

ROUND THE HORN

P(3M) = 75dB						
Loudspeaker	f(Hz)	Input(v)	2nd	3rd	4th	5th
QUAD	1K	2.04	-59	-60	-69	-66
	2.8K	5.6	-62	-49	-	-
	5K	3.5	-66	-51	-	-
AUDAX	1K	1.01	-59	-54	-68	-
	2.8K	0.75	-61	-60	-	-
	5K	0.64	-62	-59	-	-
JBL	1K	0.2	-53	-75	-77	-
	2.8K	0.18	-38	-27	-46	-38
	5K	0.19	-47	-31	-59	-
EMILAR	1K	0.24	-61	-66	-	-
	2.8K	0.17	-58	-73	-70	-
	5K	0.3	-47	-57	-	-
P(3M) = 85dB SPL						
Loudspeaker	f(Hz)	Input(v)	2nd	3rd	4th	5th
QUAD	2.8K	6.02	-57	-57	-80	-
	1K	3.8	-54	-49	-78	-67
AUDAX	2.8K	1.7	-57	-57	-	-
	5K	2.5	-47	-67	-	-
JBL	1K	0.67	-42	-44	-60	-59
	2.8K	0.44	-43	-36	-49	-
	5K	0.54	-41	-37	-61	-
EMILAR	1K	0.73	-50	-55	-76	-
	2.8K	0.44	-49	-65	-73	-
	5K	0.87	-38	-54	-71	-
P(3M) = 95dB SPL						
Loudspeaker	f(Hz)	Input(v)	2nd	3rd	4th	5th
AUDAX	1K	10.1	-50	-44	-79	-69
	2.8K	5.7	-49	-49	-	-
	5K	7.7	-37	-57	-	-
JBL	1K	2	-41	-49	-55	-53
	2.8K	1.5	-35	-53	-67	-53
	5K	2.1	-29	-55	-	-
EMILAR	1K	2.45	-40	-53	-68	-59
	2.8K	1.4	-40	-55	-61	-63
	5K	2.9	-29	-48	-71	-
P(3M) = 105dB SPL						
Loudspeaker	f(Hz)	Input(v)	2nd	3rd	4th	5th
JBL	1K	7.8	-26	-41	-58	-51
	2.8K	4.4	-27	-43	-55	-57
	5K	7.1	-19	-37	-60	-
EMILAR	1K	10.5	-28	-32	-45	-55
	2.8K	4.4	-29	-52	-57	-59
	5K	8.8	-20	-36	-51	-

Fig.1: Measured harmonic distortion levels of drivers under test

Philip Newell re-evaluates horn drivers in midrange studio monitoring and answers some long-standing questions

Together with higher efficiency and aspects of their far-field propagation qualities, the generally higher output capability of horns means that they still have a role to play in studio monitoring loudspeakers. The 'horns versus direct radiators' debate has continued for decades with partisan factions supporting each point of view, but few horns have been developed purely for studio use, thus most studio systems have borrowed technology from cinema, sound reinforcement and public address. In order to discover whether there was further potential in the use of midrange horns in studios, a five-year study was undertaken by Keith Holland at the Institute of Sound and Vibration Research (ISVR) at Southampton University, England. One of the main objects of the work was to attempt to determine whether the less favourable characteristics of horns are a function of horns *per se* or whether some of these characteristics were inherited along with aspects of the borrowed nature of the technology.

This article discusses the findings of the above research programme. It details aspects of horn performance considered undesirable for studio purposes, and separates individual physical parameters of horn design which give rise to many unwanted acoustic properties. The conclusion attempts to define the limits of horn performance within which the greatest number of unpleasant sonic attributes can be designed out. The work is based on physical and mathematical analysis of the problems, closely related to a rigorous series of listening tests.

The use of horn loudspeakers for public address and cinema applications is almost universally accepted as good practice. Indeed, in many of these instances, there is no practically viable alternative, as the requirements of high electroacoustic efficiency and flexibility of directivity control are not easily achieved with anything other than horns. Changing practices in the techniques of music recording have brought with them a tendency towards larger control rooms. Concurrently, control room acoustic-design ►

philosophy has tended towards lower reverberation times and in many, true reverberation does not exist at all. In these relatively large and acoustically 'dead' control rooms, a borderline case has been reached between studio monitor systems and small public address systems. Sterling attempts have been made by numerous designers to develop direct-radiator technology to meet these needs, but while many fine systems now exist, they usually require high amplifier power, and live much of their working lives close to their power handling performance limits.

