

Electrostatic Loudspeaker Basics, Part 2

By Matthew Lattis

The author continues his detailed look at ESLs, comparing basic theory with test results.

AMPLIFIER LOADING

This brief, initial discussion of the load presented by a transformer and speaker covers the case of a transformer with an amplifier connected directly to the primary and a speaker connected directly to the secondary. Refer to *Fig. 18's* bottom pane for a typical impedance/phase plot of an ESL load measured at the transformer primary. At low frequencies the primary inductance of the transformer is the dominant factor influencing impedance, and most amplifiers have little trouble in this region. As the frequency increases, the capacitive reactance of the speaker begins to take a more prominent role in the final impedance of the system, and the electrical phase swings strongly capacitive in this region.

Luckily, the impedance is still relatively high at these frequencies, and most amplifiers tolerate this kind of load as well. At high frequencies things become ugly as the leakage inductance of the transformer and the speaker load produce a series resonance and the impedance plummets. At this point the impedance is basically determined by whatever wire resistance is in the primary plus the secondary's reflected wire resistance. At the typically high frequencies involved, the demands for power (with music) are small, but some amplifiers are still very unhappy when presented with this type of load.

As a general rule, transformers with the highest step-up ratios are more problematic because the capacitance on the secondary of the transformer is multiplied by the step-up ratio squared when it is referred to the primary (e.g., 500pF on the secondary of a 1:50 transformer is 1.25μF when reflected to the

primary). The leakage inductance is also normally higher with higher turns ratios, which causes the series resonance at high frequencies to occur at a lower frequency. Good transformer design and implementation can help to lighten the load for the partnering amplifier, though, and I will discuss that a little later. For a more thorough treatment of equivalent circuits and transformer testing, Ron Wagner's *Electrostatic Loudspeaker Design and Construction* is a good resource.

Figures 18-23 present a variety of typical transformers and wiring configurations with no load, a 165pF load, and a 1060pF load. Electrical phase is the higher trace at 10Hz in each graph. The approximate capacitance of an ESL can be computed with equation 3

$$C = (0.224KA)/d \quad (3)$$

where

C = capacitance in picofarads

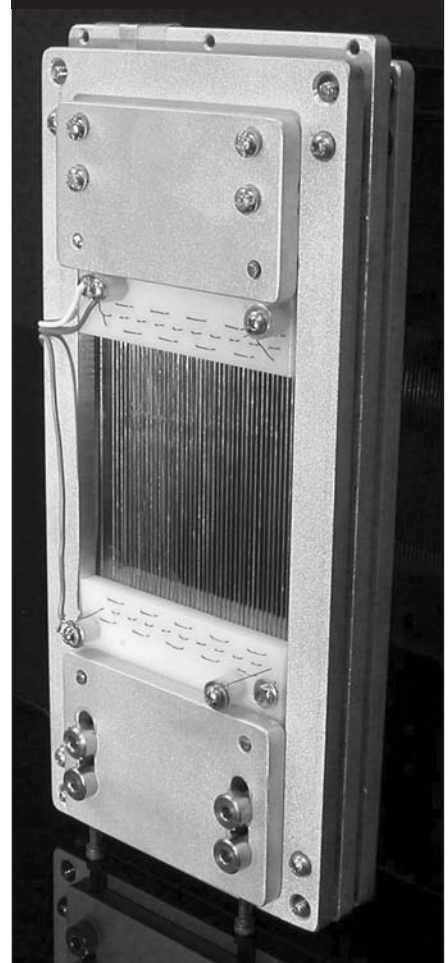
K = dielectric constant of the material between the plates (air = 1)

A = area of one plate in square inches

d = distance between plates in inches

The first transformer I will look at is a clone of the MagneTek Triad S-142A (I used a clone because the S-142A was discontinued before I started working with ESLs). Since this device was designed for use as an output transformer in tube amplifiers, it is connected in reverse when used with ESLs (the primary is used as the secondary). This model presents a few wiring options using the full primary as a secondary and various secondary taps as the primary. I tested the following configurations:

PHOTO 3: Finished unit.



Common - 4Ω:44 ratio —*Fig. 18*
8Ω - 16Ω 1:76 ratio —*Fig. 19*
4Ω - 8Ω 1:100 ratio —*Fig. 20*

Next, two toroidal models from Plitron are shown. The PAT-4133-ES is a 1:50 unit whose results are shown in *Fig. 21*. The PAT-4134-ES has a 1:75 turns ratio and is shown in *Fig. 22*. The final transformer considered in these tests is the Tranex 2-0404, which has a 1:150 turns ratio—*Fig. 23*.

