However, in the near field we must account for the true path length from each element of the array to the observer [9]. Picture an observer at a normal listening position relative to the array. This might be perpendicular to the midpoint of the array and at a distance on the order of only two to three times the array length. In this case elements at either end of the array are significantly farther away then central elements. Even prior to rotation of the array, a near-field model must include the reduced level and extra phase rotation of the end elements that are farther away.

Near-field polar rotation can be modeled as Keele does in his paper on Bessel arrays [10]. However, with our near-field model it was decided that a rectangular coordinate geometry was more useful than a polar one. Rather than full rotation we wanted to model the typical observer's vantage geometry for real-line arrays in a domestic environment (that is, doing deep knee bends at the listening distance). The program asks for an observation distance in meters out from the line array. The observation point is then swept away from the centerline on a line parallel to the array (at right angles from the centerline) for a defined distance (Fig. 25). The program continuously recalculates the summed output of all elements along this traverse and plots the resultant curve. This can be repeated for multiple frequencies and then plotted in a two- or three-dimensional format. Since most of our arrays are symmetrical, the program only sweeps from the midpoint in one direction ("up"). A nonsymmetrical array can be easily accommodated by calculating the center-up sweep and then reversing the string of coefficients (effectively "inverting" the column) for a sweep in the other direction.

Further variations of the program allow position sweeps perpendicular to the array (along its central axis). In addition the observation point can be fixed and the frequency varied to show an array-related frequency response.

4.1 Effects of Observation Distance on Array Beamwidth

To explore the effects of observation distance on the array beamwidth, a sequence of near-field passes or sweeps were simulated for the 23-tweeter array at ever greater distances. As the distance was increased, it was hoped that this would ultimately show a profile indistinguishable from the far-field polar response. The results were plotted in two ways:

1) The vertical sweep distance was held constant while the distance to the observation line was doubled repeatedly. In other words, the range of observation height remained unchanged with the observation distance. Obviously as the observation distance increases, the swept vertical *angle* decreases.

2) The vertical sweep distance was made proportional to the observation distance. In this way the vertical sweep angle was kept constant.

Fig. 26 shows the response of a 23-element array plotted against the vertical height for equal sweep lengths taken from ever greater distance. The stimulus was 4 kHz. Notice several points. For the near passes (out to at least 4 m) the level is roughly constant to the end of the column (at 0.88 m) and then tapers off. This again substantiates the claim of constant level within the endpoints of a long array. Also, the first three curves show differences in level of approximately 3 dB per doubling of the distance, again supporting that, to at least 4-m distance, the system acts as a practical line source. The 8- and 16-m observation distances show a marked reduction in beam height and are distinctly less square. All the curves show a certain amount of ripple, which is of higher density for the nearest curve, with progressively "slower" ripples as the observation distance increases.

Fig. 27 shows the case where the extension of the height is held proportional to the vertical extension of the measuring distance. In this case we start 4 m out and sweep up 1.5 m from the centerline; next from 8 m out we sweep upward 3 m, from 16 m we sweep 6 m up, and so on. Although our sweep is in a straight line not an arc, this is roughly equivalent to an arc segment resulting from a 20° rotation. Results are therefore plotted versus this approximate angle. Notice here that by the third curve, 16 m out, the curve's character is fairly well defined. Also, by 16m the curves are falling close to 6 dB per doubling of the distance. Obviously from this distance outward the array is best described as having a fixed *angular* coverage.

