problem #4 involving charge migration. The second covers enclosures for ESL's, and in the third, on loudspeaker/room relationships, Walker makes a very strong case for using the dipole radiator.

Problem #5, non-linearity of the diaphragm motion is solved by what is commonly called the "push-pull" ESL. This requires placing a second stator on the other side of the diaphragm. Now when we place voltage on one stator we place an opposite charge on the other. As the diaphragm moves toward one stator and is attracted non-linearly, it moves away from the other whose force is decreasing non-linearly in a mirror image fashion, the forces on the diaphragm are then linear.

BIPOLAR BEHAVIOR

Large planar speakers are highly directional. This is a physical characteristic of large areas whose smallest dimension is as large or larger than the wavelength of the sound being reproduced

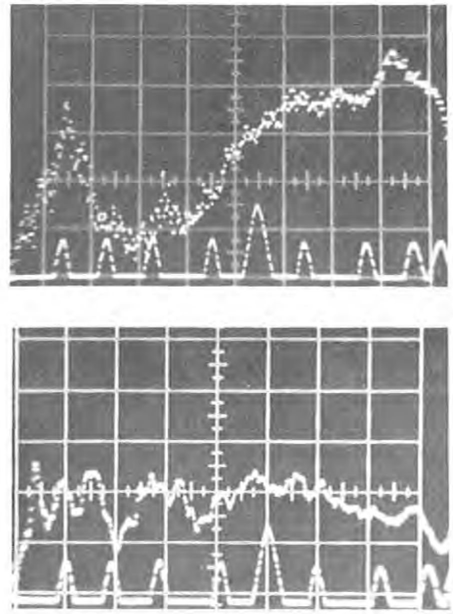

Fig. 2. Top photo, a storage oscilloscope trace of what ⅓-octave pink noise looks like fed into a real time analyzer measuring the unequalized response of Sanders' ESL panels indoors with a mike at five meters. The lower photo is the effect of an equalizer on the panels with a crossover at 120Hz. The large baseline marker in both photos is 1kHz, and the horizontal markers represent 5dB.

(a 20kHz wave is about one quarter of an inch long). Most audiophiles believe this directionality is undesirable and therefore a problem; this point is highly debatable. There are those who believe a highly directional loudspeaker is superior to wide dispersion types. [See: J. Newman, "Dipole Radiator Systems," *Journal* Audio Engineering Society, Jan/Feb 1980; Vol. 28, Nos. 1 & 2, pp. 35-39.]

Personally, I prefer the highly directional types: they minimize room resonance effects, image better, and are easier to build. Even with wide dispersion speakers one needs to be an equal distance from both, so one must listen to music seriously at only one location in the room anyway. Background music listening off-axis is no problem because the sound bounces around the room.

The image from a conventional box loudspeaker can be described as coming *from* the speaker, while the image from really superb conventional dynamic loudspeakers and from wide dispersion ESL's can be described as coming *through* the speaker: it has "transparency." However, the sound fron highly directional ESL's is different from all the others. It appears not to be associated with the speakers at all. The image seems to float in the room; it is three dimensional, and its exact location depends upon recording techniques used in producing the source material.

Some very unnatural effects are created this way. For example, a pop vocalist recorded with a great deal of artificial reverberation and a single microphone (a monophonic recording passed off as stereo) is "panned" to the center of the sound stage. The singer will appear to be singing slightly inside a very deep 30' diameter pipe; the image will be huge and very unrealistic. On the other hand, a singer recorded in a concert hall with a pair of microphones in proper stereo will appear to be of normal size and sound entirely natural.

IMAGE, SPEAKERS & MIKES

A common complaint is that planar speakers "cause" soloists to sound 10 feet wide. This is simply not true. Planar speakers accurately reproduce the poor recording techniques commonly used. Naturally recorded music sounds natural through them. If you insist on wide dispersion speakers, you can easily make them by angling several ESL strips to each other around the imaginary surface of a cylinder. This is not completely satisfactory in that the dispersion is not uniform: each narrow cell has its own narrow beam and moving about in front of the speaker causes a "venetian blind" effect. You can minimize this by using small angles between the strips; I recommend less than eight degrees.

Robert Unterbrink and I have developed a method of forming a smoothly curved ESL cell with perfectly uniform dispersion. Patents are pending on the design, and we expect commercial development. The design of this speaker will be presented at a time when I can devise good fabrication techniques for the home builder.