A quick survey of the test results shows that the modern Plitron units provide the most extended frequency response of all the transformers tested

and are an easier load to drive when similar turns ratios are involved. When compared to the S-142A clone wired for a 1:44 ratio, the PAT-4133-ES has significantly higher impedance at high frequencies and also has a 1.1dB advantage due to its 1:50 turns ratio. In the lowest pane of Fig. 18, you can see the impedance minimum at ~18kHz and the abrupt change in electrical phase in the same region which indicate the resonance formed by the S-142A's leakage inductance and the speaker capacitance. This resonance produces a low-pass filter that limits the high-frequency response of the system.

No sign of the Plitron PAT-4133-ES's resonance is visible on its plot with the same load (a resonance is still there, of course, but it is ultrasonic and, therefore, outside the range of the hardware used). With the 1060pF load the impedance of the 1:75 Plitron PAT-4134-ES is inconsequentially lower at 20kHz than the S-142A wired for 1:44, but the Plitron unit still has a bandwidth advantage. Though the phase is just starting to swing upward near 20kHz with the heaviest loading of the PAT-4134-ES,

the actual resonance cannot be seen on this plot. The 1:75 ratio provided by the Plitron unit gives it a 4.6dB output advantage over the 1:44 of the S-142A (equivalent to nearly tripling amplifier power). When you compare the 1:75 Plitron to the S-142A wired for 1:76 with the heaviest loading, the Plitron's resonance occurs over an octave higher, and it has a moderate impedance advantage at high frequencies.

LIGHTENING THE LOAD

You can use two simple methods to make an ESL load less demanding. Neither approach will make the speaker easy to drive, but *easier* is possible without much effort and can make a significant difference if your amplifier is borderline. Both methods involve placing resistors in the circuit, so there are no detrimental phase effects.

Option 1: By dividing the speaker into smaller areas and using resistors between the transformer's secondary and the individual segments, you can produce low-pass filters that can be used to adjust frequency balance and to prevent the full capacitance of the speaker from being reflected to the

primary at frequencies higher than the crossover point. This resistance is referred to as Res in the following treatment. It is Res/2 in the schematic because each resistor sees the capacitance formed from the stator-to-diaphragm. You should use plate-to-plate capacitance with Res or plate-to-diaphragm capacitance with Res/2 when calculating crossover points.

The low-pass slope is 6dB/octave with the -3dB point occurring where the capacitive reactance of the ESL segment is equal to the value of Res. The Quad ESL-57 and ESL-63 were some of the best-known units to use this technique (the 63 also used a rather elaborate time delay circuit with ring-shaped segments in the central portion of the speaker to emulate a point source). You can use equation 3 to calculate capacitance, while equation 4 defines capacitive reactance

$$X_c = 1/(6.283fC) \quad (4)$$

X_c = capacitive reactance in ohms

f = frequency in hertz

C = capacitance in farads

Option 2: Placing a resistor in series

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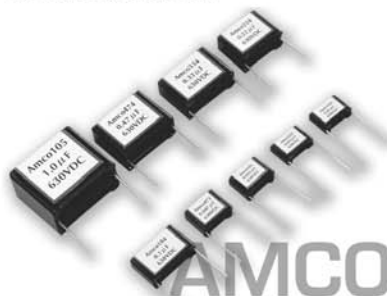
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with the transformer's primary also has several benefits and is highly recommended by Menno van der Veen, the designer of the Plitron ESL transformers. You can easily tune the Q of the series resonance formed by the speaker capacitance and transformer leakage inductance with this resistor to eliminate ringing in the speaker/transformer system. If necessary, you can also

decrease the output at high frequencies with this resistor. Additionally, you can sometimes use this extra resistance to stabilize an amplifier that is having difficulties driving an ESL load.

The following treatments of ESL transformer theory were graciously supplied by Menno van der Veen. As stated earlier, transformer theory is also covered in Ron Wagner's *Electro-*

static Loudspeaker Design and Construction (please keep in mind that loads can be reflected to the primary or secondary side for analysis).

Figure 24 shows the basic components I have been discussing.

Rep is a tuning resistor in series with primary

Res is a tuning resistor in series with secondary

FIGURE 18: MagneTek Triad S-142A clone 1:44.

