THE TECHNOLOGY OF FULL-RANGE-ELEMENT ELECTROSTATIC LOUDSPEAKERS

by James C. Strickland, President of ACOUSTAT CORPORATION

The fundamental goal of designing a loudspeaker system must be to reverse the process of the recording microphones as exactly as possible. For more than 25 years, the standard of the recording industry has been the condenser (electrostatic) microphone, which consists of a full-range-element of extremely low mass, intimately driven *acoustically* over the entire surface of the diaphragm. To reverse this exactly, one would need a loudspeaker with a full-range-element, also of extremely low mass, and driven *electrically* over the entire surface of the diaphragm – only then can the original waveform be duplicated. The above is an exact description of the electrostatic type speaker. It is interesting to note that as a mechanism for reversing the role of the microphone, a cone system is inherently wrong, in that: 1) It splits the musical spectrum with crossovers, i.e., it is not capable of full-range-element design, 2) It has high mass (comparatively), and 3) It does not intimately drive the diaphragm surface at all points of radiation.

Although the electrostatic loudspeaker element has long been known as the only transducer capable of maintaining the integrity of the signal generated from the condenser (electrostatic) microphone, the implementation of electrostatic loudspeaker systems has been far slower than that of the condenser microphone. As discussed below, this was due to many design difficulties associated with the much higher power and voltage in a speaker, as compared to those in the electrostatic microphone.

THE ELECTROSTATIC ELEMENTS

The electrostatic panel consists basically of a very thin mylar diaphragm, which is coated with a conductive and sandwiched between two electrodes. These electrodes can be either perforated conductive plates, or wires. (Further discussion of these two types of construction is presented later in this paper.) It is important to note that these electrodes do not physically touch the diaphragm, but are positioned a small distance away on both sides. This is one of the most important differences between the electrostatic and the cone type or planar-magnetic type of loudspeaker elements, and is the reason for much of the electrostatic's superiority. That is, the electrostatic element must move only the thin diaphragm – not the diaphragm plus wires, voice coils, etc.

The audio signal is applied to the electrodes and in turn an electric field is created around the diaphragm. This field acts on the thin (.00065 inches thick) mylar diaphragm with a push-pull force causing the diaphragm to vibrate. As you can see, the electrostatic does not depend on the mechanical motion of voice coils or wires, but instead uses an ultra-low-mass diaphragm set into motion by an instantaneous electric field. Therefore, the *entire* diaphragm is driven by the audio signal, not just one small area of the diaphragm, as is the case with other types of loudspeaker elements. This enables the audio signal applied to the electrostatic element to have several million times more intimate control over the diaphragm (and therefore air motion) than a good cone system, and several hundred thousand times more than the planar-magnetic type element.

It should be obvious that the electrostatic element, due to the physics of its design, can have the best transient response, the lowest distortion, and the widest frequency response of all the types of loudspeaker elements.

A BRIEF HISTORY OF ELECTROSTATIC LOUDSPEAKERS

Because of their low mass and excellent transient behavior, electrostatic loudspeakers first appeared as tweeters. It was assumed initially that their smaller excursion would limit their ability as bass reproducers, yet it turns out that this is not the case. The large radiating area associated with the electrostatic element permits a far better acoustic impedance match than does the much smaller area provided by even a *fifteen* inch woofer. Thus large excursions are not necessary for robust bass if sufficient moving surface is present.

It is also true that early attempts at full-range electrostatic loudspeakers did not utilize full-range-elements. They followed past cone speaker practice and employed separate electrostatic woofers, midranges, and tweeters. These designs revealed some of the merits inherent to electrostatics, but failed to utilize the greatest single advantage of the electrostatic principle – that the elements can superbly cover the *entire* audio range without crossovers. All Acoustat speakers are, and have always been, crossoverless full-range-element designs.

