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DIRECT RADIATORS VERSUS HORN LOADING: DESIGN PRINCIPLES AND HISTORICAL PERSPECTIVE IN SOUND REINFORCEMENT

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1. INTRODUCTION

Horns and direct radiators have provided the basis for electroacoustic sound reinforcement over its century of history. Both have benefitted from technological and engineering evolution as well as artistic demands for improved quality. The trends of fashion and acceptance have depended on engineering, economics, and a degree of opportunism.

A survey tutorial of the significant design criteria of both methods of transduction and transmission will be presented, and their application in various embodiments will also be discussed in historical perspective, showing common influences and interactive trends.

2. HISTORICAL PERSPECTIVES:

In the early days of transducer development, horn systems were the only means possible for achieving suitable levels for speech reinforcement. Early power amplifiers were limited to about 10 watts output capability, and horn-driver efficiencies on the order of 20% to 30% were necessary to reach the desired sound pressure levels.

In general, the direct field level at a distance of one meter produced by one acoustic watt radiated omnidirectionally from a point source is 109 dB (Beranek, 1954, p. 314). If we use a 10-watt amplifier with a horn-driver combination that is 30% efficient, we can produce 3 acoustical watts. If the horn has a directivity index (DI) on axis of, say, 10 dB, then we can increase that level to:

$$\text{Level (re 1 meter)} = 109 + 10 \log (3) + DI = 124 \text{ dB } L_P$$

At a more realistic listening distance of 10 meters, the level would be, by inverse square relationship, 20 dB lower, or 104 dB. If better coverage was needed, more horns could be added and splayed as required.

There is little documentation of early examples of general speech reinforcement, and that art progressed fairly slowly (Green and Maxfield, 1923). The first example of large-scale sound reinforcement occurred on Christmas Eve, 1915, when E. S. Pridham, co-founder of the Magnavox company, played Christmas carols for an audience of 50,000, using Pridham-Jensen rocking armature transducers connected to phonograph horns (Hilliard, 1976). Western Electric set up a public address system capable of addressing 12,000 persons through 18 loudspeakers in 1916 (Thrasher, 1946, p. 24).

The first distributed system was employed in 1919; 113 balanced armature driving units mounted on long horns were strung along New York City's Park Avenue "Victory Way" as a part of a Victory Bond sale (Thrasher, 1946, p. 25; Beranek, JASA, 1954). The first successful indoor use of a public address system was at the 1920 Chicago Republican Convention, which also employed the first central cluster configuration (Thrasher, 1946, p. 25). On 4 March 1921, President Harding's inauguration was amplified (Thrasher, 1946, p. 24), and on 11 November 1921, President Harding's address in Arlington, Virginia, was transmitted by Western Electric, using Egerton's 1918 design four-air-gap balanced armature units. For the first time, 150,000 people, at Madison Square Garden in New York, in the adjoining park, and in the Civic Auditorium in San Francisco, simultaneously listened to a person speaking (Beranek, JASA 1954).

It was the cinema that paved the way for rapid development of professional sound reproduction. Talking pictures required more than speech intelligibility, however. The single horns of the day were limited in response to the range from about 125 Hz to 3 kHz. While this was adequate for speech, music required greater bandwidth, especially at lower frequencies (Flanagan, Wolf, and Jones, 1937).

The first widely accepted cinema system used a two-way approach. A multicellular high-frequency horn with a compression driver was coupled to a cone driven, folded low-frequency horn assembly (Clark and Hilliard, 1938). Its high level of performance and approval by the Academy of Motion Picture Arts and Sciences, in the form of a technical achievement award, led to its acceptance as an industry standard. (Hilliard, 1936).

The next step in low frequency (LF) response was to employ multiple large diameter direct radiators in some sort of "directional baffle" that could both load the drivers for increased efficiency and give them a degree of forward directionality (Olson, 1937). The best LF direct radiating transducers of the day were about 10 dB lower in efficiency than horn systems, but their use was mandated due to size and complexity of orthodox bass horns. When employed in multiples, they could provide excellent coverage and level in large theaters. In time, the various directional baffles evolved into the familiar front-loaded quasi-horns that are forever identified with the cinema (Lansing & Hilliard, 1945). Field coil energized transducers also gave way to permanent magnets following the war (Lansing, 1946).

The LF transducers chosen for this application had relatively small moving masses and high $(Bl)^2/R_E$ ratios. This enabled them to efficiently handle the acoustical load, transformed by the horn, and maintain good response up to about 400 Hz, at which point the HF (high frequency) horn took over. The HF horn itself was undergoing modifications aimed at improving its directional response. RCA favored the radial horn, while Bell Laboratories favored the multicellular device (Wente & Thuras, 1934). Bell Laboratories later pioneered the use of the acoustical lens in similar applications (Kock and Harvey, 1949; Frayne and Locanthi, 1954).

By the early 1950s, HF horns had established their primacy in the frequency range above 500 Hz, while hybrid LF horns, which relied on reflex loading of cones below about 100 Hz, dominated the range below 500 Hz. These families of components formed the basis of post-war sound reinforcement activities and held that position for nearly 25 years.

By the early 1970s, available amplifier power, which had been steadily rising through the introduction of consumer high fidelity during the mid-1950s and 1960s, reached the point where beneficial tradeoffs could be made among the three eternal loudspeaker variables of *size, efficiency,* and *LF bandwidth*. As early as the mid-1950s, consumers began to enjoy relatively small sealed systems that provided substantial LF output (Villchur, 1954). Additional analysis and synthesis of ported enclosure design by Thiele and Small (1971), following the earlier work of Locanthi (1952) and Novak (1959), led to the general adoption of ported enclosures as a LF building block in professional sound system design.

Through the use of Thiele-Small driver parameters, LF systems could be rationally designed for best response and enclosure size. Gone were the days of cutting and trying – and also gone were the days of poorly designed LF transducers. Thiele-Small analysis pointed to the need for identifying the right cone mass, resonance, excursion capability, *Bl* product, and enclosure volume and tuning to achieve a targeted performance goal.

During the 1970s and early 1980s, ported LF systems became the basis for most sound reinforcement LF design. For many music and speech applications the horn HF crossover frequency was raised from 500 Hz to 800 Hz and higher with cone drivers filling in the midrange (Martin, 1976). This change from the old two-way philosophy was brought on by modern program requirements for generating increased level. Higher power handling transducers were substituted in the LF horns, but these new drivers forced the power bandwidth of the horn downward. With the crossover frequency raised to improve high frequency reliability, the result was grossly uneven power response (Engebretson, 1982).

The conservative motion picture industry continued with two-way solutions, but traded in its hybrid bass horns for standard ported systems, and retired the old multicellular HF horns of the thirties (Engebretson & Eargle, 1982). The concept of flat power response in system design stated that not only uniform direct arrival sound was important; reflected sound (proportional to the total radiated power of the system) should itself be uniform. This goal could be more easily met with ported LF systems, along with uniform coverage HF horns (Hilliard, 1969).

The well-engineered ported LF system of the 1970s established its dominance at the low end of the frequency spectrum. The combination of low-cost power, low-distortion, high-power LF transducer development, and enclosure simplicity has given the ported system an advantage at low frequencies that horn systems could never match.

Keele (1976) made an instructive comparison between LF horns and direct radiators. For the same LF cutoff, the horn will have highest efficiency; a large complex enclosure, and will require a small number of drive units. By comparison, a direct radiator, multiple driver vented box will have moderate efficiency; a small, moderately simple enclosure; a large number of drivers, and higher power handling capability (because of the multiple drivers). In Keele's words, "This roughly means that if one has a lot of space, not much money to spend on drivers and amplifiers, and lots of cheap labor - build a horn. If labor is not cheap, and you don't have much space, and you can afford drivers and amplifier power - build a direct radiator."

Through the late 1980s and 1990s, however, the professional sound industry has seen a return to horn systems for covering the range down to about 300 Hz. The reasons have to do not with efficiency *per se*, but rather directional control. These new horns have taken the form of large format compression drivers, or cone transducers designed for horn-driver applications, and large horns optimized for the range from 100 - 300 Hz to 1 - 3 kHz, with ported LF systems handling the range below. Rapid flare HF horns are now employed, and their distortion characteristics, level for level, are up to 10 dB better than the older hardware (Eargle & Gelow, 1996). New digital methods of signal control have made multi-way systems more more acceptable than they were in the days of passive dividing networks, through time alignment and steep crossover slopes.

As we continue our discussion of direct radiators and horns, we will present a detailed analysis of the engineering fundamentals of both methods of transduction. This discussion will cover basic operating principles, directional control, and distortion mechanisms associated with each method. We will follow this by a discussion of systems concepts common to both kinds of transducers.

A final section of the paper will present a chronology of major events in the evolution of direct radiator and horn loudspeakers as they have influenced professional sound.

3. DIRECT RADIATORS:

3.1. Early Development

Ernst Werner Siemens' 1874 US Patent 149,797 was prophetic; he described in detail a radial magnet in which a coil of wire was placed. The coil was connected with a radiating surface which Siemens described as the frustum of a cone. He had literally invented the cone loudspeaker -- with nothing to play over it except *dc* transients and other telegraphic signals. He remarked at the time that it could be used "for moving visible and *audible* signals."

Half a century later in 1925, Rice & Kellogg of General Electric described "a new hornless loudspeaker" that was very much the same as that of Siemens, a similarity that prompted Rice to say, "The ancients have stolen our inventions!" (Hunt, 1954).

The basic difference in the Rice & Kellogg design was the adjustment of mechanical parameters so that the fundamental resonance of the moving system took place at a lower frequency than that at which the radiation impedance had become uniform. The motion of the cone was mass controlled, and it looked into a rising radiation impedance. This in effect provided a significant frequency region of flat power response for the design. Details of this are shown in Figure 1.