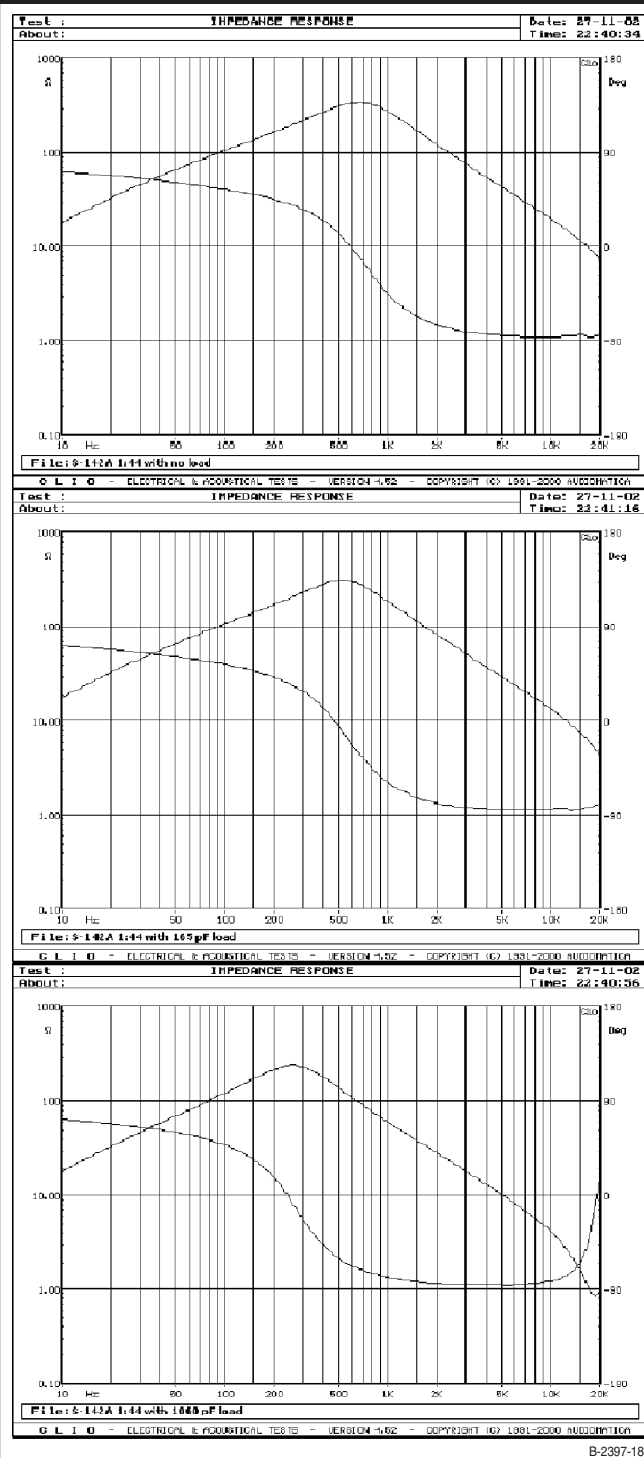
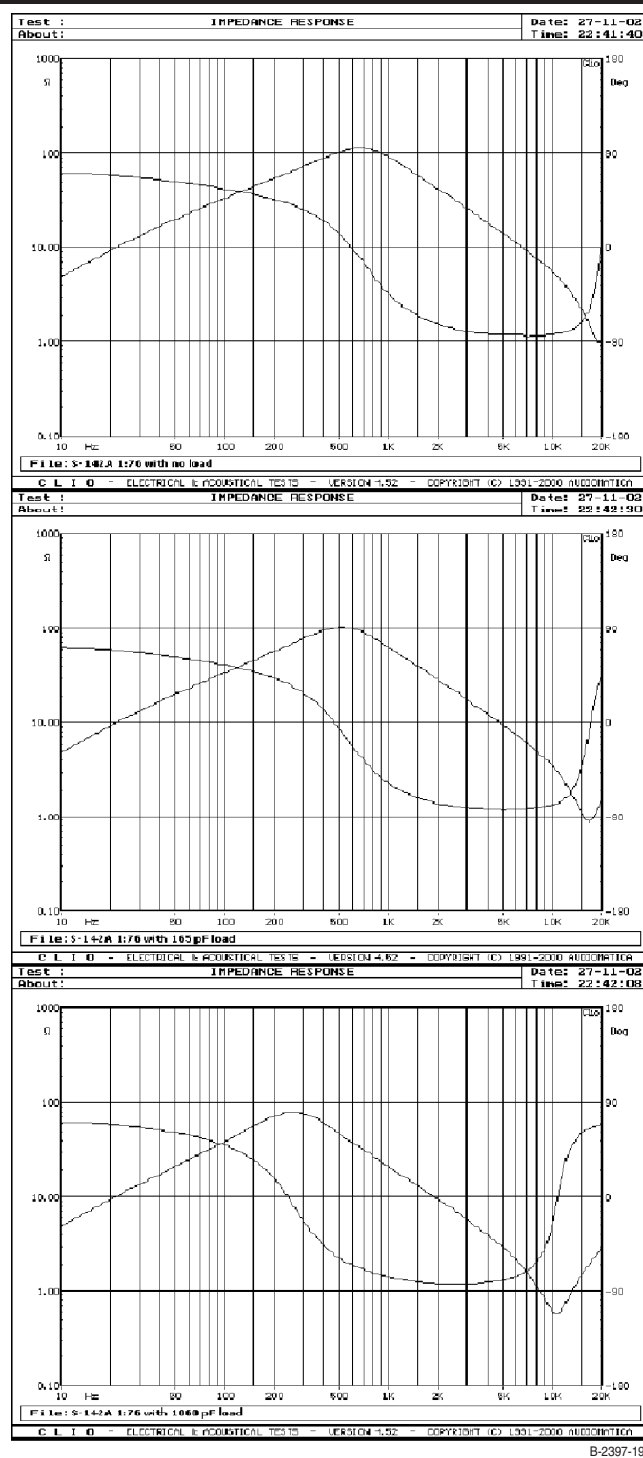