In terms of construction, most of the early electrostatic loudspeakers used the coated, perforated conductive electrode approach to panel design. This is a logical approach since the use of such plates is in keeping with the wording of all the electrostatic theories. The principle difficulty, however, is that the perforated plates will develop charge concentrations in the most difficult areas to uniformly coat with an insulating material – with the effect of too much insulation where it is least needed and too little insulation where it is most needed, i.e., at the sharp corners of the holes in the perforated conductive plate. The results of this method of construction have been unreliability of the electrostatic element, typically in the form of arcing and actually melting the thin mylar diaphragm.

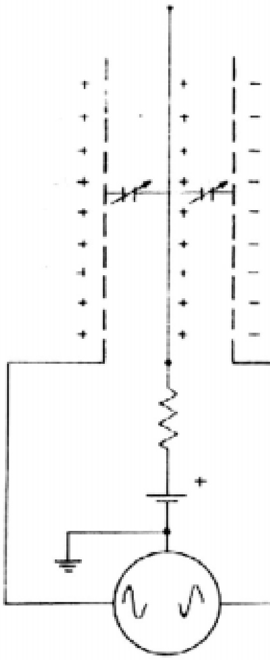
Several methods have been used to provide necessary dielectric integrity. Michael Wright used an insulating gas to prevent electrical breakdown. Harold Beveridge created an epoxy matrix panel design. But, in 1953 the most practical new idea for creating a reliable electrostatic element was patented by Arthur Janszen – The Sheathed Conductor panel design. Although difficult to construct on a large scale, the sheathed conductor panel design opened the door for a new era of dielectric integrity. The sheathed conductor construction was used in several early Janszen designs including the Janszen and RTR tweeters.

About 1963, James Strickland became involved in a project to adapt the Janszen principle to a larger scale, using the cube-louver structure later refined at Acoustat. This pioneering work led to the first truly full-range electrostatic elements, which were not only dependable, but virtually indestructible – The Acoustat full-range electrostatic panels.

HOW IT WORKS, THE CONSTANT-CHARGE CONCEPT

While not nearly as old as the concept of the electrostatic loudspeaker, the idea of a constant-charge electrostat is far from new. Well over twenty years ago, electrostatic loudspeaker theoreticians including Frederick V. Hunt, Arthur Janszen, Peter Walker, Michael Wright, and others, had seen the unique advantages in an electrostatic transducer concept in which a diaphragm is kept at an essentially constant charge and placed within a spatially uniform electric field, varying with the audio, created by opposing plates driven push-pull, as shown in figure 1.

FIGURE 1 Physics of a Constant Charge ESL



$C = q/V$

$J = CV^2/2$

$F = Eq$

Where: C capacitance in farads
V voltage in volts
J energy in joules
F force in newtons
E electric field in newtons per coulomb*
q charge in coulombs

*newtons per coulomb and volts per meter are alternate units of measure of electric field

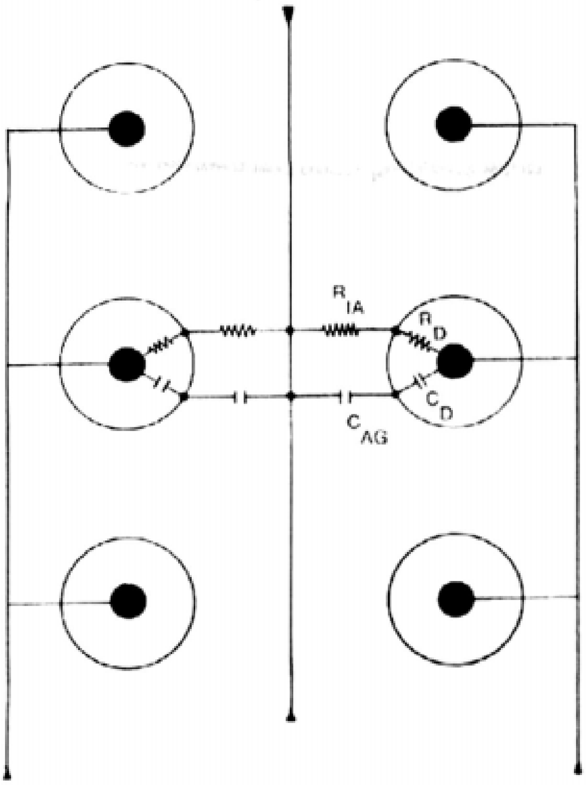
It should be noted that constant-charge does not mean constant-voltage. Constant-charge means that the number of excess electrons (or the number of "holes" in the case of a positively biased diaphragm) remains virtually constant despite the changes in the relative potential of the driving plates and in the proximity of the diaphragm relative to the plates. Thus, it is necessary for the voltage of the diaphragm to float according to the audio driving voltages and the position of the diaphragm with respect to the two plates. When the constant-charge principle is applied, the second order (square-law) non-linearities drop out of the force equations. This permits the electrostatic loudspeaker to maintain very low levels of distortion throughout the entire excursion-space of the diaphragm. This advantage is impossible to duplicate in a magnetic driver.