The top curve in Fig. 27 is for a 4-m observation distance, the distance at which our polar curves were measured. It compares closely to the shape of the primary lobe of the 23-tweeter array as measured in Fig. 4 (4.3 kHz). (Fig. 27 presents the responses from 0°, the center of the primary lobe, to 20° to one side.) Note

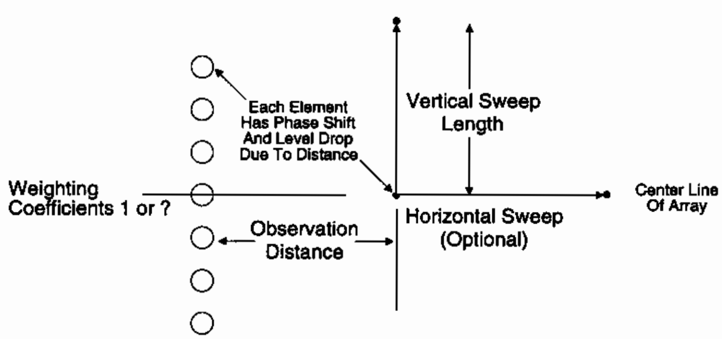

Fig. 25. Geometry of near-field array simulations.

that the first dip at 2.5°, followed by peaks at 5 and 8°, can be seen both in the top curve of Fig. 27 and across the central lobe of Fig. 4. Searching either curve for the −6-dB point reveals a beamwidth of about 23° (11.5 × 2). This 23° prediction is close to the 25.4° "within the endpoints" angle estimated in an earlier section, resulting from the rotation of a 1.76-m array at 4-m distance. Note that with the farther observation distances this primary lobe shrinks to a −6-dB beamwidth of about 3°. This is much more in line with the far-field predictions of the polar program (Fig. 12).

Hence we can resolve one of our major incongruities. In the near field a finite line source does have roughly uniform radiation for all observation heights within its length. However, in the far field the array appears very directional. In polar terms the angular width of the primary lobe, at real listening distances, has expanded to many times the far-field width.

4.2 Where Does the Far Field Start?

A common rule of thumb is that the far field begins at distances equal to three times the largest dimensions of the source or, in our case, at three times the array length. For the 23-element array this would be 3 × 1.76 = 5.3 m. In the case of our 23-source array at 4 kHz the border between near field and far field appears to be at about 8 m.

A further definition of far field is that in the far field, the array appears like a point source. As with a point source, the sound pressure level will be seen to drop 6 dB for every doubling of the observation distance. A second indicator that the far field has been reached is then to plot level versus distance and to note when the drop for each doubling of distance settles at 6 dB.

A variation allowed in the near-field program is to sweep the observation point along, rather than perpendicular to, the array centerline. The observer remains

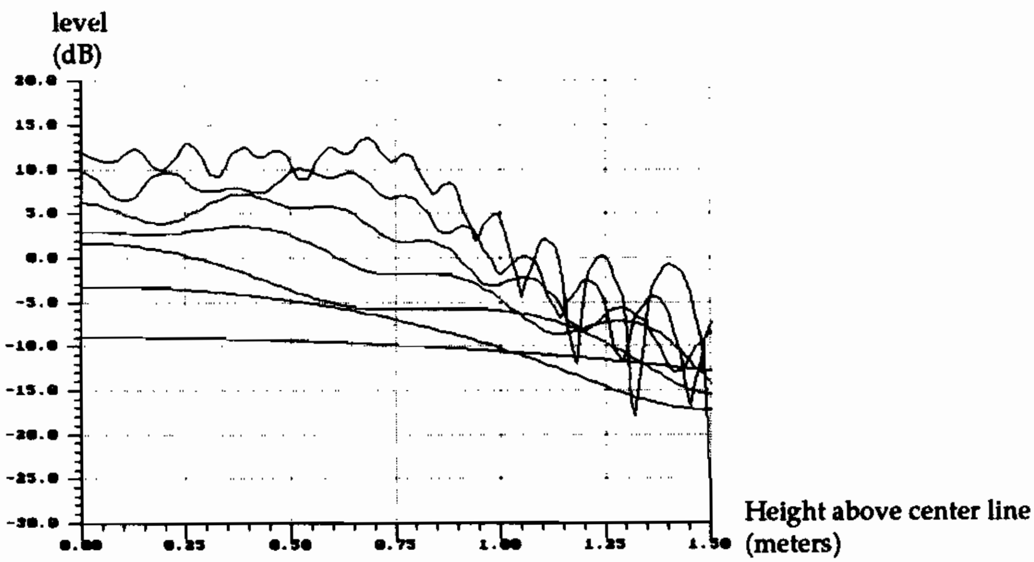

Fig. 26. Level versus observation height for 23-element array, 4 kHz. 1.5-m vertical sweep taken from 1 m out (top curve) to 64 m.