Reliability has been a problem with commercial ESL's. I am pleased to say my original speakers, built in 1974, are still running fine and I have never replaced a diaphragm since working out their "bugs." I attribute this to the availability of better materials such as polyester film. I did not put grille cloth on my speakers because tests indicated this ruined their high frequency response. Foam grille didn't hurt the frequency response but messed up the phase response. I have therefore had some problems with insects getting into the speakers and causing arcing, which eventually burns pinholes in the diaphragms. I have probably several hundred pinholes, but the speakers still sound fine, and I cannot detect this has harmed their performance in any way.

I have since found some grille cloth that doesn't mess up the sound, and would use it in the future. It is a plastic fiber cloth marketed by Mellotone. While it is quite expensive, the smooth fibers do not harm the high frequency response and the weave is fine enough to keep out bugs. There is absolutely no need to use dust covers. I even sand balsa wood in my listening room and it gets into everything, but the speakers do not seem to care. Occasionally I blow out dust with compressed air or gently vacuum them, but I do this only for appearance, not for performance reasons.

LINEARITY PROBLEMS

The typical commercial ESL does not have linear frequency response even though theory indicates the diaphragm should be very linear. The reasons for this are numerous. First of all, the high frequencies have a narrower dispersion than does the midrange, which effectively makes the speaker sound

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"bright." The low frequency phase cancellation previously mentioned begins at a considerably higher frequency than you might expect. For example, the minimum dimension of a cell of my design is 24". Looking at *Fig. 1*, it would appear the wave length of a 500Hz tone would equal the speaker's minimum dimension and that the low frequency rolloff would begin there. Well, it obviously begins much higher than that: it becomes noticeable at 2kHz.

Fig. 2 demonstrates early tests with a spectrum analyzer: the frequency response (1 cm. from diaphragm center). *Fig. 4* is a composite of theory and objective measurements that I feel accurately reflects the true behavior of the ESL alone at far field (my listening location).

Fig. 5 reveals the techniques I used to flatten the frequency response. The ESL's bass is severely attenuated and is highly irregular because of phase cancellation and fundamental resonance. The best way to correct this is to simply avoid using the ESL in that region. This also makes high SPL's possible, as I discussed above.

The ESL response above 400Hz is still rising, and the system will still sound bright and thin unless something is done to correct this. With modern electronics it is possible to make a high quality equalizer that presents a mirror image depression to the high frequencies. I described this in my 1975 article, and I am sorry to say many readers felt this would degrade the high frequencies and so did not use it. The fact is the equalizer attenuates the high frequencies, but then the entire ESL section level is raised until the highs are back to normal balance. The net effect of this is that the midrange is elevated to its proper level and the sound is now properly rich and full.

EQUALIZATION: YES OR NO

"Techno-freaks" will be loth to put an equalized signal into the speakers because they believe it degrades the sound. However, there is simply no question that the system is far more natural with the equalizer, and once one hears the system with the equalizer, no listener has been willing to do without it. It adds no detectable sonic distortion.

I went to considerable effort to minimize the "modern" distortions such as TIM and SID. I discarded the