CONSTRUCTING A FULL-RANGE ELECTROSTATIC PANEL WITH REAL WORLD MATERIALS

The electrical characteristics, such as operating voltages and climatic variations, are largely determined by the ionization characteristics of air and by the properties of the insulating material used on the electrostatic plates; whether they are perforated plates or sheathed conductors. Acoustat's early work with sheathed conductor electrostats was done with polyethelene insulated wire affixed to the cube-louver structure. With a polarizing potential of ten to fifteen thousand volts, these polyethelene insulated panels yielded high sound pressure levels – in the damp south Florida climate. But, the panels were not consistent in all climatic conditions. After further research and experimentation, plus a careful restudy of Arthur Janszen's patent, the problem became obvious. While the use of good insulation, such as polyethelene, had seemed logical, polyethelene was in reality too good an insulator – in fact, about a thousand times too good.

A return to Janszen's prescription of polyvinylchloride (PVC) insulated wire allowed more reasonable voltages and also overcame the climatic variability. The reason for this can be seen in figure 2 – which is a cross sectional view of an operating real world electrostatic panel.

FIGURE 2 A Sheathed Conductor Electrostatic Viewed Into the Axes of the Wires



R_{IA}	resistance of ionized air
C_{AG}	capacitance of air gap
R_D	resistance of dialectric
C_D	capacitance of dialectic

Air typically shows low level ionization when exposed to an electrical potential gradient of about one thousand volts per millimeter. Since Acoustat uses a wire-to-diaphragm spacing of about 2.5 millimeters, with a diaphragm bias of about five thousand volts fed through five hundred megohms, it can be seen in the static (no audio) condition, the DC potential drop between the diaphragm and the surface of the sheathed conductors will be approximately twenty-five hundred volts. Thus, nearly all the remaining potential drop will occur in the insulation of the sheathed conductor – which may be viewed as a ballast resistor to bring the air gap between the sheathed conductors and the diaphragm to a proper value for the best operation of the system. Too low an insulation resistance results in noisy operation, while too high an insulation resistance results in reduced operating level.

Probably the greatest advantage of the sheathed conductor technique is the high reliability and dielectric integrity which can be provided by a manufacturer of mil-spec PVC insulated wire. These wire grades have shown virtually unlimited life once they have passed the manufacturer's rigorous voltage breakdown testing.

Thus, while sheathed conductor panels are difficult to build, they are totally reliable, as shown by the tens of thousands put into use by Acoustat over the last six years, without a single known over-driving failure.

INTERFACING, THE RIGHT QUESTION AND THE RIGHT ANSWER

In the spring of 1980, Acoustat perfected the Magne-Kinetic Interface (patent pending), a new approach to matching a crossoverless electrostatic to conventional power amplifiers. This solution is rapidly becoming appreciated as the only truly practical solution to the extremely difficult problem of driving a full-range-element electrostatic loudspeaker with conventional amplifiers.

We have been asked many times since the introduction of the MK-121 Interface, "Why didn't you do this before?" The best answer to this question comes from a realization of just how complex the electrostatic transducer's load characteristics look to the output of the interface.