On the other hand, systems using horn-loaded, midrange systems, even in control rooms of 60m² or more, are rarely driven much beyond 20% of their design power handling capacity. As such, a long and stable working life can be expected, together with lower amplifier power-requirements and a good reserve of damage tolerance. Another desirable attribute of horn loudspeakers is that they tend to produce an output in the form of a spherical expanding wave, free of many of the 'lobing' problems of the pistonically derived output from direct radiators.

No attempt is being made here to claim overall superiority of any one type of drive system, as many subjective aspects of performance differ greatly from one listener to another. However, if some of the negative attributes of one system can be detected, isolated, and ultimately circumvented, then it will provide designers of future systems with more options in their quest for their optimum design requirements.

The test programme

The basis of the research work was to find links between measurable characteristics of horn performance and perceived subjective sonic characteristics. In order to reduce some of the tedium and general impracticability of first manufacturing, then setting up experiments for the measurements of every interesting development suggested by the research, a 1-parameter computer analysis technique was developed, then rigorously tested against actual measurements of real horns. This technique has already been published^{1,2} together with the development of an impedance tube measurement system³ which made practical the rapid measurements for the physical-numerical cross correlations.

An extensive programme of listening tests was carried out in the large anechoic chamber of the ISVR, and again, a general outline of this

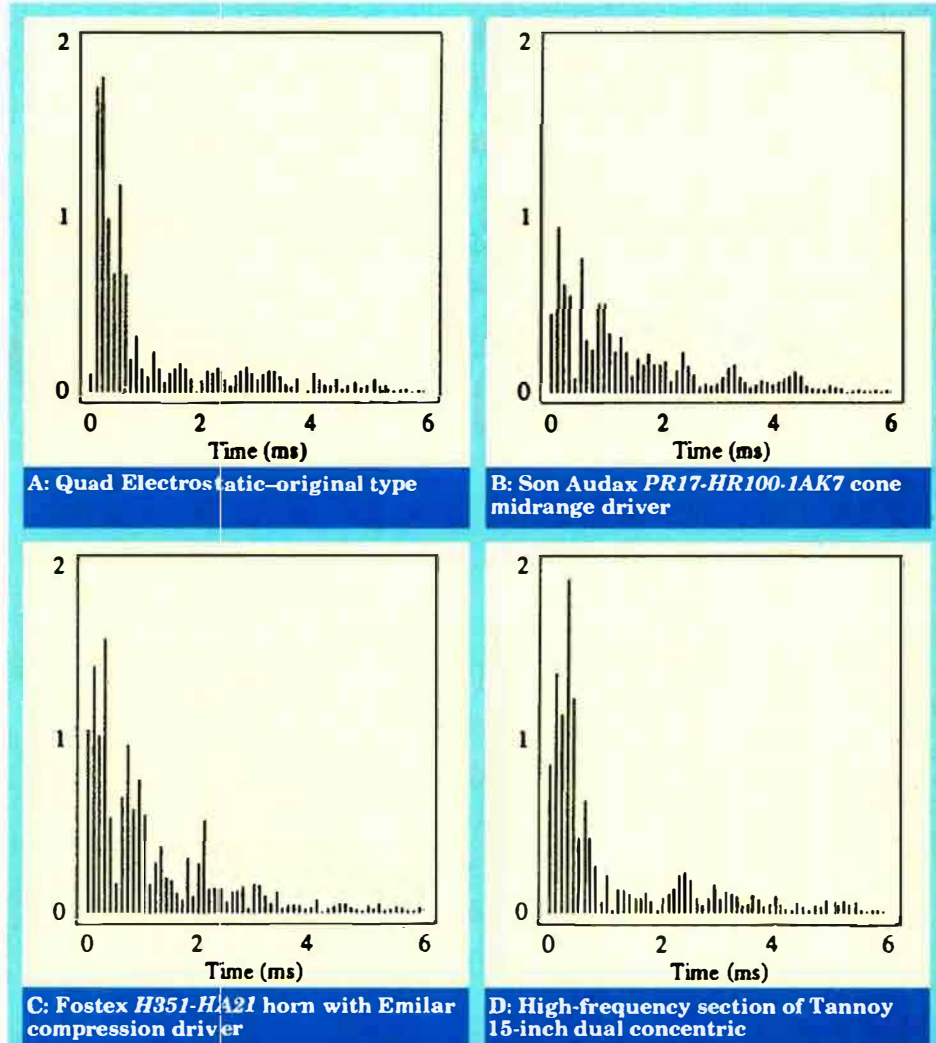


Fig.2.1: Power cepstra of archetype loudspeakers

procedure has already been published.⁴ Measurements of nonlinearities, both in the horn flares themselves, and in the horn-driver combinations were cross-referenced with the results of the above listening tests, and a finite amplitude model was developed^{5,6} to predict nonlinearities in different flare shapes. Cepstral analysis was undertaken⁷ in order to isolate discrete reflection patterns in different horns not easily discernible from conventional measurement techniques. The research project was compiled into a thesis for which Keith Holland received his PhD at Southampton University in December 1992.⁸ As individual aspects of the research are so well documented in the papers¹⁻⁷ above, this article concentrates on the less-widely promulgated aspects of the conclusions.