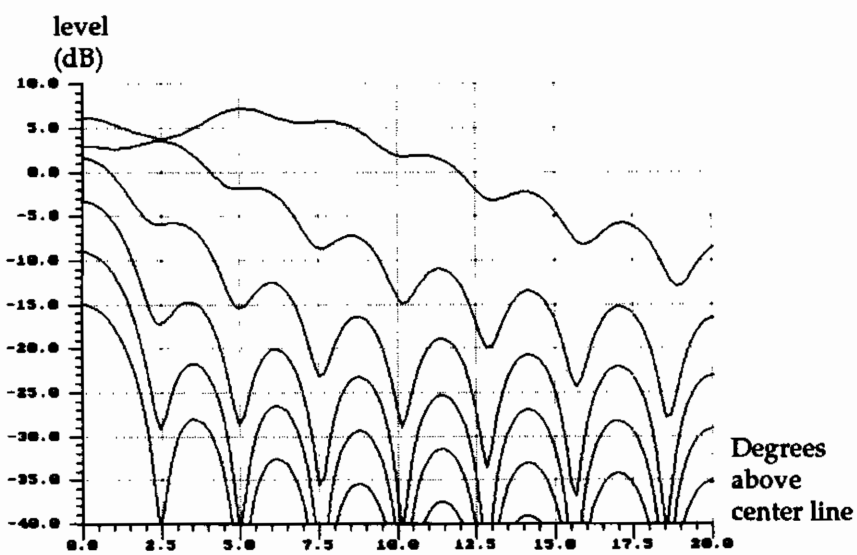

Fig. 27. Similar to Fig. 26, but vertical sweep proportional to horizontal distance for constant 20° sweep. Curves from 4 m out (top curve) to 128 m.

on a line bisecting the array while receding away. When the resultant level drop is plotted against the logarithm of the distance (distance doubling in a regular plot interval) we can determine if the array's level is falling at a regular rate [9]. The common assumption would be that the level would drop 3 dB per doubling of the distance over distances where the array "looked like" a line array. At greater distances the array's finite length would eventually become insignificant and the level drop would become 6 dB per distance doubling. At this point you have, by definition, reached the far field.

Modeling of the long array shows a surprising and strongly frequency-dependent result. Figs. 28–30 show the computer predictions of level versus distance for the three frequencies of 1, 3.2, and 10 kHz. At higher frequencies it may take many times the array length for the dropping level to settle out. In Fig. 30 we see that for 10 kHz the response did not settle until a distance of over 30 m, or 15 times the array length.

This periodic variation observed in these curves can be understood if we examine Fig. 31. A simple array is drawn with an arc centered on an observation point and through the array's center tweeter. All tweeters above and below the central tweeter will be incrementally farther from the observer than the distance defined by this arc. The consequent phase retardation of each outer element determines whether it contributes in phase to, or subtracts out of phase from, the central elements. A partial null can occur when, at a given distance, the vector summations of the array elements' phases (and levels) tend to cancel.

What we observe is that the level continues to undulate with increasing distance until the outermost elements are (predominantly) in phase with the center. As the observation point becomes more distant, the arc flattens out. Eventually even the outermost elements will have no more than 1/4 wavelength *extra* delay, and no more ripple can occur.