Two separate characteristic curves present themselves, which define the drive problem. A full-range electrostatic array has an impedance which is almost totally capacitive, and this impedance falls by almost a thousand-to-one ratio over the audio band. Such an array also has an associated voltage-sensitivity curve which is far less radical, only about a three-to-one (10 dB) total range. Unfortunately for the interface designer, these curves track *somewhat* in the lower half of the spectrum, and are *opposite* in the upper half of the audio spectrum.

From the above it can be concluded that the pursuit of a single "ideal" step-up transformer is an endeavor doomed from the outset. The problem is not just that the answer is impossible, but that the question is wrong! Focusing on this wrong question has no doubt retarded the pace of electrostatic development. The proper question pursues a simultaneous solution to the impedance match and the voltage match problem and leaves the solution open to invention.

Asking the right question made the MK-121 possible. Making it a reality required an intensive study of transformer and electrical network properties. Out of this study came the conclusion that a two-transformer, band-overlap configuration had the theoretical possibility of yielding a simultaneous solution to the problems of impedance and voltage matching. Even the very first prototype units showed us that this was, without question, the right approach.

THE MK-121, HOW IT WORKS

The MK-121 has solved a problem which designers have been grappling with for at least twenty-five years. Two physically and electrically different push-pull transformers and a few passive parts allow the circuit to operate in a quasi-parallel, band-overlapped manner, effectively sharing the drive problems of impedance and voltage matching. The overlap is more than one-third of the audio band, virtually the entire critical midrange region. This overlap has a median frequency of about 1500 Hz, as shown in figure 3.

FIGURE 3 Transformer Overlap of MK-121

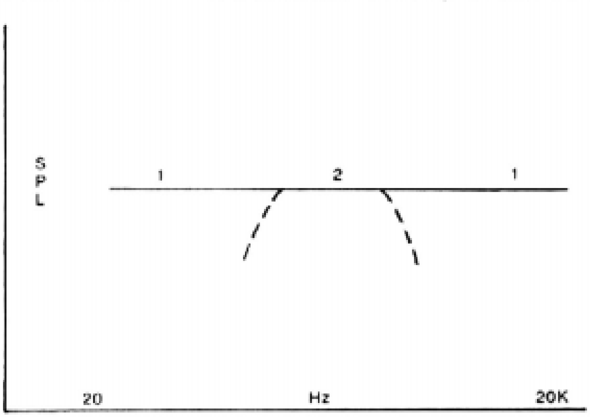


Figure 4 is a simplified schematic of the MK-121 Interface and bias supply. Out of this simple but sophisticated circuit come several essential advantages:

1) The secondary impedance of the smaller (high-frequency dominant) transformer is only about 1½% of the larger unit.
2) Any residual electrical resonance can be pushed to the top extreme of the audio band – just as the mechanical resonance is located in state-of-the-art condenser (electrostatic) microphones. Gone is the plague of mid-band resonance found in single transformer designs.
3) The passive components which connect the signal to the elements have a serendipidous effect not immediately expected. This effect is a magnetic analogy to bi-amping. Difficult low frequency and infrasonic signals do not get a chance to intermodulate the purity of upper-band pass-through. The net result is startlingly useful – the MK-121 will drive the elements with far less distortion on difficult dynamic material than could any collection of transformers alone, or even a direct-drive amplifier!
4) The efficiency is much better than any single transformer design could yield, making the drive situation quite reasonable for quality amplifiers.
5) The vastly improved impedance match allows sonic superiority beyond that previously achieved by Acoustat, or others.