The listening tests involved over 7,000 comparisons of 20 different drive units and nine different sounds. The drive units consisted of horns of many different flare shapes, moving-coil direct radiators, and an Electrostatic. The nine sounds were essentially nonmusical, but contained different combinations of transient and steady-state or tonal content. They were band-limited (1kHz–6kHz) on playback, in order to avoid problems either solely due to horn cut-off or other out-of-band anomalies. It was hoped that the different combinations would help to isolate any 'horn sound' which the units may possess. The initial question was whether all the horns would group together, either on some of the sounds or on all of them. After the results had been numerically, statistically, and 'common sense' analysed, there

were groupings—but not in ways which had been anticipated.

Of the four reference 'archetypes' to which other samples were compared, two were direct radiators and two were horns. Of the direct radiators, one was a Son Audax 6½-inch moving-coil unit (B), and the other a Quad Electrostatic (A). Of the horn 'archetypes', C was a Fostex H351-HA21 long (490mm) sectoral horn driven by an Emilar EK175 drive unit, and D was the 'high' frequency section of a Tannoy 15-inch dual concentric, with the bass cone forming the high-frequency horn flare.

General findings

In general, the horns with a throat-to-mouth distance of more than about 350mm were deemed to sound like archetype C, while the horns with a throat-to-mouth distance of less than 350mm were generally judged to sound like archetype B. Within each of the long-short groups however, there were some odd exceptions. One of the 'long' horns was a Fostex wooden-flared sectoral horn, 440mm in length from throat to mouth. Possibly more strongly than any other horn in the entire test, this horn was judged to sound like the direct radiator cone, archetype B. The whole thing consisted of a very short 'throat extension', coupled to what were effectively large semicircular lips with a horizontal flare of 140°. The horn produced undesirable throat impedance plots, implying an uneven pressure amplitude response when connected to a driver, nonetheless in auditioning before the tests began, the horn was generally considered 'musical', ►

Cepstral analysis was undertaken in order to isolate discrete reflection patterns in different horns not easily discernible from conventional measurement techniques

