Electrostatic Headphone Amplifier

By a significant margin, the most common loudspeaker transducer used today is based upon electromagnetic principles. These “speaker drivers” typically take the form of a round rigid “cone” loosely suspended at its perimeter driven by a “voice coil” which surrounds a fixed magnet. The cone is driven into motion from current delivered to the voice coil. Two contradicting requirements – high cone stiffness and low assembly mass limit the performance of these designs (although planar and ribbon designs have reduced these issues in exchange for increasing costs).

By contrast, electrostatic loudspeaker transducers (see *Figure 4*) provide a deflection force to a 3 to 5 mil suspended diaphragm (usually mylar) using electrostatic forces. The (slightly) conductive diaphragm (approximately 10Ω/sq) is suspended between two acoustically transparent “stators” which themselves are driven by a high voltage out of phase audio signal (see *Figure 5*). The diaphragm is biased with a high voltage (level dependent upon relative physical distances) relative to the stators. The result is a push-pull force exerted on the diaphragm across the entire surface displaces the surrounding air. The stators are usually insulated to prevent arching if and when the diaphragm approaches the stators. In theory, the superiority of the electrostatic transducer is due to the low mass of the diaphragm (approaching the mass of air), the application of the force across the entire surface, and the push-pull force that reduces even harmonic distortion. As a result, properly designed electrostatic transducers will provide low distortion, outstanding transient response, and wide bandwidth compared to even planar magnetic designs. This superior audible performance is not without both electrical and acoustical challenges including limited dynamic range (limited by the full excursion of the diaphragm), low frequency rolloff (due to their bi-polar room coupling), high-frequency beaming (inversely proportional to the width of the diaphragm), and the need to provide low distortion, large voltage excursions. Headphones minimize these challenges due to their controlled acoustical environment, small size, and low output requirements. Consequently, properly designed esl headphones (along with careful attention to the driving means) are capable of the most audibly transparent audio reproduction (neglecting the loss of room special cues) available.

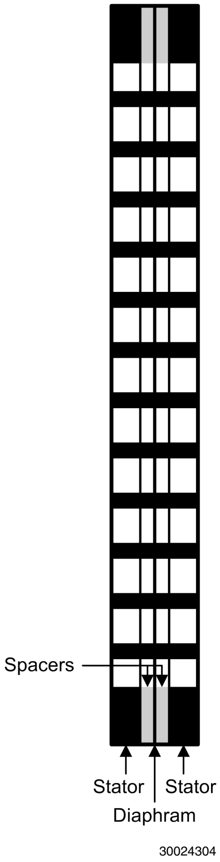

FIGURE 4. Typical ESL Construction

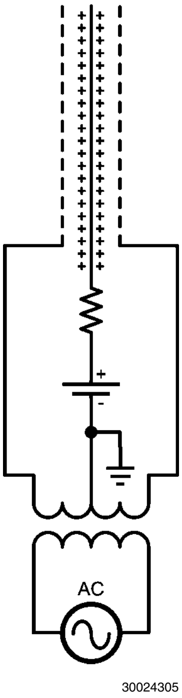

FIGURE 5. ESL Operating Principle

The electrostatic transducer used in nearly all commercial designs is a push-pull constant charge design where a diaphragm is placed within a uniform electric field. A high resistivity coating is applied to the diaphragm to provide for a constant charge across its surface. The superior linearity of this design has been described in detail previously 3,4,5 where it has been shown that an esl can be theoretically free of distortion when the charge on the diaphragm remains constant as it moves between the stators. Under these circumstances, the force on the diaphragm will be defined by

F= Q*E(t) (newtons)
where Q = 2eAV / d (coulombs)
E(t) = v(t) / 2d (volts / meter)
C = eA / d (farads)
therefore F = CVv(t) / d (newtons)
where C = capacitance of the transducer (diaphragm to stator)
V= Bias Voltage (volts)
v(t) = time varying signal
d = diaphragm to stator spacing (meters)
A = Diaphragm Area (sq-meters)
e = 8.85 * 10^-12 (farads / meter)

The electrostatic transducer is primarily capacitive in nature (in contrast to the low impedance, mostly resistive- inductive, load of the electromagnetic transducer) and therefore demands a source capable of delivering suitable charging currents. Because the predominance of commercial loudspeakers are electromagnetic based, all commercial amplifiers are designed to interface with these low-impedance loads. Accordingly, all electrostatic loudspeaker manufacturers provide the needed bias voltage and voltage amplification in the form of an add-on “interface unit” typically consisting of a bias supply and step up transformer with a suitably high step up ratio (*Figure 5*). Unfortunately, it is difficult to design a wide band transformer with superior performance when high step-up ratios are required. A superior solution is to drive the stators directly with a large voltage swing, wide bandwidth amplifier capable of delivering the current necessary to support the capacitive load imposed by the transducer.