FIG. 3

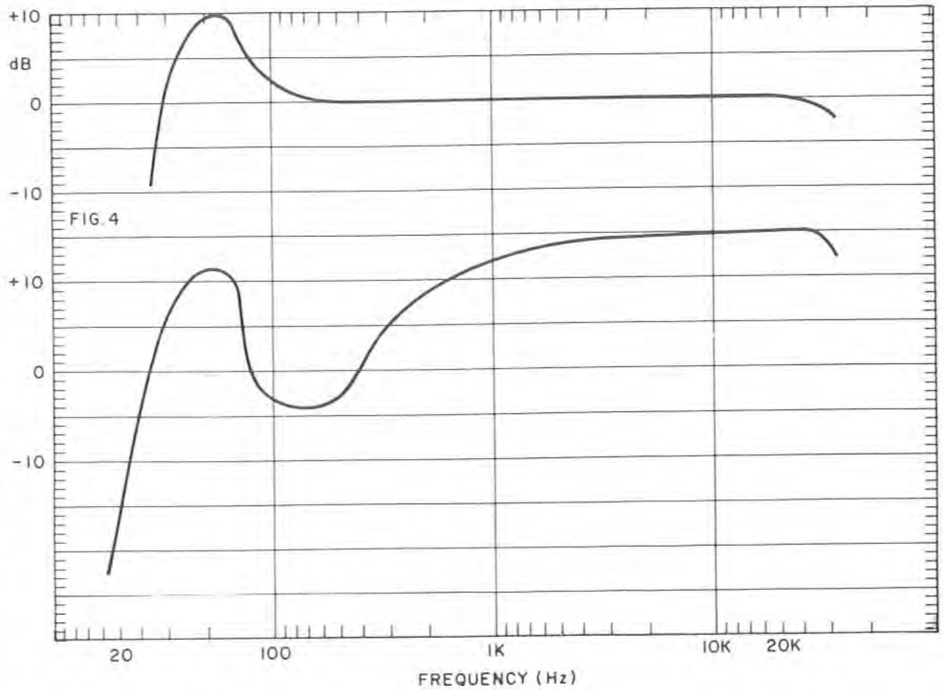

Fig. 3. Near field ESL response.

Fig. 4. Far field ESL response.

FIG. 5

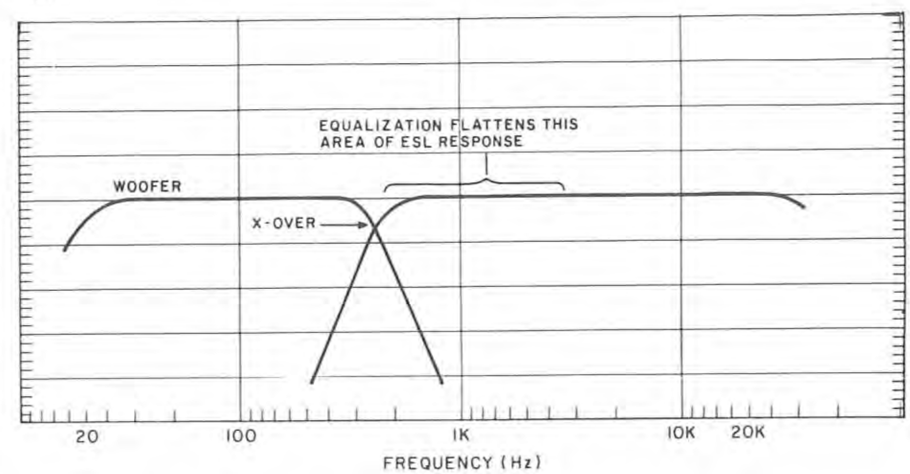

Fig. 5. Composite system response.

FIG. 6

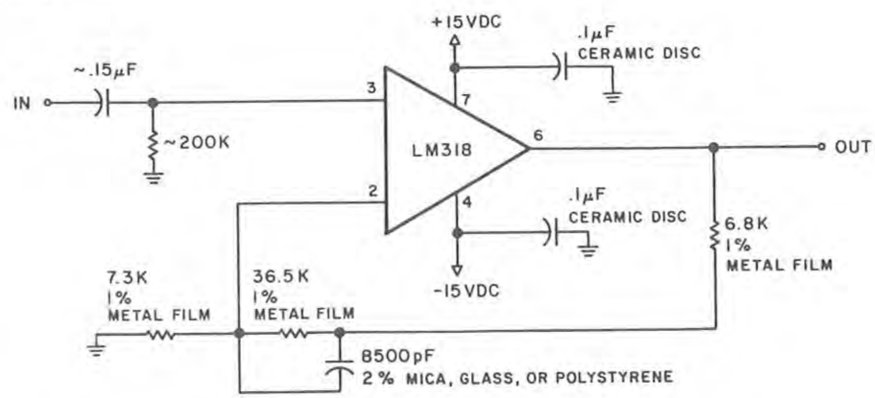

Fig. 6. Schematic for one channel of an equalizer with gain for the electrostatic panels.

earlier equalizer in favor of a much simpler one utilizing the very high performance LM318 IC, and placed the equalization in the ICs feedback loop in order to isolate it from the impedance loading effects of the associated equipment, which had been a problem in some installations with the earlier passive system. In addition, the equalization stage has 18dB of gain, making the system's sensitivity equal to a typical loudspeaker system.