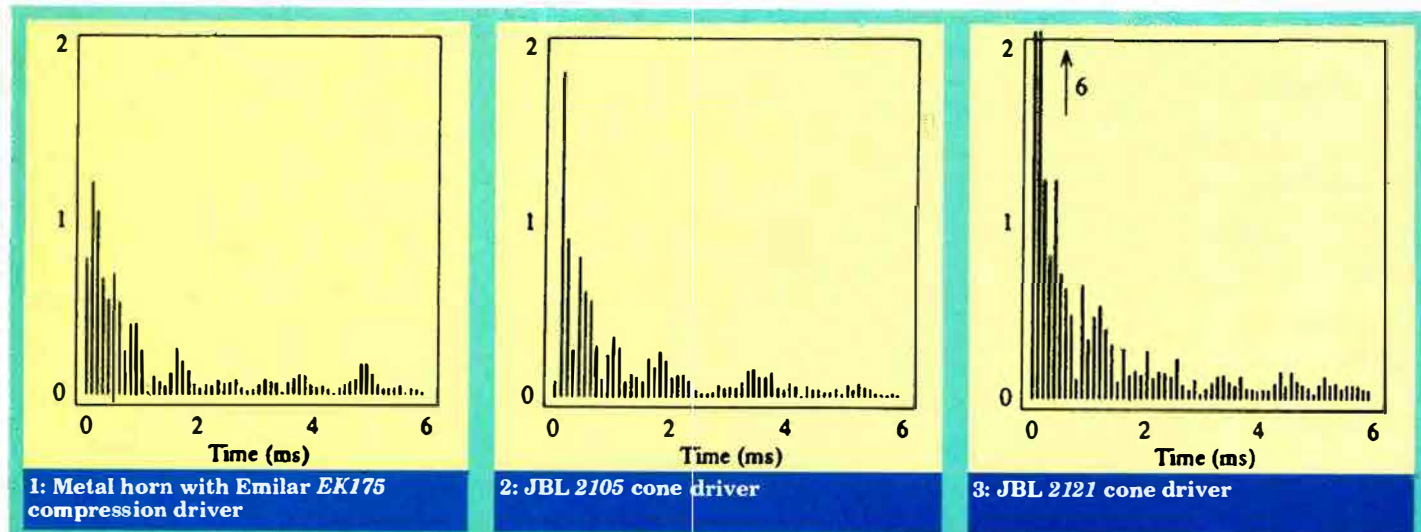


Fig.2.2: Power cepstra of sample loudspeakers

pleasant to listen to, and definitely not horn-like.

Among the short horns (350mm or less) two failed to group with the direct radiator, archetype B. One horn was the AX2, specifically designed for the tests as a result of the 'seminumerical' 1-parameter modelling, and information gleaned from the use of the impedance tube. The horn was 180mm from throat to mouth, and possessed a rapid flare which prior analysis had suggested to be a requirement for a desirably smooth mouth termination, avoiding any sudden cross-sectional changes where the mouth meets the baffle. The horn showed an overall similarity to archetype D, the Tannoy dual concentric, which was itself a short, axisymmetric horn. The third nongrouping

horn was a Yamaha aluminium sectoral horn which was a 'borderline' 300mm in length. Unsurprisingly, this horn straddled groups B and C, but also gave a great number of results showing it dissimilar to any of the archetypes. Only on four of the nine sounds did it clearly group with B or C.

Nonlinear distortion

The first attempts to explain these anomalies—and the 'break' at 300mm to 350mm—focussed on nonlinear distortions. Much has been presented on the subject of horn distortion, to the extent where it is taken as a fact in some circles that it is harmonic distortion which makes many horns

sound hard and unpleasant. There are three predominating sources of this harmonic distortion. Firstly, there are the electromechanical limitations of the drive unit, including thermal power compression effects, suspension nonlinearities and magnet-gap problems. Secondly, is the nonlinearity produced as a function of the volumetric changes between the diaphragm and the phase plug on positive and negative half-cycles; and thirdly is a distortion produced by nonlinear propagation within the horn itself, which can, at very high levels, lead to shock formation.⁹

To test the less well-documented third cause, a finite amplitude model was devised for computer prediction. Most standard 'horn' formulae are calculated on the basis of infinitesimal wave amplitude but, in reality, usable sound

waves have finite amplitudes. Superimposed on the initial sound waves are reflections from the mouth and obstructions within certain horns, plus complications due to phase dispersion within the horn flare. The model⁹ proved highly successful and gave good correlation with actual measured results, which used a Community M4 as a signal source, capable of producing signals with less than 1% harmonic distortion, even at 150dB. The test setup was complicated and unwieldy, requiring the use of two specially-treated, adjoining rooms, so once adequate verification of the computer model had been achieved, it was certainly the most practical choice for further study on other horns.

Fig.1 shows a table of actual, measured results comparing harmonic distortion levels of a direct radiating cone, an Electrostatic, and two horn loudspeakers, all used in the listening tests. The results show that at low levels (below 90dB) at 3m, there is no significant difference in distortion levels of the different devices. At high levels, say >110dB, very few drivers can produce such continuous sine wave levels, so comparison is not really relevant. Furthermore, certain audiological reasons reduce the relevance of very high-level measurements in a studio environment. From the above measurements and the computer analysis of the finite amplitude model, it was possible to separate out the distortions attributable to each of the three main causes previously mentioned. Much second harmonic distortion can be attributed to propagation nonlinearities, with most higher-order harmonics being driver related. None of this,

Once adequate verification of the computer model had been achieved, it was certainly the most practical choice for further study on other horns