3.2. Region of Flat Power Response

Figure 1A shows a section view of the cone loudspeaker with all electrical, mechanical, and acoustical parameters labeled. The equivalent circuit is shown at B; here the mechanical and acoustical parameters are shown in the mobility analogy.

When mounted in a large baffle, the moving system looks into a complex acoustical load as shown at C. The resistive component rises with frequency to approximately $ka = 2$, above which point it is essentially constant (ka is equal to cone circumference divided by wavelength, or, $2\pi a/\lambda$). System response is shown at D. Its efficiency over the so-called piston band is given (Small, 1971) as:

$$\eta = [\rho_0(Bl)^2]/2\pi c R_E M^2_{MS} \qquad (1)$$

where ρ_0 is the density of air (kg/m^3), $(Bl)^2/R_E$ is the electromechanical coupling coefficient (N^2/W), c is the velocity of sound (m/s), and M_{MS} is the mass of the moving system (kg).

The larger the coupling coefficient is, the lower the resonant Q at f_0 and the higher the piston band efficiency will be. The reverse is true; the higher the Q at f_0, the lower the piston band efficiency. Depending on the application, both kinds of response may be useful to the design engineer.

It can easily be seen that, for maximum extension of the piston band, the lower f_0 must be, and the lower the system efficiency will be. The efficiency-bandwidth product, for a given cone diameter and coupling coefficient, thus tends to be constant over a relatively large range.

3.3 Mutual Coupling

In the LF range over which their response is essentially omnidirectional (ka = 0.2 or lower), a doubling of closely spaced driving units will result in an increase in acoustical output of 3 dB for a fixed input power reference level (Wolff & Malter, 1929; Klapman, 1940; Zacharia and Mallela, 1975). The progression in efficiency increase is shown in Figure 2 for one, two, and four LF transducers, respectively. In each case, the electrical power delivered to each ensemble of drivers is constant. Assume that the reference power into the single driver is one watt; then for the set of two drivers, the power per driver is one-half watt, and for the set of four, the power per driver is one-quarter watt.

One may imagine that, in the two-driver case with both drivers wired in parallel, those two drivers have, in a sense, coalesced into a new driver – one with *twice* the cone area, *twice* the moving mass, and *half* the value of R_E. Thus, by Equation 1, the efficiency will have been doubled. For the case where the two drivers are wired in series, the analysis goes as follows: The "new" driver has *twice* the cone area, *twice* the moving mass, *four-times* the $(Bl)^2$ product, and *twice* the value of R_E. Again, by Equation 1, there will be a doubling of efficiency.

Mutual coupling often appears to give something for nothing. What is often overlooked is the progressive lowering of the effective ka value of the combination of drivers. With each doubling of cones, the ka = 2 frequency moves downward by a factor of $\sqrt{2}$, since this is the inverse of the value by which the effective cone circumference has increased. If the process of adding drivers is continued unchecked, the response will soon become quite boomy. What is needed to achieve useful LF response extension is to reduce f_0 accordingly for each doubling of drivers.

When this is done, it will be seen that the fundamental bandwidth-efficiency product has not been changed. Good systems engineers have known for many years that mutual coupling is a limited, and limiting, process.

3.4 Distortion
3.4.1 Mechanical Effects. The primary distortion mechanism in cone transducers is due to mechanical stress-strain limits. Small identified a standard mechanical displacement limit from rest position in the axial direction as the excursion at which 10% harmonic distortion is reached. This limit is known as x_{MAX}. While a loudspeaker may be operated beyond this displacement limit, at least on a momentary basis, the 10% linearity departure is generally recognized as a safe limit for good engineering practice. Since cone motion increases as the inverse square of frequency down to the f_0 region, it is easy to see how the x_{MAX} limitation can be encountered in normal operation.

The onset of cone displacement limits at low frequencies can be alleviated by using ported LF enclosures. The nature of this design is shown in Figure 3. A section view of a ported system is shown in Figure 3A, and the equivalent circuit is shown at B. The design relies on controlling the Helmholtz resonance of the enclosure to provide an"assisted output," via the port, that minimizes cone motion (and thus distortion) at low frequencies. Thiele-Small parameters are universally used today to synthesize these systems.

Virtually all design programs for ported systems will indicate the displacement limits so that the design engineer will always be aware of whether a system, still on the drawing board, will go into displacement overload before it reaches thermal overload. Good engineering practice demands that a ported system remain within the driver's thermal limits down to f_0. Below that frequency the electrical drive signal is generally rolled off to avoid subsonic over-excursions of the cone.

3.4.2 Port Turbulence in Vented Systems. In ported systems the ultimate output at low frequencies may be limited not by considerations of maximum cone excursion but rather by air turbulence in the enclosure port when the system is operating at the tuning frequency (Gander, 1986). A tentative limit here is to restrict the port air velocity so that its peak velocity does not exceed about 5% of the speed of sound. In general, ports should be designed with contoured boundaries to minimize turbulence and the noise and losses it often produces.

3.4.3 Thermal Effects. Modern cone transducers intended for heavy-duty professional applications take advantage of newer materials and adhesives to make them more immune to thermal failure. Thermal failure is reached when the power dissipated in the voice coil as heat cannot be removed at a sufficient rate to maintain a safe operating temperature. A great deal of loudspeaker development goes into designing structures and moving elements that are not only resistant to heat, but aid in its removal from the transducer (Henricksen, 1987; Button, 1992).

For most applications in sound reinforcement, the effects of loudspeaker heating are more likely to result in component failure than those associated with displacement limitations. *Dynamic linearity* or *power compression* are terms used to describe the effects of heating on audio performance (Gander, 1986). The data shown in Figure 4 presents the frequency response of a single 380 mm LF transducer with inputs of 1 watt and 100 watts. In each case, the chart recording of the levels has been adjusted to account for the 20-dB offset between the curves. In this manner, the response differences can be clearly seen. If there were no dynamic compression, the two curves would lie on top of each other. As it is, the progressive heating results in an increased value of R_E, which lowers the efficiency. The effect of dynamic compression is to remove much of the dynamic and transient character from musical performance reinforcement.

Another way of viewing the same effect is shown in Figure 5. Here, several 380 mm transducers have been driven with a wide-band signal, and the effect of temperature rise is plotted with time. For each transducer design, the reduction in output level eventually reaches an asymtotic value that depends on how effectively heat can be removed from the voice coil and magnet structure. In general, large diameter voice coils remove heat more efficiently than smaller ones; additional measures such as increasing convection cooling and increasing radiation to outside elements can be helpful as well.

3.4.5 Distortion in Transducer Magnetic Systems. Many aspects of the direct radiator's magnetic system can affect the distortion performance in a transducer (Gander, 1981). The primary effect is the variation in magnetic operating point that comes as a result of signal current in the voice coil modulating the magnetic structure's operating point. This happens to some degree in all designs, but the effect on acoustical performance depends on the degree of flux modulation of the static magnetic field. The general result of flux modulation is to increase the level of single-ended, or second harmonic, distortion.

Figure 6 shows the demagnetization curves for three magnetic materials, Alnico V, typical ferrite, and neodymium based systems. Typical operating points are shown on the curves by the black dots. With the Alnico V system, the flux curve has a moderate slope in the operating region, and there is little tendency for flux modulation to be a problem. However, a strong input signal can result in permanent demagnetization if the operating point is forced down on the steep portion of the curve to the left of the operating point.

With the ferrite magnet there is a certain amount of flux modulation due to the uniform slope of the curve. With the high-energy neodymium materials, the demagnetization curve is located so high in the second quadrant of the B-H representation that the magnetic circuit is very likely to be operating at or near saturation. In this case the degree of flux modulation will be minimum.

Figure 7 shows how a typical problem was solved. The distortion data shown at A is characteristic of an older 300 mm diameter LF transducer operating with an Alnico V magnet structure. Keeping the same moving system but changing to a typical ferrite magnet structure yields the data shown at B. Note the significant increase in mid-frequency distortion.

The data at C shows the effect of a ferrite magnet system outfitted with undercut polepiece geometry and a large, low resistance aluminum flux shorting ring placed at the base of the polepiece. The significant reduction in second harmonic distortion results from the setting up of an induction current in the shorting ring that counteracts the normal tendency of voice coil current to shift the magnetic operating point. JBL referred to this design as Symmetrical Field Geometry, (SFG™).

Other magnetic distortion effects include:

1. The generation of eddy currents in local iron structures; this results in an increase in third-harmonic distortion.

2. Inductance modulation of the voice coil, due the the varying amount iron instantaneously surrounded by the voice coil. This results in increased second harmonic distortion.

3. Temperature effects. as the magnetic structure heats up; flux density and efficiency are reduced. The effect is similar to the resistance increase caused by voice coil heating. Upon cooling, normal performance is restored.

3.4.6 Thermodynamic and FM Distortion Effects. Thermodynamic distortion, or air overload, is present in very small quantities in direct radiator systems and may be disregarded in the normal operation of cones and domes.

Frequency modulation (FM) components are more likely to occur, especially at low-mid frequencies, where high cone excursions at lower frequencies may modulate higher frequencies as the cone's velocity attains a significant percentage of the velocity of sound. The effect is quite noticeable in single-cone systems, but is minimized in multi-way systems. Beers & Belar (1943) have discussed the phenomenon in detail.

Another aspect of thermodynamic distortion present in sealed direct radiator systems is due to the nonlinearity of the enclosed air spring. In general, if the maximum instantaneous change in enclosed volume can be limited to about 0.5%, the effect of the nonlinearity can be ignored (Gander, 1986). The type and amount of enclosure damping material in a sealed enclosure has the additional effect of increasing the actual enclosed volume. The work of Leach (1989) is significant in this area.