Fig. 6 is the revised schematic of the eq/gain stage. For those of you who have preamp gain to spare and are able to measure electrical frequency response, I have included the schematic of a passive equalizer (*Fig. 7*) with an adjustable high frequency corner which will allow you to "tweak" it to the correct frequency response curve. The insertion loss of this is nearly 20dB, so you will probably have enough spare gain to use it unless you listen only at low levels. I personally don't use a preamp at all, just a passive attenuator for level control of high level circuits, so I had to have additional gain in my system offered by the gain section of the equalizer. *Fig. 8* shows the frequency response of the eq/gain section alone.

FIG. 7

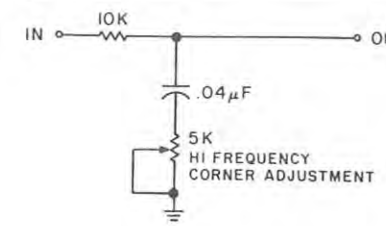

Fig. 7. A passive equalizer with 20dB insertion loss for use before the power amp driving the ESL panels.

FIG. 8

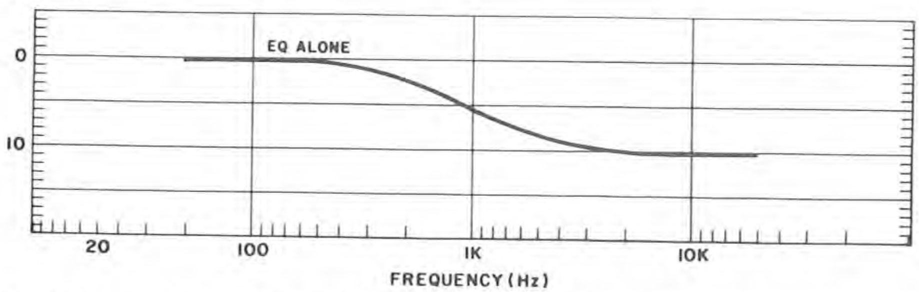

Fig. 8. Response curve of the effect of the active equalizer/gain circuit shown in Fig. 6.

CROSSOVERS

Electronic crossovers are a must. Beside the fact that they are audibly superior to passive high level crossovers, the ESLs capacitive characteristic makes it very difficult to get proper response from passive crossovers. You have several crossover choices. You can make passive 6dB/octave crossovers, but the slopes are really not steep enough even though in theory they are superior to any other type. I have used them and they work, and I have included a suitable schematic in *Fig. 9*. This, like the passive equalizer, has a large insertion loss so if you use it you had best have an extra 20dB of gain available. You will also have to "tweak" to the correct crossover points based on the im-

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pedances you are driving with it.

The Old Colony crossover kit is 12dB/octave and active, works very well and has no insertion loss. It is also very cheap, and being quite small you can build it and the eq/gain stage on the same small chassis and drive them by the same power supply. Several authors have tested crossover slopes and the general consensus of opinion is that odd order Butterworth filters are better than even order ones—in other words, each "order" in the filter is 6dB, and therefore a 6dB filter is 1st order, 12dB is 2nd order, 18dB is 3rd order, 24dB is 4th order, etc. In theory the Old Colony crossover should not be best because it is even order. However, I could detect no obvious problems with it with one exception: I could not determine the correct phase between woofer and ESL.

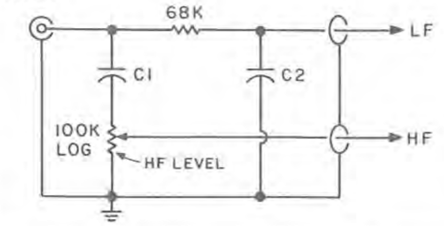
Clearly, there should be a difference, and with 18dB/octave filters there was one. The upper bass/lower midrange sounded properly full in one phase and thin and incoherent in the other phase. One phase was obviously correct. I therefore feel 18dB/octave crossovers are superior to 12dB/octave crossovers. However, the fact remains that unless you make a direct comparison the Old Colony units have no detectable problem. A complete article concerning these crossovers appears in *The Audio Amateur*, issue #2, 1972, p. 10.

I personally use crossovers by DeCoursey, who offer them in various forms and slopes. I simply bought completed boards and installed them in my eq/gain stage. They are about two inches square and cost about $40 per channel. I did not make my own because the precision components required are not readily available to the amateur constructor. (DeCoursey Engineering Laboratory, 11828 Jefferson Blvd., Culver City, CA 90230.)