Both the parallel sweeps and the sweeps perpendicular to the array point to one conclusion: when long arrays are used for home loudspeakers, the listener is very likely to be in the near field. The majority of published

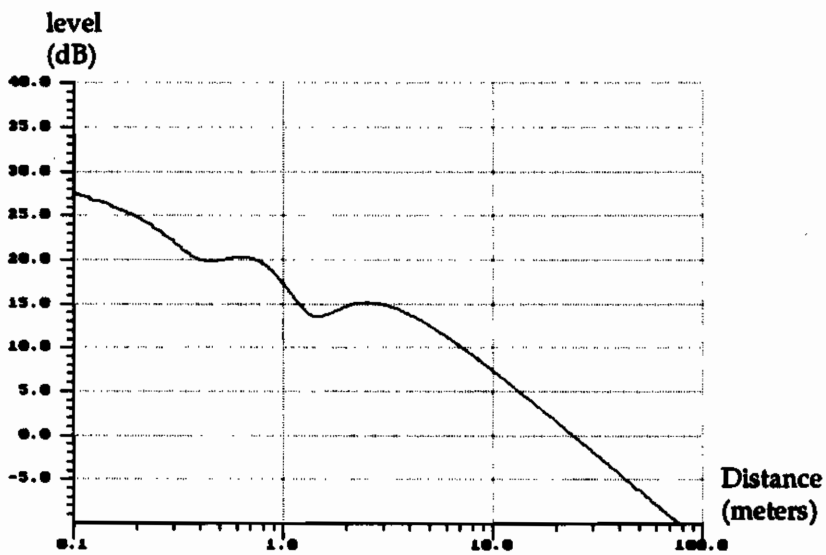

Fig. 28. Level drop with distance, 23-element array, 1 kHz.

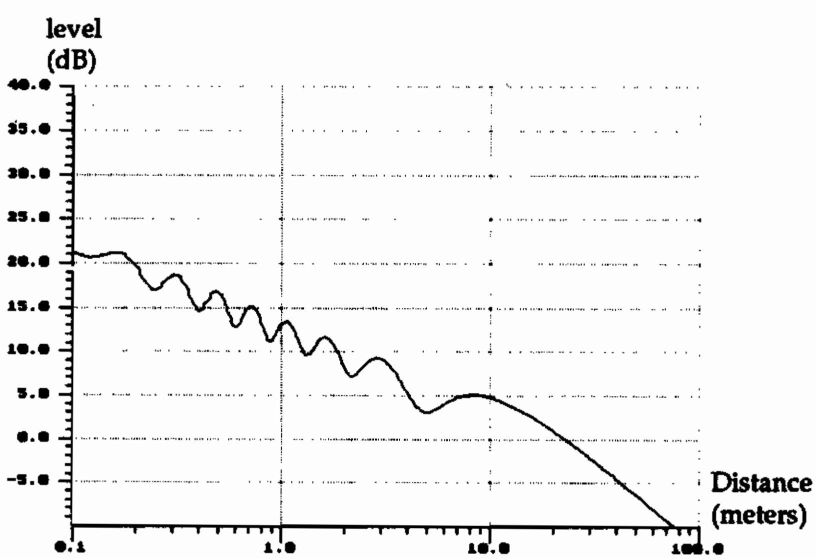

Fig. 29. Level drop with distance, 23-element array, 3.2 kHz.

literature on line arrays deals with their use as public-address systems [2], [4], [6], [7], [11]. This far-field usage has prompted researchers to concentrate on far-field polar performance. Although line sources or multi-element line arrays have long been popular in various expensive home loudspeaker systems, few "high-end" designers have explored the theory of their particular applications.

4.3 High-Frequency Broadening of the Polar Response

The 16-kHz measured polar response of the 23-tweeter array (Fig. 6) showed a surprising rebroadening of the beamwidth to a radiation angle not too dissimilar from what might be expected for a single 1-in (25.4-mm) tweeter. This blooming of high-frequency directivity is the last remaining unexplained phenomenon.