3.5 The Decoupled Cone

Over the years, loudspeaker designers have observed that, at high frequencies, the cone ceases to move as a single unit, but rather breaks up into more complex motions. These result in an effective lighter moving mass at high frequencies, extending the HF response of the system. This was first commercialized by the Altec Duocone loudspeaker (Badmaeiff, 1958). The effect is often difficult to control in production, and there is always the likelihood that FM distortion will become a problem. Figure 8A shows a section view of the cone profile used in the Duocone loudspeaker, and a mobility mechanical circuit is shown at 8B. The modern soft dome HF unit exploits this effect more predictably through high damping of the moving system.

3.6 Directional Properties of Direct Radiators

Finite element analysis (FEA) provides a means of analyzing in detail the directionality of loudspeaker cones and domes, taking into account multiple breakup effects. Assuming that the moving systems have only a single degree of freedom, the polar data in Figure 9 shows the theoretical directionality of a piston mounted in a large baffle as a function of *ka*. The on-axis DI of each directional pattern is also shown in the figure (Beranek, 1954; Olson, 1957). Similar data is shown in Figure 10 for a piston mounted at the end of a long tube. These two conditions simulate normal mounting conditions for loudspeakers. For many routine acoustical applications, this data is sufficiently accurate.

3.7 Gradient Loudspeakers

The simplest gradient loudspeaker is an unbaffled cone transducer operating as a *dipole*. The natural directional response for a dipole is a cosine pattern, or a "figure-eight" (Olson, 1973). Dipoles are notoriously inefficient and have not been widely used in sound reinforcement applications; however, there are certain applications where the specific radiation pattern could be very useful. During the early 1970s, Altec produced a modified gradient loudspeaker in which one side of the dipole operated in series with an acoustical signal delay. The delay produced a hypercardioid pattern in much the same manner as a typical dynamic microphone does.

Figure 11A shows a section view through the hypercardioid loudspeaker. The output from the rear of the transducer is sent through a constant delay, provided by the path length and the resistive elements in that path. The result of the delay is that, at 135°, output from front and back of the transducer will cancel. For useful output from the front of the transducer, the signal fed to the system must be equalized with a 6-dB per octave rise for each halving of frequency. The equivalent circuit of the Altec 614 ExtendaVoice loudspeaker is shown at B, and off-axis polar data is shown at C. A system such as this would normally be used for speech purposes in highly reverberant conditions where the loudspeaker's DI of 6 dB would work to its advantage. Vertical stacks of the device can increase total output capability as well as increase the DI.

4. HORNS AND COMPRESSION DRIVERS

4.1 Early Development

Many engineers and physicists have contributed to horn-compression driver development over the years. Early versions of the horn were used by many tinkerers who did not really understand how the the horn worked – they knew only that somehow the horn increased acoustical output (Hanna and Slepian, 1924). The first example of thorough engineering was carried out by Bell Telephone Laboratories (Wente & Thuras, 1934), working from the model of horn impedance described by Webster (1919). Significant later development was carried out by Klipsch (1941), who designed a remarkably compact bass horn, and Salmon (1941, 1946), who described the impedance characteristics of several important horn designs, including the hyperbolic, or Hypex, profile (Leach, 1996).

Figure 12 shows the real part of the radiation impedance for hyperbolic, exponential, and conical horn profiles. Here, only the exponential and hyperbolic profiles provide useful output at low frequencies. In our discussion we will restrict ourselves to the exponential profile, since it has found almost universal application in recent decades.

Figure 13A shows the real and imaginary parts of throat impedance for a long exponential horn. For a horn of practical length, we might observe impedance components such as those shown at B. The slight peaks and dips in response are due to reflections from the mouth of the horn back to the throat. There is an optimum mouth size for a horn of specific cutoff frequency to minimize reflected waves from the horns mouth (Keele, 1973)

The compression driver is designed to match the impedance of the electromechanical system to the throat of the horn, and the radiation impedance, reflected to the electrical side of the circuit, is:

$$R_{ET} = [S_T(Bl)^2]/\rho_0 c S^2_D \quad (3)$$

where S_T is the area of the driver throat and S_D is the area of the driver diaphragm. The phasing plug in the driver is the means by which the ratio of the two areas is adjusted.

When the driver is attached to the horn, the efficiency in the range where the horn's radiation impedance is essentially resistive is:

$$\eta = [2R_E R_{ET}]/(R_E + R_{ET})^2 \quad (4)$$

where R_E is the voice coil resistance. When the voice coil resistance is made equal to the radiation resistance, the efficiency of the driver over its normal passband will in theory be 50%. (In practice, efficiencies of the order of 30% can be attained; this is only about 2 dB below the theoretical maximum.)

4.2 Region of Flat Power Output

The data of Figure 14 shows the normal power response for a compression driver/horn combination when the horn's throat impedance is resistive. The LF limit is due to the primary resonance of the driver; normally, for a typical HF compression driver, this is in the range of 500 Hz.

The principal midband rolloff commences at what is called the mass break point, f_{HM}, given by:

$$f_{HM} = (Bl)^2/\pi R_E M_{MS} \quad (5)$$

where M_{MS} is the mass of the moving system. For most HF compression drivers the mass breakpoint takes place around 2500 to 4500 Hz. It is considered a fundamental limit in HF drivers, inasmuch as today's magnetic flux densities are maximized in the range of 2 tesla, and minimum moving mass is limited by metals, such as titanium and beryllium, that are are not likely to be improved upon in the near future.

Two additional inflection points are often seen in the HF driver response curve: one is due to the volume of the front air chamber in the driver, the space between the diaphragm and the phasing plug. Its effect on response may be seen as low as 8 kHz in some drivers. Voice coil inductance may cause an additional HF rolloff at high frequencies. This may be compensated for through the use of a silver or copper shorting ring plated on the polepiece in the region of the voice coil. (See section 2.4.5).

4.2.1 Reactance Annulling. In some compression driver designs, a mechanical stiffness in the form of a small air chamber is located adjacent to the driver's diaphragm. The mechanical reactance resulting from the stiffness directly cancels the mass reactance portion of the radiation impedance, resulting in a more resistive impedance in the region of the cutoff frequency. The effect of this is greater acoustic output for a given drive voltage (Plach, 1953; Plach and Williams, 1955).

Reactance annulling is not normally used in HF compression drivers, but it is used in the design of bass horns, most notably in the case of the Klipschorn, where it results in extended response down to about 35 Hz (Klipsch, 1941).

4.3 Distortion

The dominant cause of distortion in compression driver-horn systems is due to thermodynamic, or air, overload (Rocard, 1931). This comes as a result of extremely high pressures that exists at the horn throat:

$$Lp = 94 + 20 \log \sqrt{W_A(\rho_0 c)/S_T} \qquad (6)$$

where W_A is the acoustical power generated and S_T is the throat area (m^2).

For example, in plane wave propagation, an intensity of one watt per square centimeter will produce a sound pressure level of 160 dB. For levels in this range, successive pressure peaks are tilted forward as they propagate down the horn due to the increase of sound velocity at elevated temperatures under adiabatic conditions.

Thuras, *et al.* (1935) analyzed the problem, leading to a simplified equation giving the percent second harmonic distortion in horn systems:

$$\text{Percent 2nd HD} = 1.73\,(f/f_c)\sqrt{I_T} \times 10^{-2} \qquad (7)$$

where I_T is the intensity in watts per square meter at the horn's throat, f is the driving frequency, and f_c is the cutoff frequency of the horn.

Figure 15 presents measurements of the 2nd harmonic distortion produced by two horns of differing cutoff frequencies. The fundamental output in each case was held constant at a level of 107 dB at a distance of one meter, and the second harmonic distortion has been raised 20 dB for ease in reading. The scale on the right ordinate indicates the second harmonic distortion in percentage. The cutoff frequency of the horn used for the data shown at A is 560 Hz, while that of the horn used for the data shown at B is approximately 70 Hz. The average difference in distortion is 8 dB.

A horn with a high cutoff frequency has a rapid flare rate, and as such will lack good directional control at low frequencies. This is a tradeoff that the design engineer has to reconcile for a variety of applications. For example, sound reinforcement applications require specific pattern control in the range from 300 Hz upward, while music monitoring applications may require horn pattern control no lower that about 800 Hz.

If the exact mechanism for a given kind of distortion can be defined mathematically, a model can be implemented and used to predistort the signal, resulting in reduced distortion in the system's output over a given power operating range. Klippel (1996) describes the techniques used here.

4.4 The Role of Secondary Resonances

As shown in section 3.2, the power response of a horn driver is flat up to its mass break point, above which the response rolls off 6 dB per octave. However, beneficial secondary resonances may be used to increase the driver's output above this point (Murray and Durbin, 1980; Durbin, 1982). These resonances generally occur in the surround sections of the diaphragm and are decoupled from the diaphragm itself. As in the case of decoupled resonances in cones discussed in section 2.5, the lowering of moving mass at higher frequencies can result in a considerable increase in useful HF response. Figure 16 shows the response for three different drivers, all with 100 mm diameter diaphragms and mounted on the same horn. The JBL 2440 has an aluminum diaphragm and a half-roll surround. The secondary resonance is about 9 kHz. Response is maintained fairly flat to that frequency, falling off rapidly above. The TAD 4001 has a beryllium diaphragm with a half-roll surround. Note that, due to the greater stiffness of the material, the secondary resonance has been moved out to about 17 kHz. The JBL 2441 driver has an aluminum diaphragm, with special surround geometry that moves the secondary resonance to beyond 20 kHz. This results in smooth, extended response within the normal audio band with no pronounced peaks.