FIGURE 19: MagneTek Triad S-142A clone 1:76.



Ces is the capacitance of the electrostatic speaker from plate-to-plate

If you omit Res to simplify the analysis, at high frequencies you are left with the equivalent circuit shown in Fig. 25 and covered in equations 5, 6, and 7. All of the relevant primary elements are reflected to the secondary side in this analysis.

Lss is the leakage inductance of the transformer in henries

Cis is the secondary winding capacitance of the transformer in farads

Ces is the capacitance of the electrostatic speaker from plate-to-plate in farads

Rt is a combined resistance reflected to the secondary and is defined in equation 5

$$R_t = (N_s/N_p)^2(Z_{out} + R_{ep} + R_{ip}) + R_{is} \quad (5)$$

Ns = number of turns in the transformer's secondary winding

Np = number of turns in the transformer's primary winding

Zout = output impedance of the amplifier in ohms

Rep = tuning resistor in series with

FIGURE 20: MagneTek Triad S-142A clone 1:100.

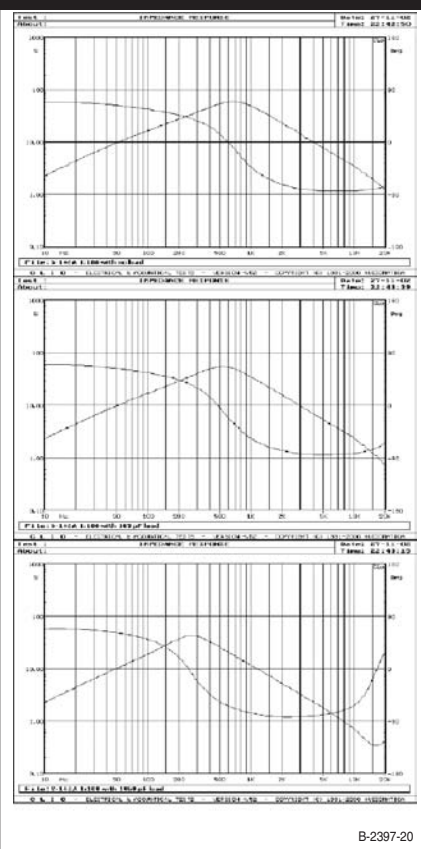
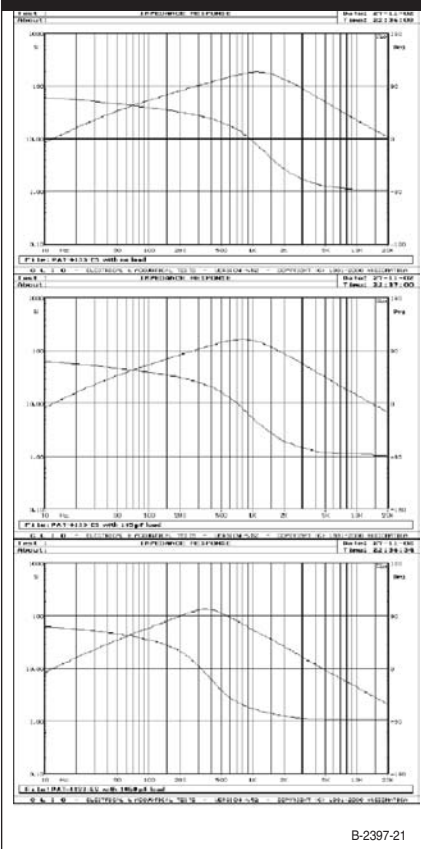