Fig. 32 shows a plot versus "angle" of the 23-element array at 8 kHz and calculated for two distances. The upper curve is for 4 m, the lower for 32 m out. The upper curve shows that in the near field the response has broadened and the sidelobe has nearly merged with the front lobe. The profile can hardly be described as a lobe in that it is very broad. Only a depression centered on 12° remains. The 20° "rotation" of this plot can be compared to the frontal response of Fig. 5, the polar rotation of the real array measured at the same 4-m distance. Again the agreement is excellent. The bottom far-field curve shows a very narrow frontal response with a beamwidth of perhaps 3°. This is comparable to the near on-axis response of Fig. 14.

Fig. 33 shows a similar pair of curves, but for 16 kHz. Compare the top curve (4 m) to the measured polar response of Fig. 6. At this frequency the near-field curve has lost all shape; only ripple remains. No evidence of the front and side lobes seen in the lower (32-m) simulation remains.

For an explanation, remember that the formation of lobes requires the coming into phase of the contributions of all the elements when viewed from some vantage point. At a distance this happens when the array angle, the resultant interunit distance, and the radiated wavelength coincide. Intuitively, in the near field the distances of the various elements are randomized (or, more properly, scattered). Reference to Fig. 31 shows how all elements will have, in the *near field*, even for on-axis radiation, a different distance from the observer. The arrival phases are so "randomized" that at very high frequencies, in the near field, lobes cannot form. For very high frequencies, elements sum with regard to power rather than summing coherently. So we see that the polar response reverts to that of the elements themselves, plus ripple. This ripple can be heard on pink noise when moving vertically within, say, 1 m of the array. But in general it is undetectable from a typical listening distance.

4.4 Improvement of Near-Field Performance

It would be ideal if the near-field quality of "approximately constant level with height" could be made even

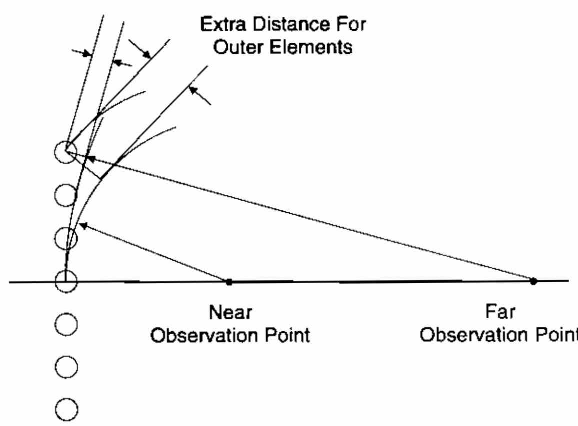

Fig. 31. Excess distance for outer elements.

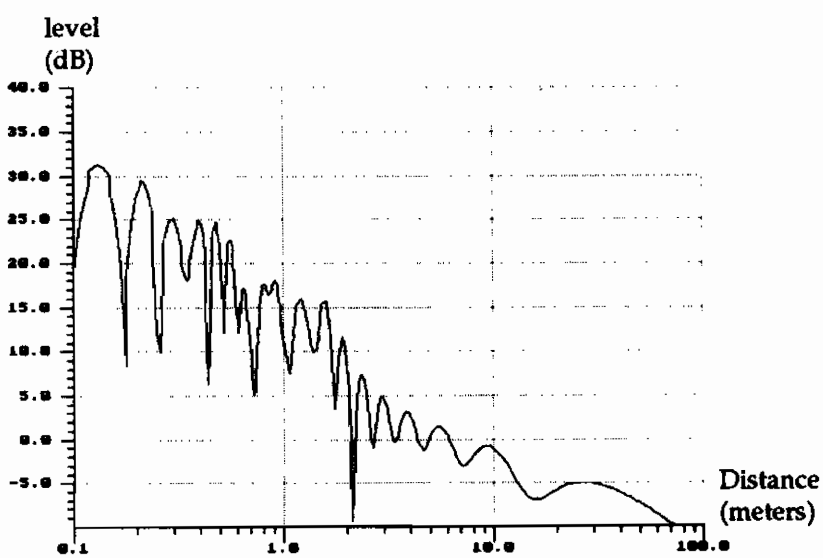

Fig. 30. Level drop with distance, 23-element array, 10 kHz.