4.5 Directional Response

The basic exponential horn exhibits directional response as shown in Figure 17. Over decades of development, numerous methods have been used to improve directional performance at high frequencies for sound reinforcement applications:

A. Multicellular Horn. In the early days (Wente and Thuras, 1934), groups of exponential cells, each about 15 degrees wide, were clustered together to define a specific solid radiation angle. This produced excellent results at mid-frequencies, but there was pronounced "fingering" of the response along the cell boundaries at higher frequencies.

B. Radial Horn. In this design, the horn's horizontal profile is conical, with straight, radial sides defining a target coverage angle. The vertical profile is tailored to make a net exponential profile along the horn's primary axis. The nominal horizontal and vertical -6 dB beamwidth of a radial horn is shown in Figure 18A (Olson, 1957).

C. Acoustical Lenses. A slant-plate acoustical lens can be placed at the mouth of an exponential horn to diverge the exiting waves in one dimension, as shown in Figure 18B (Kock and Harvey, 1949; Frayne and Locanthi, 1954).

4.5.1 Uniform Coverage Horns. Also known as constant coverage horns, these designs date from the mid-1970s to the early 1980s (Keele, 1975; Henricksen and Ureda, 1978; Keele, 1982; Smith, Keele, and Eargle, 1983). The basic design common to a number of manufacturers uses a combination of exponential loading, wave guide principles, and flared terminations to produce uniform nominal coverage angles in the horizontal and vertical planes. The general shape of the beamwidth curve is shown in Figure 19A, as it applies to the horizontal and vertical planes independently. Figure 19B shows the measured beamwidth and DI of the JBL 2360 Bi-Radial® horn.

5. ARRAYS

Both horns and direct radiators may be treated the same in terms of arraying. In this section we will examine some useful concepts. Single element, line, and planar arrays differ in their radiation characteristics over distance, as shown in Figure 20. The simple inverse square relationship of a point source (A) is modified by a line array as shown at B, and a very large planar array will show little attenuation with distance up to limits proportional to the array dimensions (Rathe, 1969). A finite planar array will have the characteristics shown at D. Long horizontal line arrays have been placed above prosceniums in performance spaces to extend the range of high direct-to-reverberant ratio toward the rear of the space; large planar arrays are the mainstay of mega-event music reinforcement (Davis and Wickersham, 1975).

5.1 The Simple Line Array
Kuttruff (1979) describes the polar response of an omnidirectional line array in the plane of the array as:

$$R(\theta) = \left(\sin[1/2\,Nkd\sin\theta]\right) \Big/ \left(N\sin[1/2\,kd\sin\theta]\right) \qquad (8)$$

where N is the number of elements in the array, k is $2\pi f/c$, d is the spacing of the elements in the array, and θ is the measurement angle. For four elements, the polar response is shown in A through D. The directivity factor is shown at E.

A four-element array, as shown in Figure 21, will exhibit good pattern control over the range from $d/\lambda = 0.5$ to 2.0. At higher frequencies the pattern will exhibit narrowing and lobing, and simple arrays of more than six elements will have unsatisfactory characteristics.

5.2 Tapering the Line Array
The accepted method of extending the uniform coverage range of a line array is through frequency tapering, or shaping, to allow the array to in effect reduce in size with rising frequency. Some techniques are shown in Figure 22. Electrical frequency tapering is shown at A, and acoustical frequency tapering is shown at B (Klepper and Steele, 1963). A unique "barber-pole" array is shown at C (Kleis, 1959).

5.3 The Product Theorem
The product theorem (Kinsler and Frey, 1980) states that an array composed of uniform directional elements will exhibit the same far-field response as a like array of omnidirectional elements *multiplied* by the directional properties of one of the single directional elements. This is another way of stating the principle of superposition, and it can be used to advantage in estimating the directional response of complex arrays.

5.3.1 The Bessel Array
Franssen (1980) describes an array of elements whose amplitude drive characteristics are derived from Bessel coefficients (Kitzen, 1983; Keele, 1990). A simple 5-element array is shown in Figure 23A, and simplified wiring diagrams to derive the drive coefficients are shown at B and C. The far-field response of the array, modeled with

omnidirectional sources, is shown at D. Note that the response is essentially omnidirectional over a 100-to-1 wavelength ratio.

Via the product theorem, each omnidirectional element could be replaced with a directional element, all oriented in the same direction, with the resulting response of the array exhibiting the chosen directional characteristic over the same 100-to-1 wavelength ratio.

The Bessel array has great potential for speech reinforcement in live spaces. Its phase response varies with angle and frequency, however, and it is thus difficult to integrate the concept into a standard system.

5.4 Very Large Arrays for Music

Concert sound reinforcement in very large venues, indoors or out, requires large arrays, and the accepted method of assembling these arrays is to use building blocks that are each relatively full-range units. Thus, the assembled system, normally resembling a large plane, or sets of planes with curved sections connecting them, has much in common with the principles described in Figure 20. As an example of this we show in Figure 24 an elevation view of a typical large vertical array (A) along with the on- and off-axis response (B) measured in an arc along the listening plane (Gander & Eargle, 1990).

The great virtue of these systems is their ability to deliver very high sound pressure levels at considerable distances with very low distortion. The primary defect is the dense lobing and "time smearing" that inevitably results from such a multiplicity of sources covering each single listening position. Actually, the aim here should be to keep the coverage at each listening position as dense as possible, inasmuch as the greater the number of effective sound sources, the finer the lobing patterns and the denser the received signal will be in terms of critical bandwidth.

5.5 Prospects for the Future: Steerable Arrays

To some extent this technology is already on hand. Relatively simple arrays can be reconfigured, through sequential timing, to steer their beams as needed (Augspurger and Brawley, 1983; Augspurger 1990; Meyer, 1990). While far-field modeling may be fairly simple, the fact that most listeners are seated in the transition region between near and far fields makes the problems of reconfiguration and uniformity of coverage fairly difficult. These are our challenges for the future (Meyer, 1984).

DIRECT RADIATORS VERSUS HORN LOADING: DESIGN PRINCIPLES AND HISTORICAL PERSPECTIVE IN SOUND REINFORCEMENT

6. HISTORICAL TIMELINE OF HORNS AND DIRECT RADIATORS IN SOUND REINFORCEMENT

Date:	Horns:	Common Influences:	Direct Radiators:
1874			Siemens patent
1907		Thermionic Valve (Vacuum Tube)	
1915	Pridham & Jensen Magnavox horn/driver		
1916	First PA system, Western Electric (W. E.)		
1919	Webster horn paper		
1920	First indoor PA with central array		
1925	WE 555 driver	Two-Way System with Crossover, Minton and Ringel (RCA)	Rice & Kellogg , GE
1926		Talking pictures	
1928	W. E folded "Roxy" horn, Wente and Thuras		
1929			Wolf & Malter (RCA) mutual coupling
1930		Wolf & Malter (RCA); horn, direct radiator, and array directivity	Thuras (W. E.) vented box
1933	Multicellular horn, Wente (W. E.)		
1934	"Auditory Perspective" experiments (Bell Labs, W. E.)		
1936	Shearer horn system, MGM		

DIRECT RADIATORS VERSUS HORN LOADING: DESIGN PRINCIPLES AND HISTORICAL PERSPECTIVE IN SOUND REINFORCEMENT

1937	W. E. 594 driver		
1941	Klipsch corner horn		
1942		Alnico Magnets	
1943			Altec 604 co-axial
1945	Lansing and Hilliard; Altec A-2 and A-4 theater systems		
1946	Salmon: Hypex horn		
1949	Acoustic lenses, Kock and Harvey, Bell Labs		
1953	Frayne and Locanthi; JBL 375 (2440) driver and acoustic lenses		
1954		Ferrite Magnets	Villchur, AR Acoustic Suspension System
1958			Kleis, Philips column loudspeaker
1963			Klepper and Steele; Tapered line array
1967	Altec A-7, Klipsch La Scala	Electric Rock Touring	WEM Columns Shure Vocal Master
1969	Altec Cinema Bins at Woodstock	Woodstock, Isle of Wight rock festivals	4x4 LF array of D-130s at Woodstock
1970	JBL Perkins bass horns	High-power Amplifiers	WEM Festival System
1971			Thiele & Small
1973	Martin Audio bass horn, "Philishave" midrange horn		

1974			Grateful Dead "Wall of Sound" large surface-source discrete array
1975	EV CD horns		
1976			Clair Brothers S-4 system
1977	Altec "MantaRay" horns		
1978	JBL 2441 HF driver		
1979		Processed Systems (Meyer)	
1979	Turbosound TMS-3 system		
1980	JBL Bi-Radial horns		
1981	Community M4 driver		
1982	JBL 2445 ferrite driver with titanium diaphragm	Digital Compact Disc introduced	
1986			Showco Prism® controlled directivity sound system
1987	Neodymium compression drivers: JBL 2450, EV NDYM-1		
1991	JBL Array Series with first neodymium magnet woofer		

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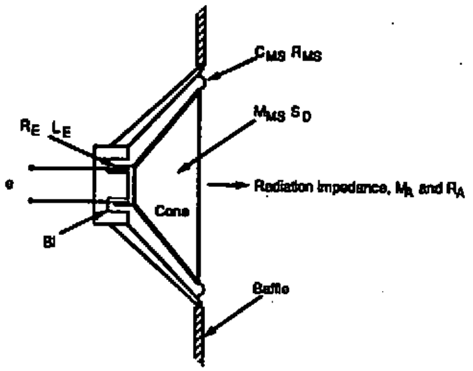
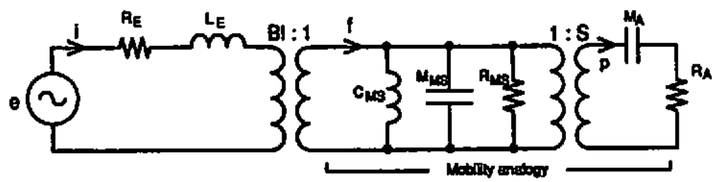
Figure 1. A direct radiating transducer. Mechanical view (A); electrical equivalent circuit (B); radiation impedance for a piston mounted in a large baffle (C); frequency response of the system (D).