PERFORMANCE

Fig. 10 is the total system electrical response with the eq/gain and 18dB/octave crossovers. Note that the correct crossover point is 460Hz. When this is combined with the equalization the actual crossover point is reduced to 400Hz which I have tested extensively and found to be optimum for this system. Please resist the urge to cross over lower: this causes a large depression in the frequency response in the 200 to 500Hz region, and the clarity

FIG. 9



	C_1	C_2
500Hz	0.0039µF	0.0056µF
1kHz	0.0022µF	0.0022µF
2.5kHz	560pF	0.001µF

Fig. 9. A passive 6dB/octave crossover with adjustable high pass gain control. Values in the chart set crossover points at various frequencies.

and detail in the bass and lower midrange are definitely *not* improved.

Fig. 11 is a block diagram of the system as well as a schematic diagram of the correct connections for transformer coupling the ESL to a conventional amp. If you want high SPL's, use a modern "super amp"—not that the speakers require a lot of power, but rather that they need a lot of voltage and large amplifiers have higher voltage power supplies than low powered ones. The amplifier should run no warmer when driving the speakers at high levels than it does when it idles. If it gets hot, that indicates you are getting DC in the output, usually because the amp is one of the DC coupled types and is getting a little bit of DC at the input from one of the crossover IC's.

Most IC's have a small DC offset, usually around .05 volts. When this is amplified, you may have a volt or so of offset in your power amp. Into essentially a dead short such as the primary of a low impedance transformer, lots of current will flow and the amp will overheat. The solution is simple: install a small capacitor between the crossover and the amplifier. For the ESL amp, .01µF is adequate. The capacitor should be a non-polarized type such as polycarbonate, polyester, mica, or glass; do not use electrolytics for coupling. If the problem also exists in the woofer amp (usually noted because the woofer moves away from its center and stays there when the amp is turned on), then use a .5µF capacitor.

TRANSFORMER MATCH

Finding suitable matching transformers is difficult. The problems are two: first, finding high enough turns ratio transformers is not easy, and second, high frequency response is usually poor. The problem with the frequency response seems to be leakage inductance in the transformer resonating with the capacitance of the ESL. This puts a 3 or 4dB peak in the response with a rapid rolloff above that. I have tested many transformers and find few of them will perform above 8kHz with ESL loads. This problem worsens with larger speakers, as the turns ratio increases, and as the transformer's power rating increases.

What you need is a transformer with both a turns ratio and frequency response as high as possible. In two years of searching I finally found transformers with 44:1 turns ratio with a frequency response of 20-50kHz. They will drive an ESL with a capacity of 2400pF essentially linearly to 20kHz. You can buy them through me—see the end of this article.

You may be able to use audio output transformers from a good tube amplifier. Ideally they should have a very high primary impedance—8kΩ if possible. Install them backwards: connect the transformer's 4Ω taps to your

FIG. 10

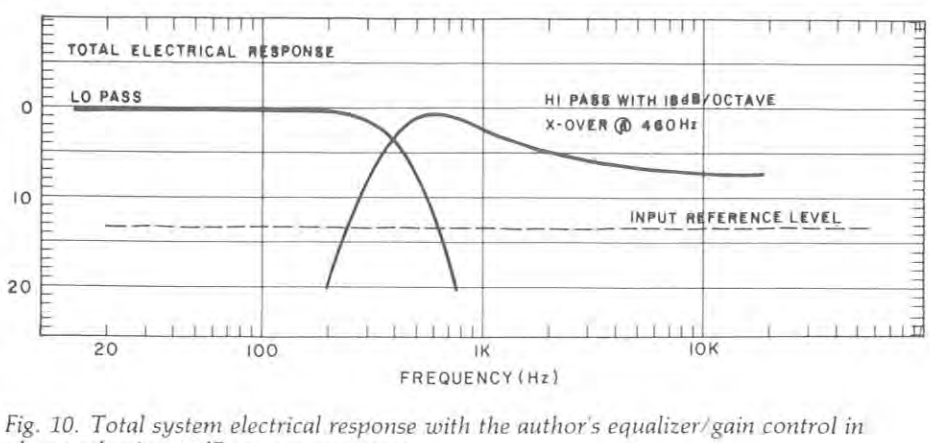


Fig. 10. Total system electrical response with the author's equalizer/gain control in place and using 18dB/octave crossovers.

amplifier and the 8kΩ taps to your stators. Test the frequency response by connecting a high impedance voltmeter (at least 10MΩ) to the 8kΩ leads and drive your amplifier with an audio generator so it puts out between 1 and 10 volts. Be careful not to get the voltage too high or you can arc your meter's guts. Run a frequency response sweep. You may see some irregularities in the area from 10kHz to 20kHz, but so long as this does not result in severe rolloff of the highs. You can consider it superb performance.