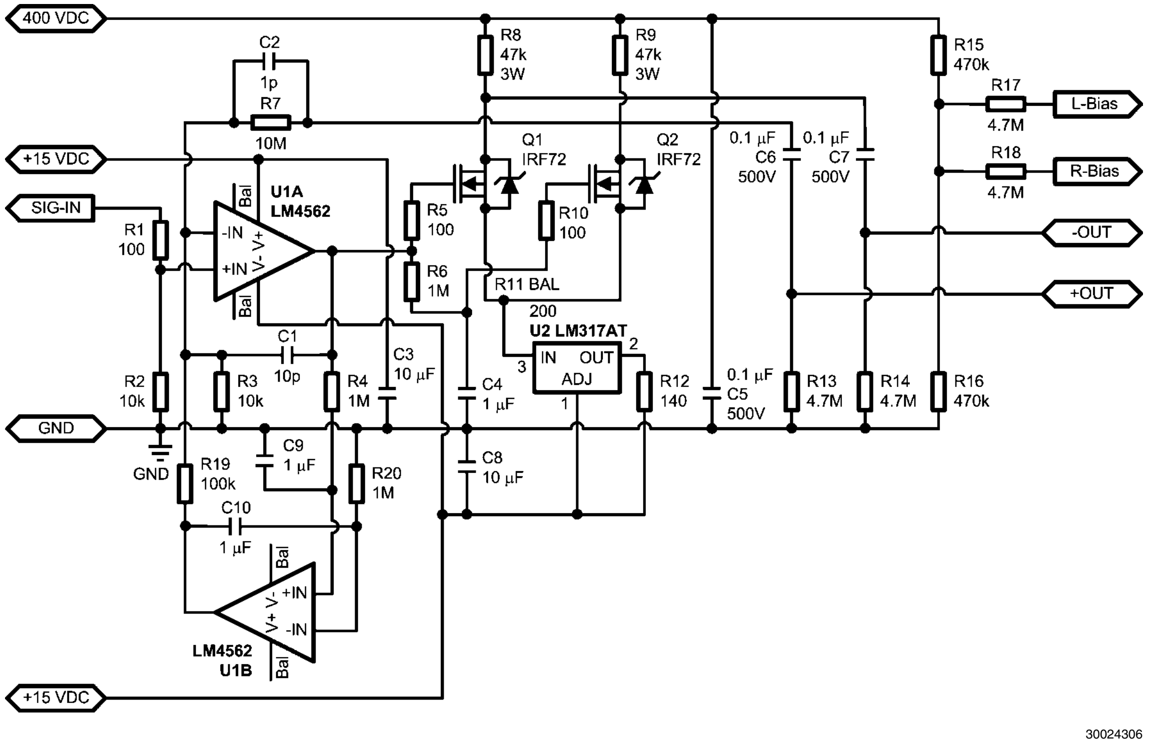

FIGURE 6. ESL Amplifier Schematic

The design presented in *Figure 6* will deliver nearly 200 Vp-p across the full audio bandwidth when interfaced to the popular Stax type 1 electrostatic headphones. A bias of 200 V_{DC} is shown although the resistive divider can be altered to provide a bias voltage up to 400 V_{DC}. Note that many of the Stax type 1 headphones have similar drive and bias requirements making this design suitable for these models as well.

From *Figure 5* it is clear that a balanced high-voltage drive is needed. In this design, one half of the LM4562 is used to drive to a discrete differential amplifier using a pair of high voltage N-Channel MOSFETs. An LM317 is used in a current source mode to insure that the CMRR remains above 60 dB. The second half of the LM4562 is used as a servo amplifier. This servo actively compensates for the fully DC feedback via R7 to insure that the output of U1A will remain at 0 V_{DC} needed to keep the differential amplifier Q1 and Q2 properly biased for maximum Vout. Potentiometer R11 allows for variation in MOSFETs and must be adjusted to have 0 V_{DC} difference across Q1 and Q2 drain terminals. For best performance regulated sources should be used for the 400 V_{DC} and dual 15 V_{DC} supplies.

The design is fully DC-coupled from input to the output but for the output coupling capacitors. Using the highest quality capacitors (polypropylene, polystyrene or Teflon) will result in the highest audible performance.

It should be noted that several alternate designs were built and auditioned including fully differential topologies however the most musical audible performance was achieved using the topology shown.

Note that is it possible to directly substitute a 6FQ7/6CG7 miniature triode or 6SN7 octal triode in place of the MOSFETs if a tube output stage is desired. In this case, a suitable filament supply will be required.

Bibliography

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