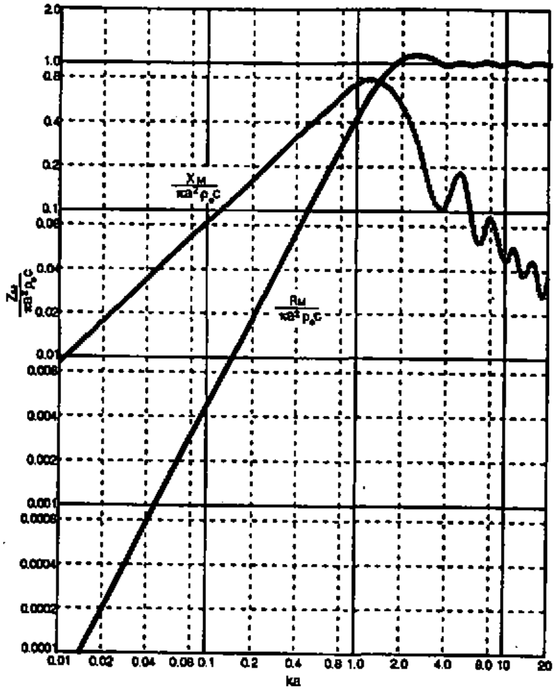


A

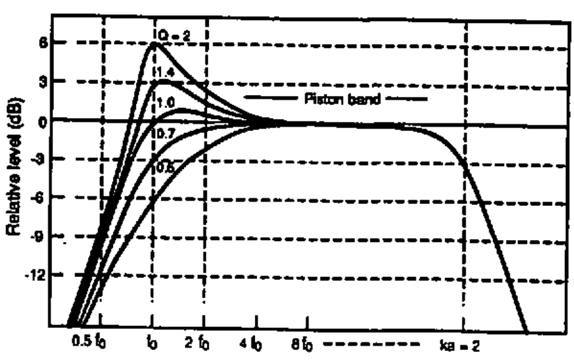


B

Figure 1. Continued.



C



D

Figure 2. Mutual coupling, 1, 2, and 4 units.

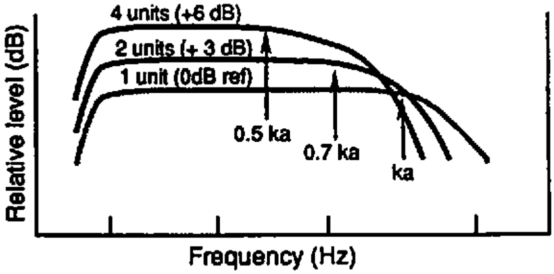
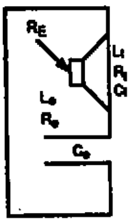
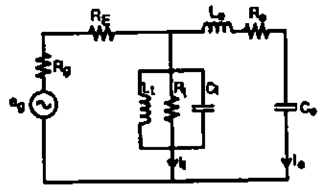


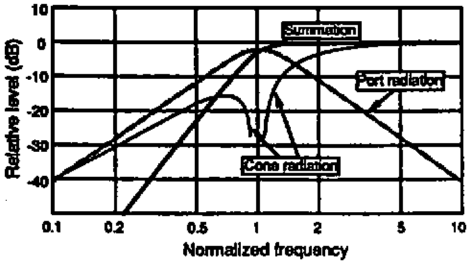
Figure 3. A ported system. Section view (A); equivalent circuit (B); cone and port contributions to output (C).



A



B



C

Figure 4. Dynamic compression in a 380 mm LF transducer, 1 watt and 100 watts.

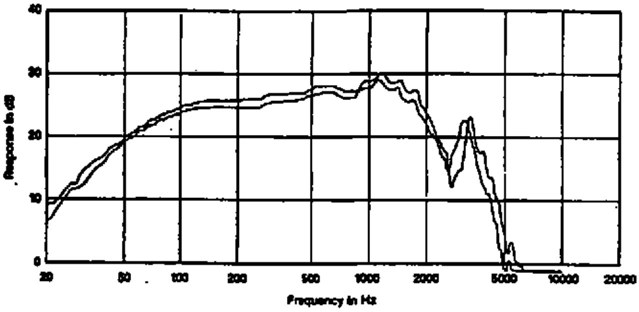


Figure 5. Dynamic compression versus time for three 380 mm LF transducers

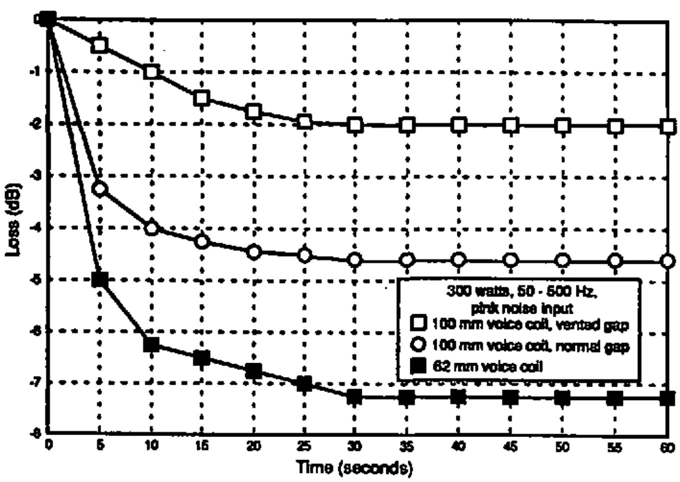


Figure 7. Distortion due to magnetic nonlinearities. Same moving system used for all measurements. Standard Alnico V structure (A); standard ferrite structure (B); flux stabilized ferrite structure (C).

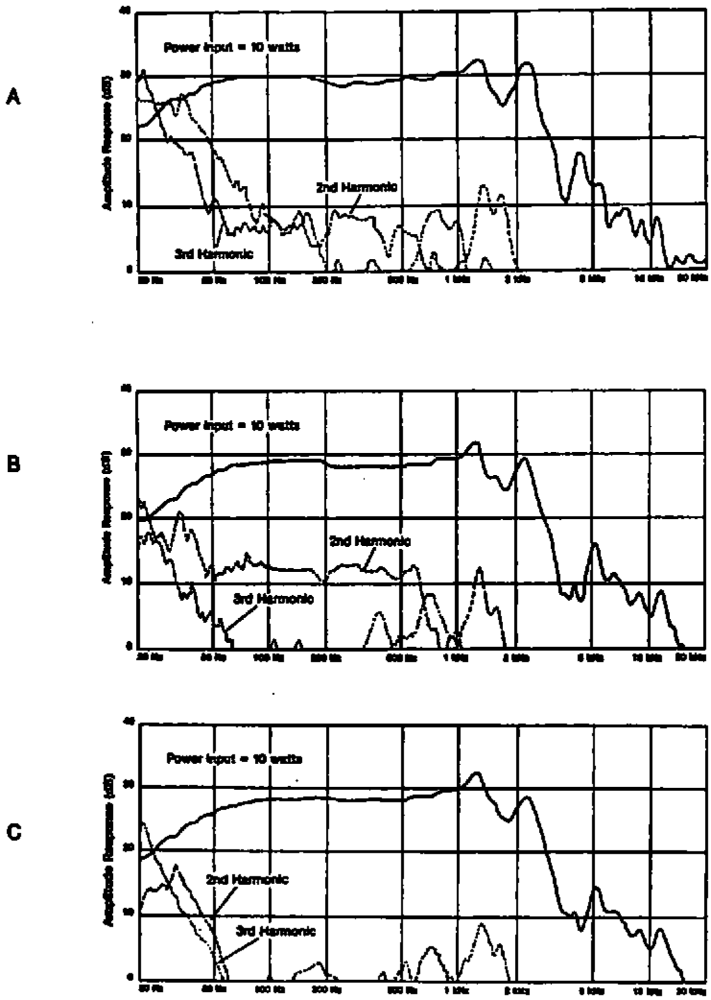


Figure 6. Demagnetization curves for three magnetic materials; dots indicate nominal operating points.

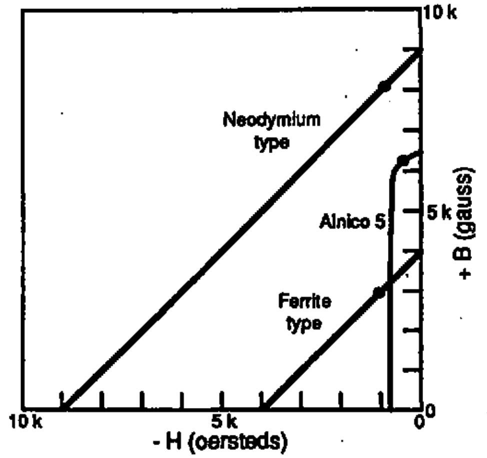


Figure 8. Details of the Altec Duocone loudspeaker. Section view of cone (A); equivalent mechanical circuit (B).