The transformer's power rating should be about 15 watts. This will take all the amplifier power you want to feed it and is small enough to have good frequency response with minimum leakage inductance. Larger transformers may work, and lower turns ratios will work, but achieving good frequency response and high SPL's becomes progressively more difficult. If you are using tubed amplifiers, try connecting the 16Ω amplifier taps to the 4Ω transformer taps; this will give you the highest voltages but sacrifice good power transfer. Since the speakers do not use power, this is no problem.

CAPACITIVE AMP LOADS

Some amplifiers may be unstable with capacitive loads. I have found problems only with a Leach low TIM amp; Crown, Williamson, Perkins, Dyna, Phase Linear, and Quad amps have all worked without difficulty. If you should have a stability problem or your amp blows fuses, try adding some series resistance: 1-10Ω seems to work OK. You may also want to try using the transformer's 8Ω or 16Ω taps; however, this will decrease your SPL's to some extent.

When deciding what amplifier to use, please ignore all the "techno-freak" ideas you may harbor about amplifiers. Several readers and I have discovered most amplifiers sound identical on the ESL's even though the same amplifiers may sound markedly different on conventional dynamic speakers. The "tube vs. transistor" controversy also becomes meaningless: transistor amplifiers do not sound "harsh" or "edgy" with these speakers. This puzzles me because generally ESL's seem to place more stringent demands on an amplifier and commercial ESL's are very amplifier sensitive.

My only explanation is that these speakers present "pure" loads to the amplifiers rather than the complex

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loads presented by the commercial units with their passive crossovers and woofer systems, often of the dynamic type. The combination of capacity, inductance, and resistance of such a load under dynamic conditions must be just awesomely complex in comparison to a simple 2400pF capacitor. The ESL also essentially requires no current, so the amplifier is working only with voltage rather than with large amounts of both. This is quite different from a conventional speaker, and is also the reason a 200 watt amplifier doesn't overload a 15 watt matching watt unit designed to do the major part of the voltage reduction, you can place a ½ watt pot across the input to allow a small amount of trimming; if it burns up, you need more resistance in R_1.

If you can get your hands on a small high voltage transformer you can place a 10kV diode in series with it to get DC. It doesn't matter what polarity you feed the diaphragm if you are using transformers. The speakers will usually take about 3kV, but they are marginally stable at that voltage and will sometimes arc, or the diaphragms will "cave in." If this happens simply turn off the power supply, go over to the speaker, and blow the diaphragm away from the stator it is stuck to. This You need only one power supply for several speakers.

High voltage test prod wire makes the best connections from the power supply and transformers to the speakers. Do not tape or otherwise hold the wires close to each other, as this increases stray capacitance; just lay them loosely on the floor. I have used common 18 gauge "zip cord" for connections and have had no arcing problems, but I don't recommend it since it is only rated for 600 volts. I like using banana plugs for connectors. Keep plenty of space between them as the voltages are high enough to cause arcing over at least a quarter of an inch. Getting shocked by the system is