FIGURE 21: Plitron PAT-4133-ES 1:50.



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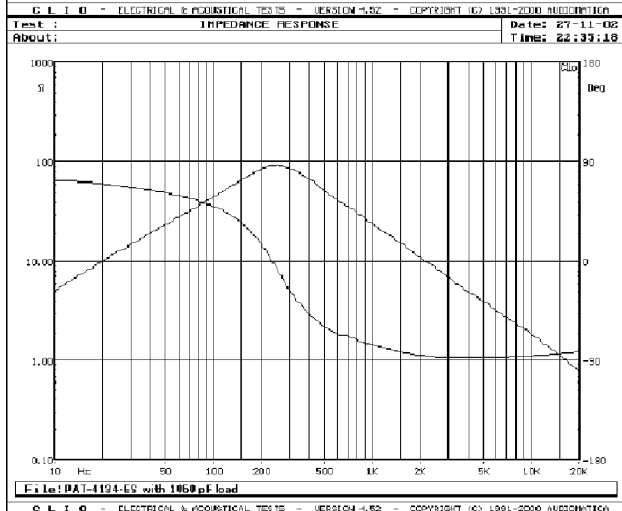
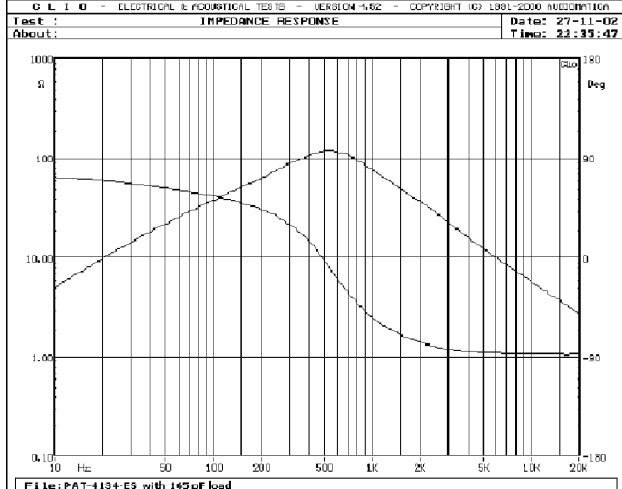
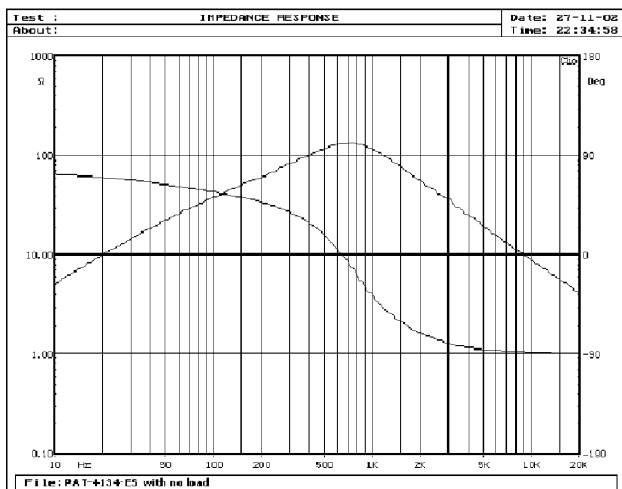
Z56548 Reproduction of the Z565 output transformer as used on the ST35 and SCA35 amplifiers, except that the output taps are 4 and 8 ohms

A470S reproduction of the Dynaco A470 output transformer as used on the Dynaco (tm) ST70 and MkIV amplifiers

A431S a reproduction of the Dynaco A431 output transformer as used on the MkII and MkIII amplifiers and Sunn guitar/bass amplifiers.