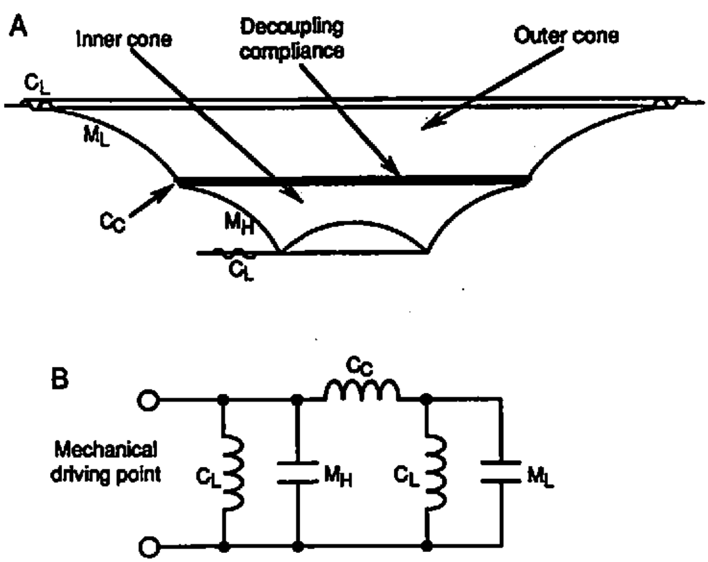


Figure 9. Directional characteristics for a piston mounted in a large flat baffle.

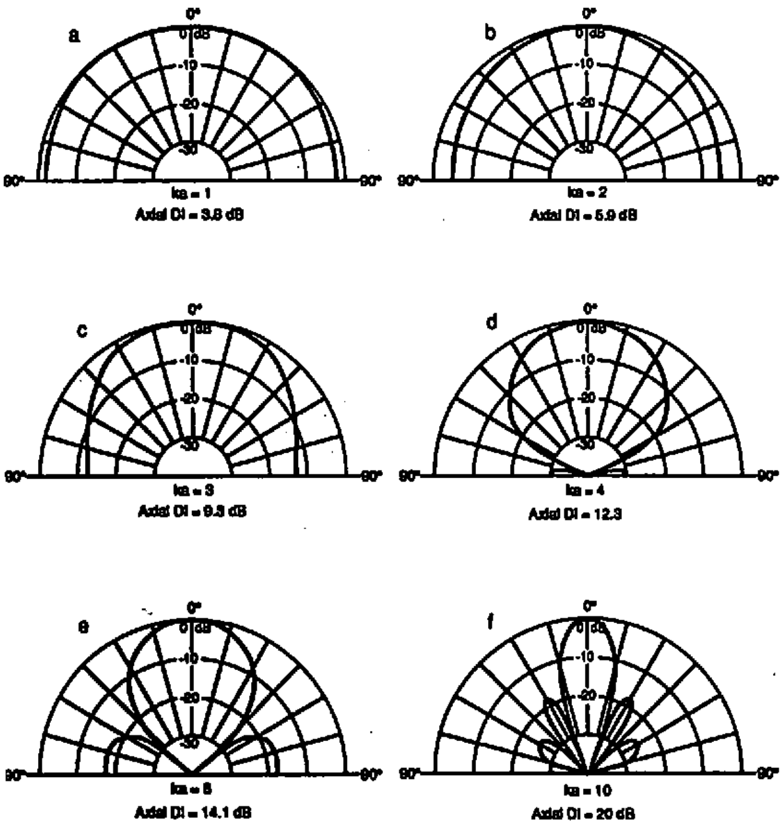


Figure 10. Directional characteristics for a piston mounted at the end of a long tube.

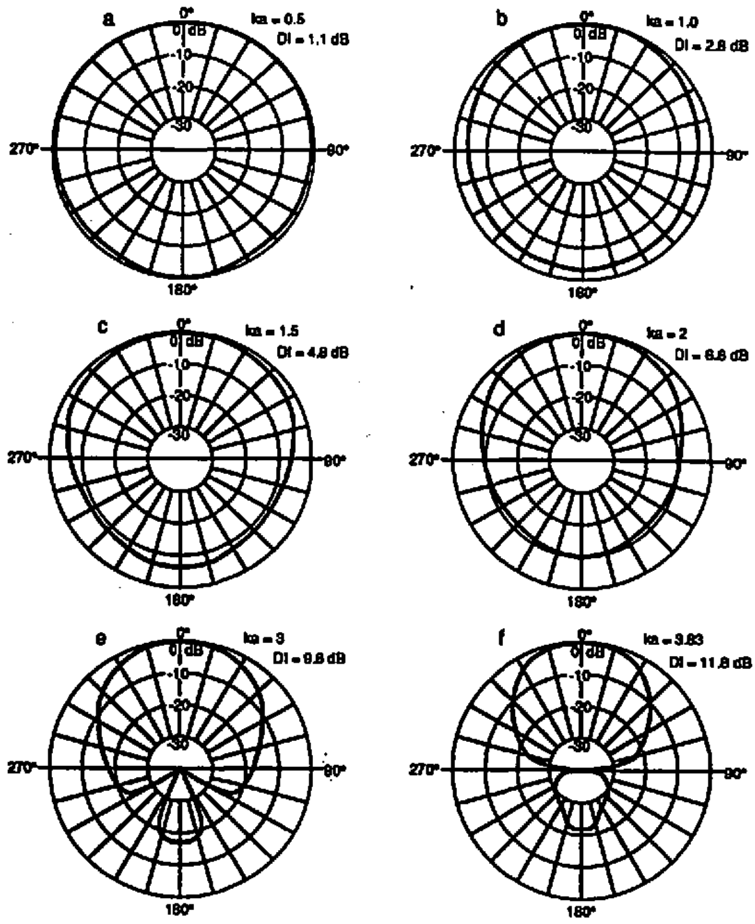


Figure 11. Details of a gradient loudspeaker. Section view of loudspeaker (A): equivalent circuit (B); frequency response (C)

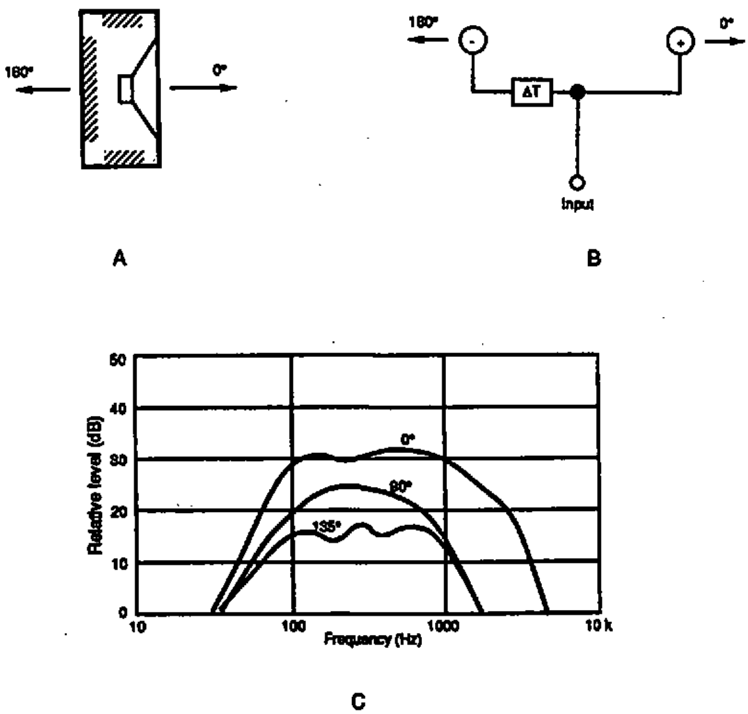


Figure 12. Radiadtion resistance at the throat of three types of horns.

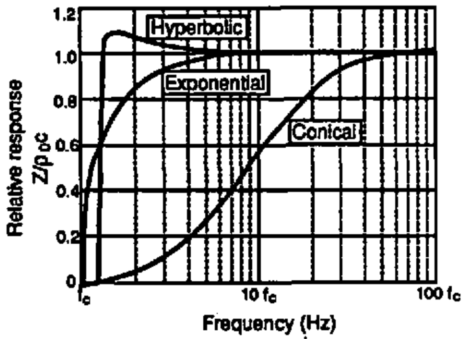
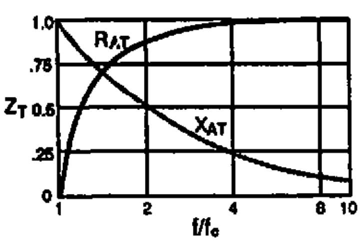
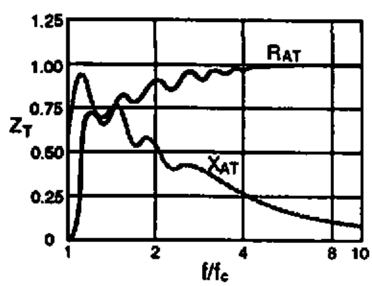


Figure 13. Radiadtion resistance and reactance for a very long horn (A) and a short horn (B).



A



B

Figure 14. Plane wave tube response and impedance of a100 mm diaphragm compression driver.

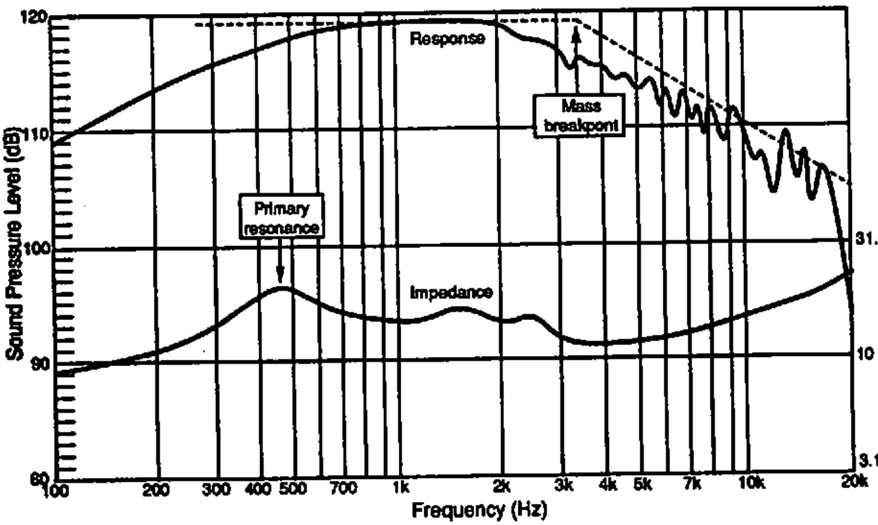


Figure 15. Distortion in two horns. Rapid flare rate (A); slow flare rate (B).