FIG. 11

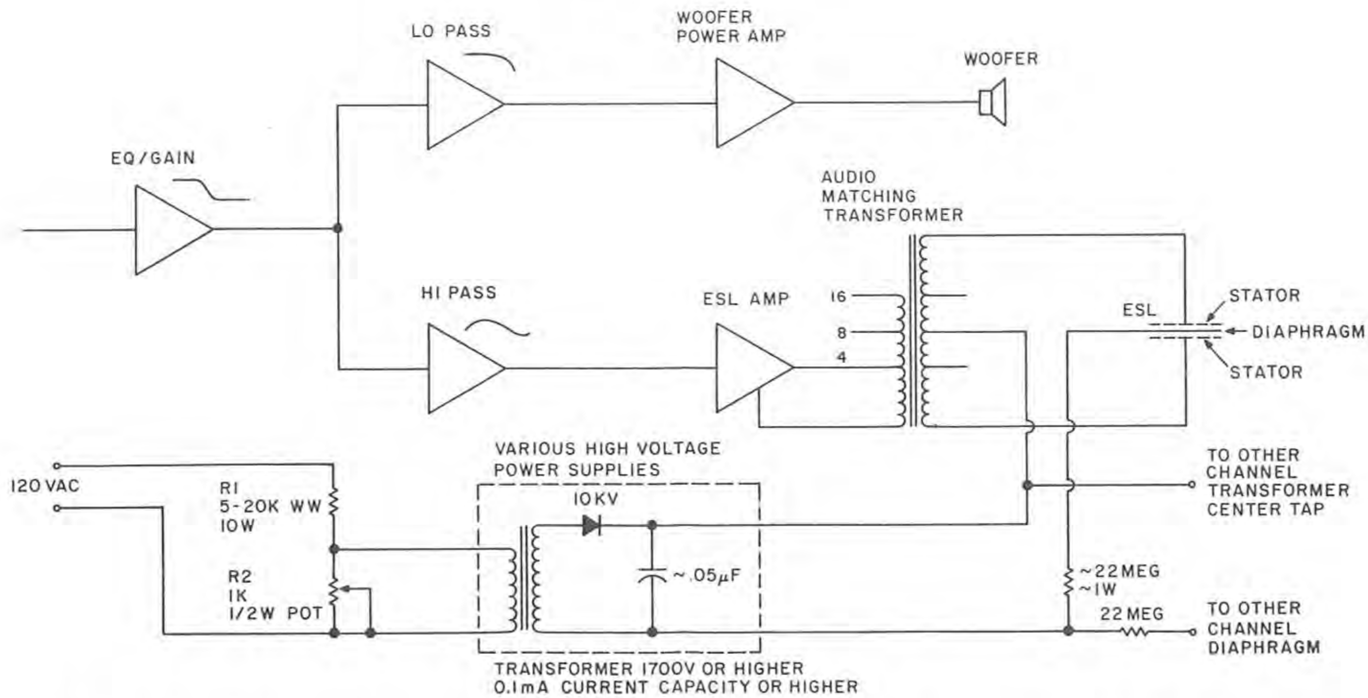

Fig. 11. Block diagram of system interconnections as well as a hookup guide for both an output transformer and a high voltage power supply. Note that each panel requires a 22mΩ resistor in series with the supply. R_1 may also be a 10 to 20W unit. R_2 should probably be a wirewound unit as well.

transformer even when the amplifier is clipping.

POWER SUPPLY

Fig. 11 includes the schematic of a typical high voltage power supply. There are several ways to approach this device. Probably the easiest is to buy a surplus electrostatic copier power supply for around $10. These are usually rated around 5-10kV and you need only 2kV, so to reduce the voltage you will have to pad the input. Generally this is done with a voltage divider at the input. If R_1 is a 10 or 20 may or may not pop a pinhole in the diaphragm; at any rate it doesn't destroy the speaker.

To be on the safe side, don't run the voltage at the "ragged edge." I find no detectable difference in SPL between 2 and 3kV even though in theory there should be. You may find you can use a flyback transformer from a television set for the supply. A small capacitor is usual at the power supply output, but I think it's unnecessary since the speaker is a capacitor. Do not omit the 22MΩ resistor in the line to each diaphragm, as this helps prevent charge migration. not lethal, but I can assure you you'll know when it happens!

DIRECT COUPLED AMPS

You may wish to build a direct coupled high voltage amplifier to drive the speakers. If so, build the high voltage diaphragm supply into the amplifier. I used to use such an amplifier but have since returned to transformers; chiefly because I finally found good ones. The DC amp is a class A device which generates a lot of heat and wastes electricity. You can achieve high SPL's with the right transformers and a conventional amplifier.

Stability is a problem with a DC amp, whose only advantage is that objectively it is considerably better than a transformer. However, the transformers I now use sound every bit as detailed as my DC amp; in fact other users have told me the inner detail seems better with transformers than with an amp! I feel this is due to subtle differences in frequency response rather than to any inherent transformer superiority, but a transformer coupled system can be just as good as a DC amp system.

THE COMPLETE SYSTEM

My recommended and proven system consists of:

1. A pair of ESL's 2'x6' in radiating area.
2. A pair of transmission line woofers.
3. A pair of stereo power amplifiers, one for the woofers and one for the ESL's.
4. A pair of equalization/gain stages.
5. A pair of electronic crossovers.
6. A pair of matching transformers.
7. A high voltage power supply.