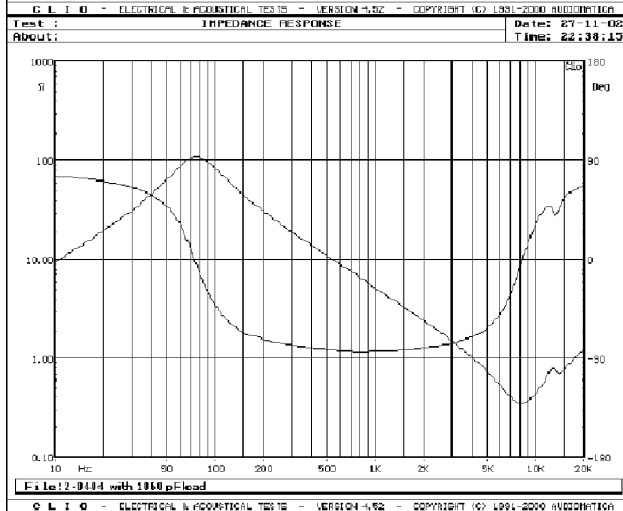
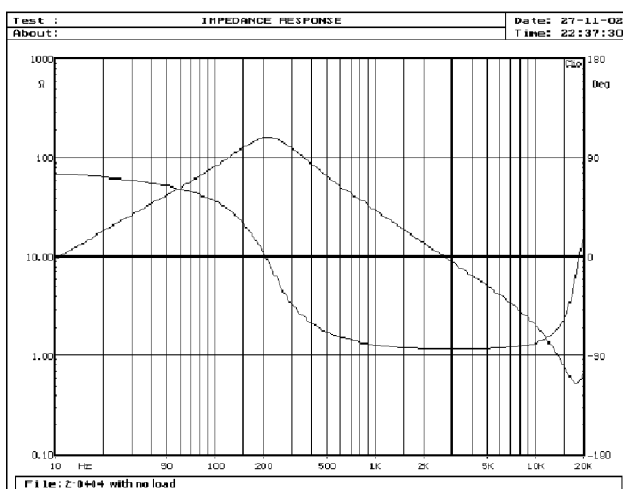
Other stuff we're working on: A420 (6600 ohm 30W) and A442 (4300 ohm 60W with tertiary screen winding)..

FIGURE 22: Plitron PAT-4134-ES 1:75.



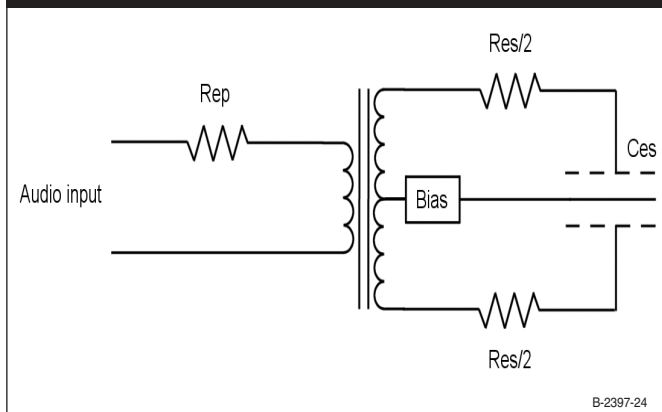
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FIGURE 23: Tranex 2-0404 1:150.



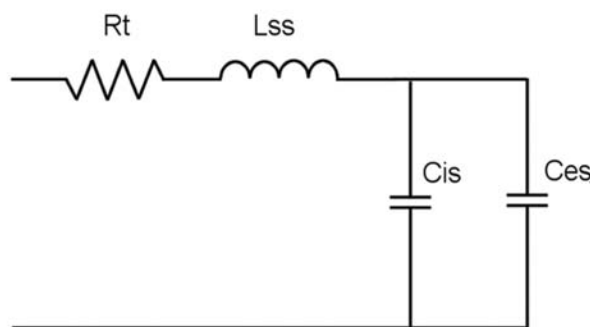
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FIGURE 24: Basic ESL/transformer configuration.



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FIGURE 25: High frequency equivalent circuit.



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primary, value in ohms

Rip = wire resistance of the transformer's primary in ohms

Ris = wire resistance of the transformer's secondary in ohms

The actual number of turns in the primary and secondary are not necessary; the ratio is all that is required in the calculation.