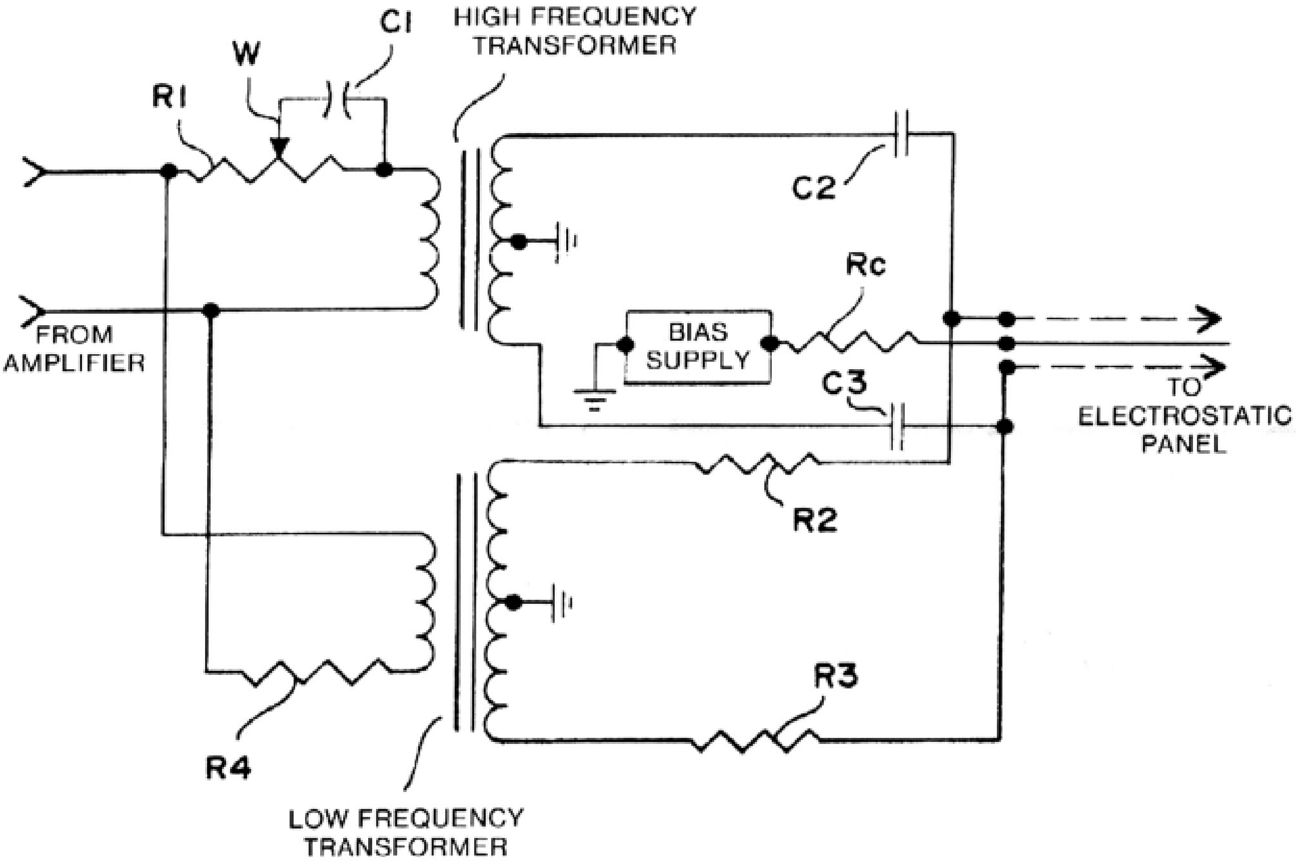
POWER AMPLIFIER REQUIREMENTS

As sophisticated and efficient as the coupling is by this method, an Acoustat loudspeaker still demands a quality amplifier, preferably in the one hundred watt per-channel range minimum for the two panel model, and scaling down to fifty watts per-channel minimum for the larger and hence more efficient four panel speakers. This power level requirement is a reflection of the fact that to have the unique merits of direct electrical action in an electric field, we must charge and discharge the capacitance which must come with that electric field. Thus, higher power levels than might be expected from the high acoustic efficiency of the transducer are needed for proper charge/discharge rate and control. It is also not unusual for the amplifier to run warmer into an electrostatic load. This is because there are few losses in the interface and elements, hence the amplifier actually re-absorbs much of the power it generated one-quarter cycle earlier. Electrostatic elements actually run ice-cold.