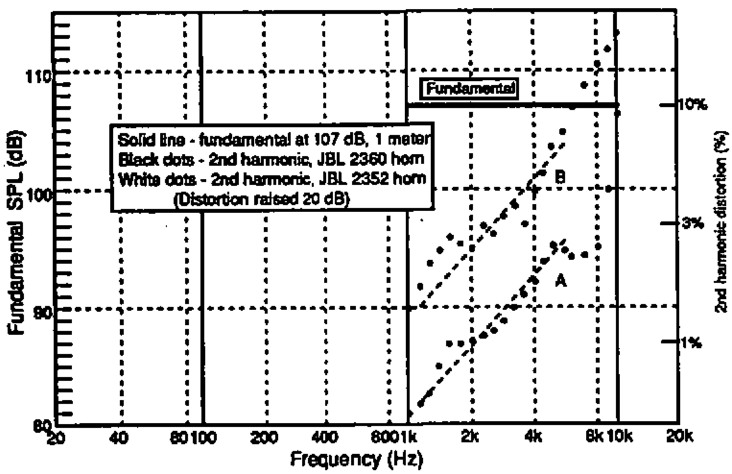


Figure 16. The role of secondary resonances in compression drivers.

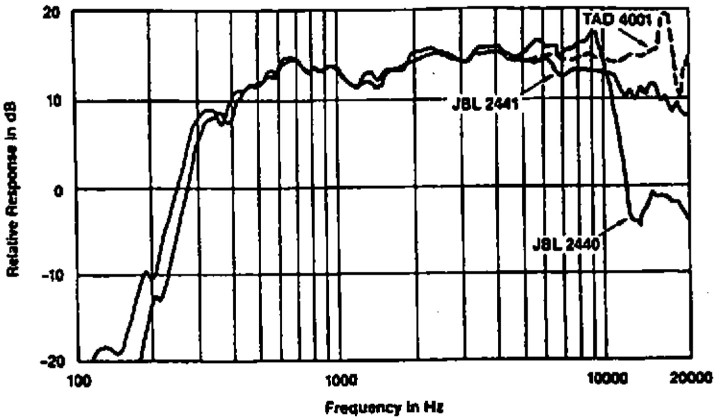


Figure 17. Directivity characteristics of exponential horns
(Data after Olson, 1957).

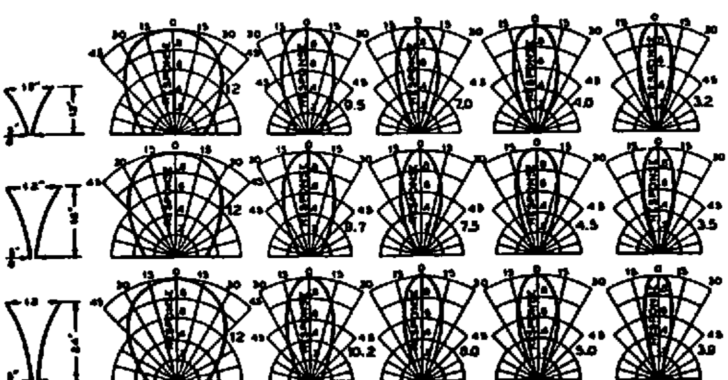


Figure 18. Beamwidth and DI for a radial horn (A) and an acoustic lens (B).

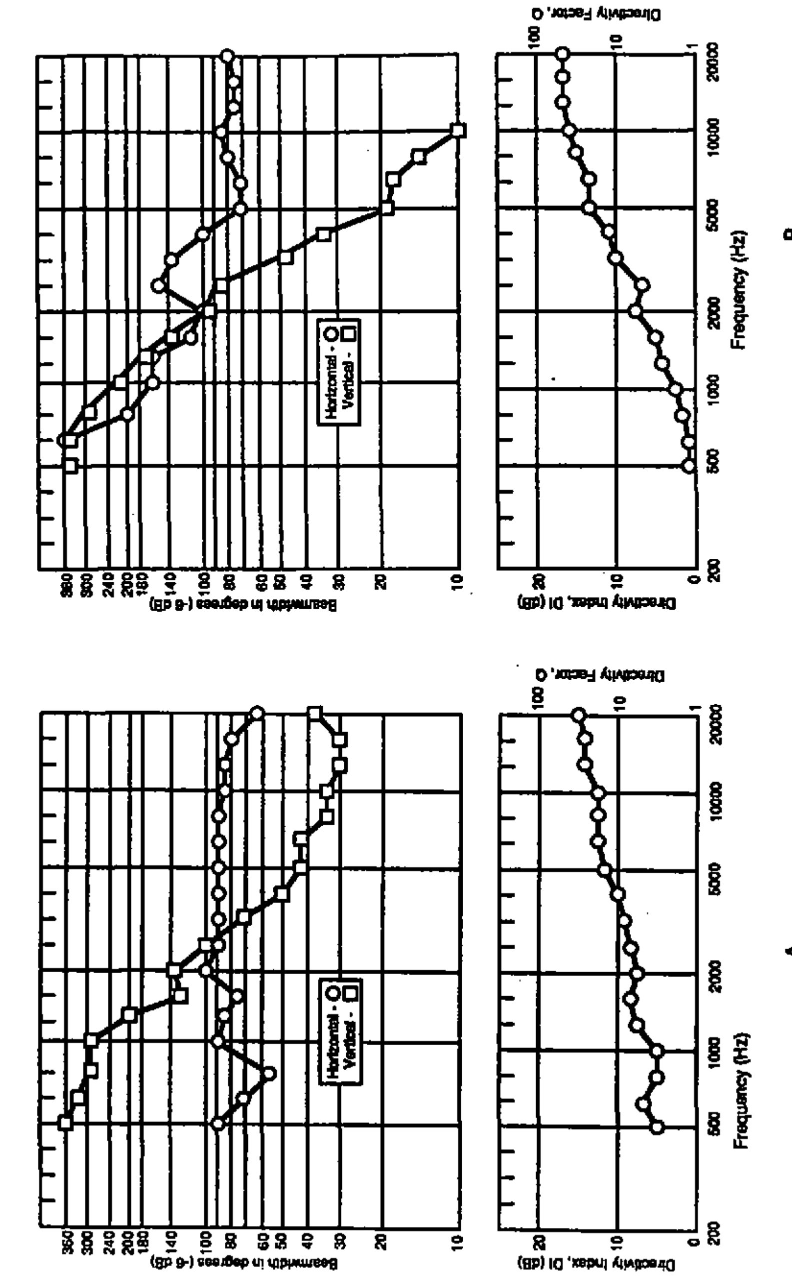
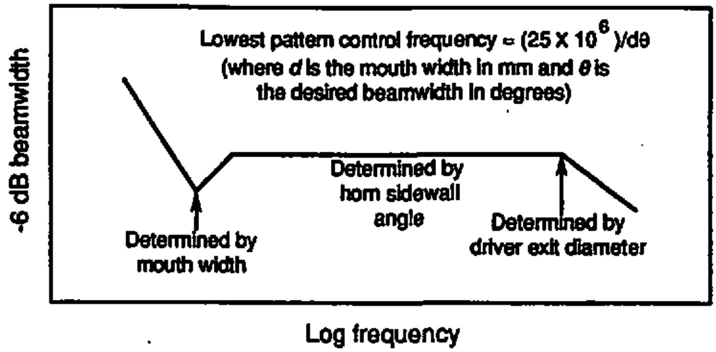
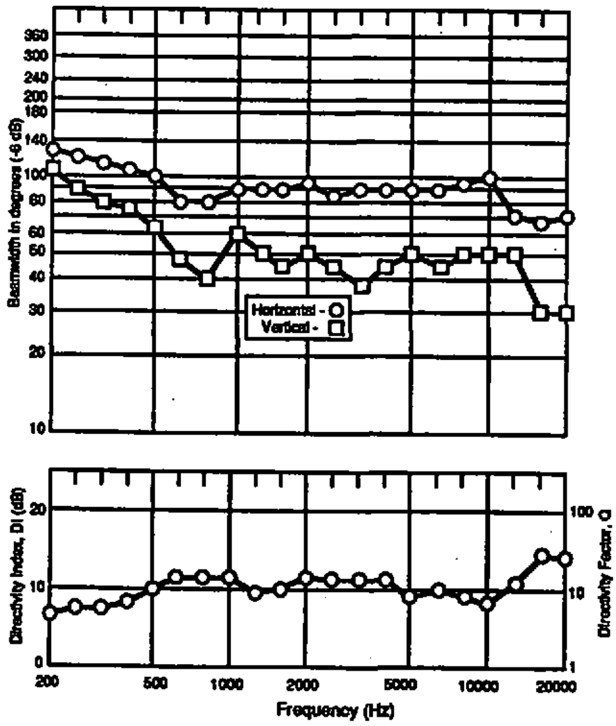


Figure 19. Uniform coverage horns. Pattern control regimes (A): beamwidth and DI for the JBL 2360 Bi-Radial horn (B).



A



B

Figure 20. Attenuation of sound away from point, line, and plane sources. Point source (A): line source (B); Plane source of differing side dimensions; example of a narrow plane (D).