Equation 6 defines the resonant frequency of the low-pass filter formed by these components.

$$f = 1/(6.283(Lss(Cis + Ces))^{1/2}) \quad (6)$$

f = frequency in hertz

capacitance is in farads and inductance is in henries

Equation 7 defines the Q of the circuit

$$Q = (1/Rt)(Lss/(Cis+Ces))^{1/2} \quad (7)$$

For the best high-frequency extension with minimum phase shift and ringing, set the Q at 0.577. You could increase the Rep beyond this point to try to stabilize the partnering amplifier or to decrease high-frequency output.

The following points were also conveyed in correspondence with Menno van der Veen.

1. He suggested a maximum DC offset of 3mV from the amplifier to ensure that the transformer has adequate magnetic headroom during operation. As little as 10mV of offset can saturate the core.
2. At both the high-frequency series

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resonance and at very low frequencies, R_t is the major factor influencing the total impedance.

3. The use of R_{ep} produces better DC offset behavior because part of the DC will be dropped across the resistor in series with the primary.

To demonstrate the benefits of using R_{ep} , I conducted the following test using an inexpensive 45W/channel receiver that was known to be slightly unstable into electrostatic loads. I used a 100MHz

Tektronix TDS 340A oscilloscope to gather the data presented in the graphs that follow. *Figure 26* shows a 2kHz 1V peak-to-peak square wave at the output of the receiver with no load. *Figure 27* shows the input and output of a PAT-4134-ES driven with the same signal while the secondary was connected directly to a 1200pF ESL. The transformer's output trace has been rescaled to compensate for the 1:75 turns ratio. R_{ep} was then added to the circuit to produce the graph shown in *Fig. 28*.

To tune R_{ep} , I added a potentiometer to the primary side of the transformer and increased the resistance until the overshoot and ringing were eliminated. I kept the resistance as low as possible to retain maximum "squareness" in the output. In this case, 1.4Ω proved optimal.

Neglecting the output impedance of the receiver and any resistance present in test leads, you have a resonance of 24kHz and a Q of 0.38. The Q implies that the system is overdamped and that the high-frequency output will be rolled

FIGURE 26: 2kHz square wave at unloaded receiver output—1V peak-to-peak.

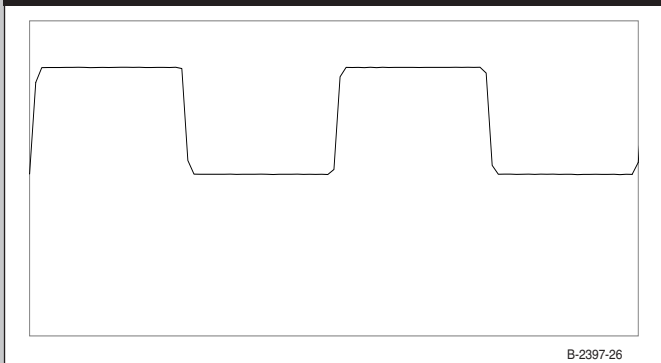


FIGURE 27: Input and output of PAT-4134-ES driving a 1200pF load.

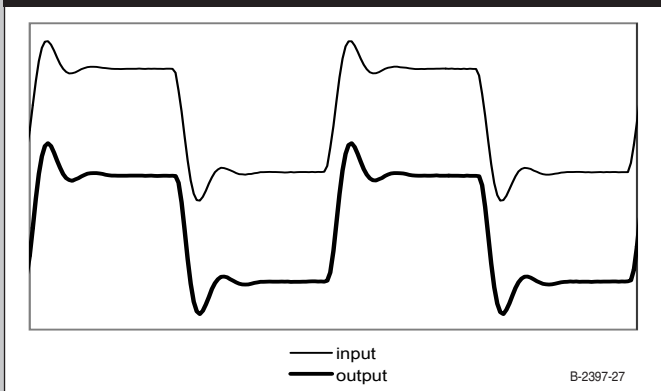


FIGURE 28: Input and output of PAT-4134-ES driving a 1200pF load with 1.4Ω R_{ep} .