CONCLUSION

Asking the right question and inventing the right answer has opened a whole new era for the crossoverless full-range electrostatic loudspeaker. Acoustat's speaker systems are now even more outstanding in performance, cost less, and can be offered in a smaller, more manageable size.

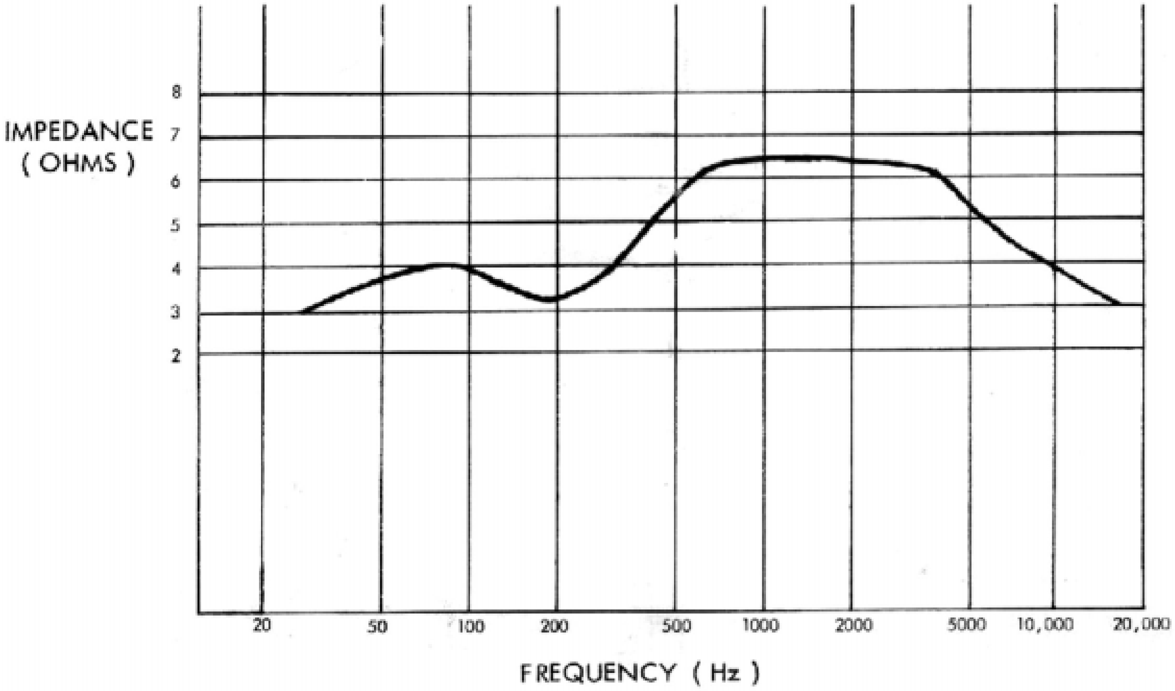
FIGURE 4 Simplified Schematic of Magne-Kinetic Interface and Bias Supply.**



**PATENT PENDING

The band-overlap operation of the MK-121 can be understood from an inspection of its schematic. The low-frequency transformer is optimized from the bottom of the spectrum, working as full range toward the top as possible, whereas the high-frequency transformer is optimized for the top of the spectrum going as full range as possible toward the lower end. Two resistors, R1 and R2, and two capacitors, C2 and C3, gradually transition the loudspeaker load from one drive impedance level to the other. It is this technique that makes the excellent impedance and power match possible between the widely varying speaker impedance and a conventional amplifier. R1 and C1 control the source impedance feeding the high-frequency transformer, and act as a high-frequency balance control. R4 is a saturation limit for the low-frequency transformer so that high infrasonic currents will not generate destructive potentials.

FIGURE 5 IMPEDANCE CURVE OF ACOUSTAT MK-121 LOUDSPEAKER SYSTEMS
(MEASUREMENTS MADE ON ACOUSTAT VECTOR-IMPEDANCE METER)



High-Frequency Control at Two o'clock Position
Maximum Phase Angle : ± 30 degrees

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