I constructed the electrostatic cells as large cells rather than small ones because I didn't want to have to build a bunch of little cells and wire them together. Two 2'x3' cells are used for each channel, stacked and mounted into a narrow wooden frame with both sides completely open. The system in the photographs has wire stators, but for general construction I recommend perforated aluminum. I'll discuss both construction methods later in this series.

FOR THE LOWS

The woofers are KEF B-139 drivers mounted in 10' transmission lines. I have tried many other types of woofer systems, including bass reflex, acoustic suspension, infinite baffle, semi-infinite baffle, and horn. In my opinion only the transmission line and the horn systems were able to produce adequate bass; only they could make the sound coherent so you could not detect the woofer's presence in the system. The entire sound appeared to have the quality of the electrostatic when the woofer system was operating correctly.

An often overlooked point is that the woofer must be in the same plane as the electrostatic. Because the crossover point is above 100Hz, one needs two

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AN ELECTROSTATIC SPEAKER SYSTEM: Part 1

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woofers for best imaging. I have used very large woofers, including 24" Hartleys, but smaller units offer distinct advantages. First, the physical size and expense of large ones is prohibitive. Second, smaller units have better upper bass response because of smaller mass. Third, the T.L. and horn systems will allow the small units to go awesomely deep. Fourth, I suspect the smaller units have less distortion because of relatively stiffer piston with less mass.

Finally, having used "sub-woofers" I feel that there is such a thing as too much deep bass. Even on master tapes essentially no musical information exists below 30Hz, but you sure can hear air conditioning noise, disc rumble, trucks shaking the ground on master tapes, etc. The KEF T.L. system goes well below 30Hz, and I often find myself using a 30Hz garbage filter to clean up the sound. Another advantage to the smaller T.L. system is it is highly efficient; a horn system is even better. I am using a pair of Williamson 20 watt amplifiers on the woofers and a 100 watt Perkins amplifier on the ESL's: the ESL amp distorts before the woofer amp does. I'll present a suitable T.L. system in the construction section of this series.

HOW MUCH?

The system's cost varies and is based more on the cost of electronics than on the cost of the ESL. ESL materials for four cells should run under $100 if you use perforated metal. The cost of frames to mount them is too variable to predict; mine were about $20. Grille cloth will cost about $12 per yard. Transformers are $35 each (from me, 1578 Austin St., Atwater, CA 95301), but you may have some lying around for free, or perhaps you can find some cheaper from a transformer company. You can build T.L. woofer enclosures for around $50 each plus the cost of drivers which may be as high as $100 per channel. Electronic crossovers can be had for about $23 a pair from Old Colony (P.O. Box 243, Peterborough, NH 03458) (plus power supply and chassis), or from DeCoursey for about $80 a pair. Eq/gain stage can be built for $30 the pair, or perhaps somewhat less.

Your largest outlay will be for amplifiers. Presumably you already have at least one to use on either the ESL or the bass. If your amp is suitable for the ESL, then you can get by rather cheaply because a bass amp is not such a problem—the Williamson amps cost under $100 from Old Colony. On the other hand, if you have something like a medium power receiver, you will probably want to use its amp for the woofers and buy a new or used "super amp" for the ESL's. A used Crown DC-300a will go for around $500, and everything goes up from there.

You will see this is no small project; it will cost anywhere from a few hundred to a few thousand dollars depending upon your innovativeness, parts on hand, and general financial condition. You can also cut a lot of corners to save considerable money, space, and time. For example, you can get by with a single ESL cell per channel. You can probably use your present speaker system for woofers. You may be able to build a DC amp cheaper than you can buy a new "super amp." You may find you can be satisfied with an ESL operated full range driven by your present system amplifier. Perhaps you can be satisfied with lower SPL's and save yourself the cost of a "super amp" by using Williamson amps throughout the entire system.

In short, you have lots of options, but unless you build the "full house" system you are going to compromise some aspect(s) of performance: you will still have electrostatic detail and quality, but you will sacrifice either SPL's, frequency response, or bass/midrange detail. In any case, you will have the satisfaction of having built your own speakers, and they *will* sound well. But by spending the time, money, and effort required to build a "full house" system, you will find the sound you can get will exceed anything commercially available; and you will have the satisfaction of having done it yourself. □

Part II of this series includes complete construction details for the ESL's and part III will detail the construction of bass systems. —Ed.

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