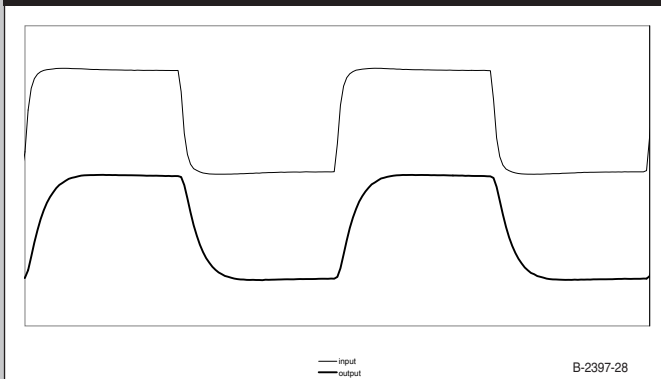
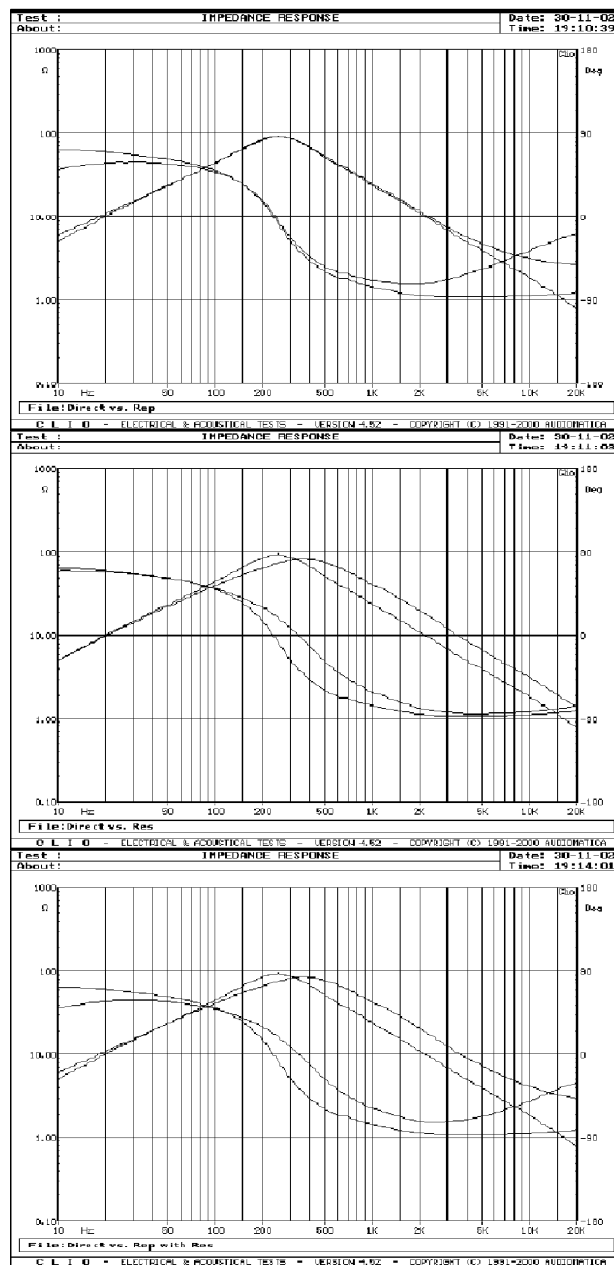


FIGURE 29: Effect of R_{ep} and R_{es} on impedance and phase.



off from its theoretical maximum bandwidth, but I will gladly trade that for the benefits the extra resistance provides for the receiver.

You can also see the benefits of Rep and Res as shown in *Fig. 29*. The top plot shows the original impedance and phase produced by a 1060pF load connected directly to the secondary of a PAT-4134-ES versus the same load driven with 2 Ω of Rep. The middle graph in the group shows the original load versus 500pF driven through 2.2M Ω of Res and 560pF driven directly. The Res provides a low-pass crossover at approximately 145Hz with a slope of 6dB/octave and helps to decrease the phase angle at mid frequencies.

The bottom plot is the original load versus both methods combined. The result of using both methods is still not the most benign load in the world, but the improvement is considerable.

CONCLUSION

I hope this article has answered more questions than it has generated. I'm still searching for the "ultimate" full-range ESL design that will convince me to dive in all the way and build a speaker that will

demand its full-time use in my system.

I hope others will share their experiences in this forum. It's not just groundbreaking discoveries that need to be written about; patents and designs that might initially seem out of date often contain many details that are still pertinent (and not widely known). If you've rediscovered the benefits of someone else's work and it hasn't been covered lately, please share with the group. **aX**

Thanks to John Triplett for the machine work—you can see some of his more ambitious endeavors at www.nothingbutcustoms.com

I also thank Galen Powers, who supplied the equipment and talent used to photograph this project.

Matthew Lattis has been experimenting with ESLs for approximately 10 years and has had projects published in **Speaker Builder** and **Audio Electronics**. His current employer specializes in plastic ophthalmic lenses and systems for their production. Eighteen US patents cover his contributions to that field.

SOURCES

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