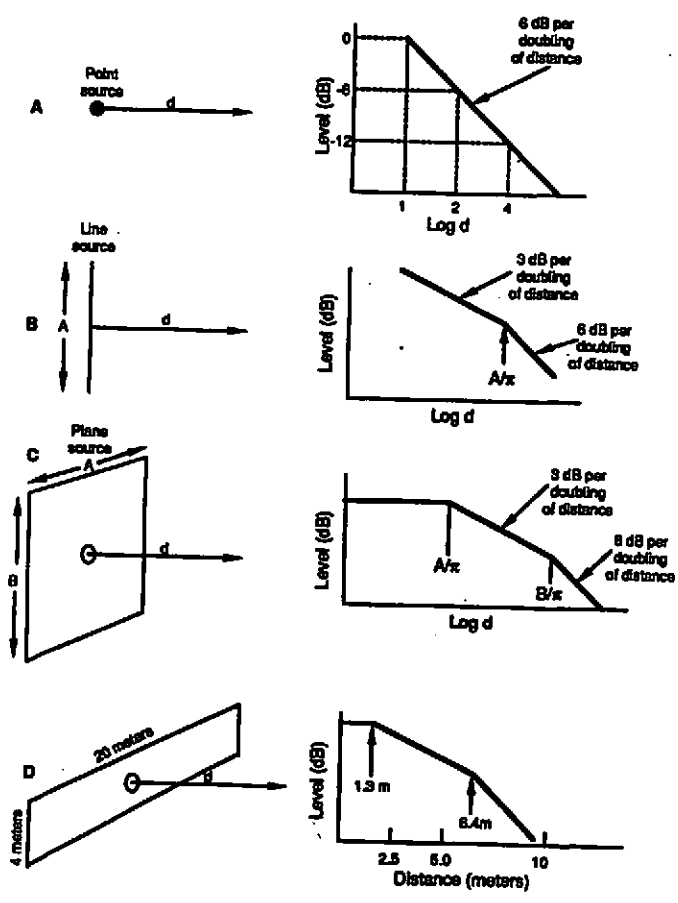


Figure 21. A simple line array of four identical elements. The spacing between elements is *d*. For *d* equal to 0.2 meter, we present the directional data for 200 Hz (A), 350 Hz (B), 500 Hz (C), and 1000 Hz (D). The directivity factor for several column arrays is given over an extended d/λ range.

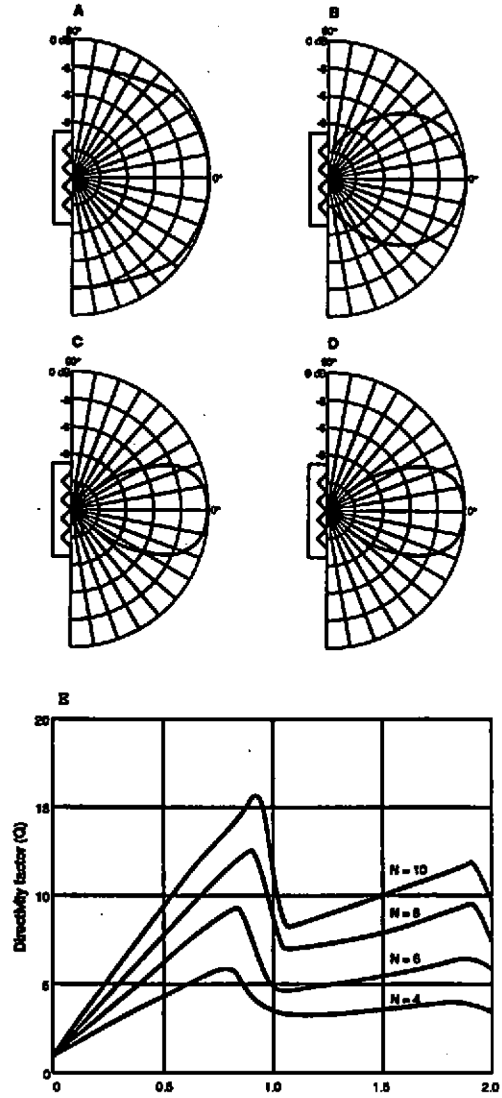
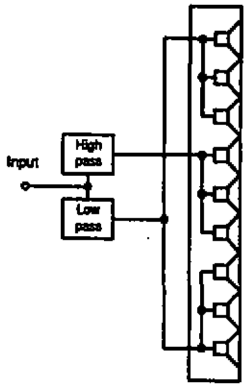
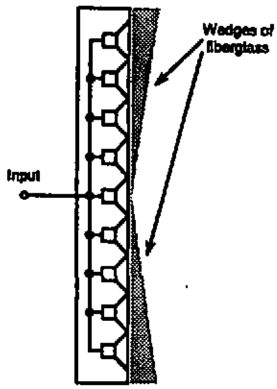


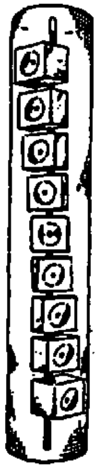
Figure 22. Tapered line arrays. Electrical tapering (A); acoustical tapering with absorptive wedges (B); tapering by placement, the "barber pole" array (C).



A



B



C

Figure 23. The 5-element Bessel array. View of array (A); two wiring diagrams that will produce the array (B and C); response of the Bessel array in the far field for a simulated omnidirectional source (D).

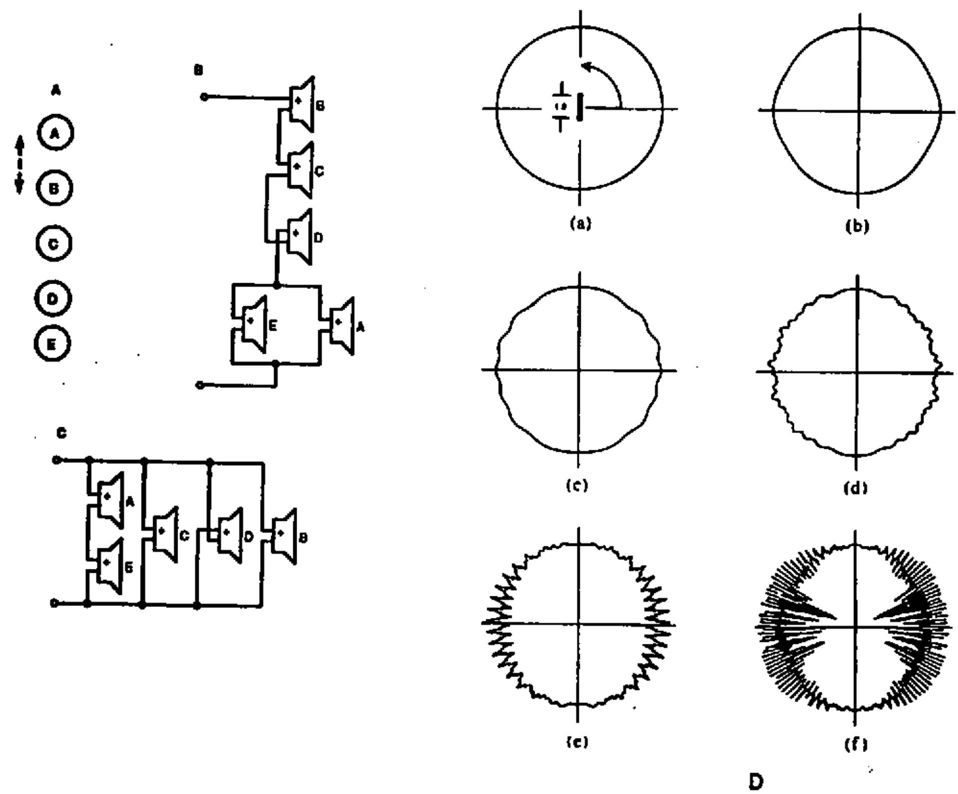
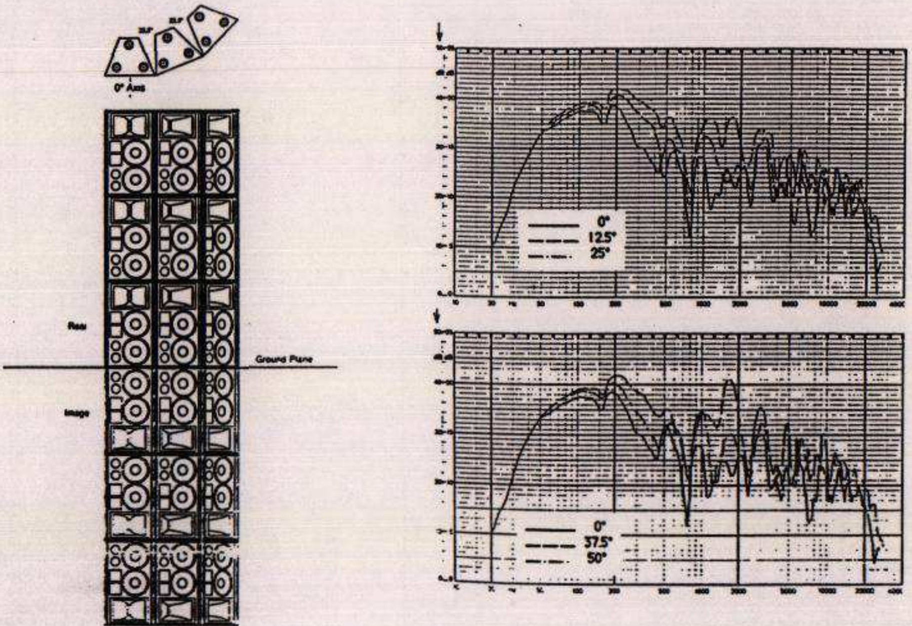


Figure 24. Large arrays for concert sound reinforcement. Views of a 9-element array of full-range systems (A); off-axis response of the array as measured on the ground plane at a distance of 5 meters (B).



A

B