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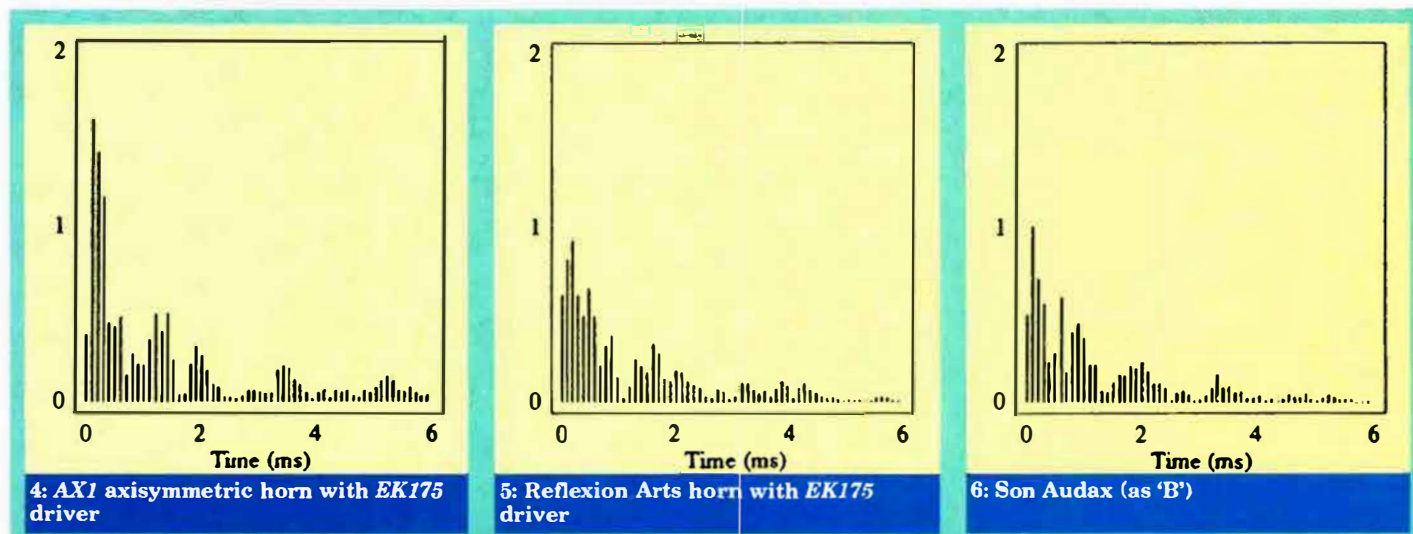


Fig.2.3: Power cepstra of sample loudspeakers

however, falls into any sort of pattern when cross-correlated with the similarities and groupings found in the listening tests. Indeed, whichever ways the results were dissected and analysed, no link could be demonstrated between harmonic distortion and audible similarity. Units with up to 20dB difference in distortion levels were deemed to sound similar, while others of almost equal distortion figures were considered to sound totally different. From the results of these tests and analyses, nonlinear distortions were emphatically *not* responsible for any characteristic horn sound.

Amplitude and phase responses

Pressure amplitude response (frequency response) was another prime candidate for producing sonic similarity or dissimilarity. After the tests were completed, a Waveform Spectral Similarity index was calculated for each loudspeaker on each sound. This was derived by calculation of the root-mean-squared error between the spectra of the original signal, and that radiated by each loudspeaker. A comparison was made speaker-to-filter-input, and speaker-to-speaker for each sound. A reasonably good tie-up was achieved here (around 80% similarity) between the calculated waveform similarity and the listening tests. Unfortunately, some of the results which refused to correlate, did so in a glaring way. Usually, when a sample driver which was deemed to be sonically similar to an archetype failed to show a similar pressure amplitude response, then a strong similarity was noted in the phase response. This has so far not yet been adequately explained.

Certainly, the agreement between listening test results and comparisons between the spectra of the reproduced signals indicate that a large part of the cause of acoustic similarity is due to the on-axis amplitude frequency response, but clearly, this was not the sole reason. For example, a JBL 2370/2426 combination was very similar in its waveform spectral similarity to the Son Audax cone driver, archetype B, for all nine of the test signals, yet in the listening tests it showed a reasonable similarity with B on only one of the nine sounds. It closely resembled the horn C on five of the signals, and was judged similar to none of the archetypes on the other three signals. The phase response of the JBL combination was more similar to archetypes C and D, the two horns.

Cepstral analysis

With neither amplitude, phase, nor harmonic distortions clearly explaining the sonic similarities or otherwise of the different drivers, it was decided to make further studies in the time domain. In order to further identify any reflections that may be produced at the mouth or within the flare of a horn, a form of power cepstrum was calculated from the modulus of the measured throat impedance. In this type of analysis, the frequency-domain representation of the modulus of the throat impedance is treated as a spectrum; the power cepstrum is then calculated using Fourier transforms. Cepstral analysis was first defined in

the mid-1960s as a means of helping to separate echoes from 'clutter' in seismic research. The power cepstrum of a transfer function is the Fourier transform of the log of the amplitude of the transfer function. The power cepstrum of each driver was plotted using a y-axis scaled in nondimensional dBs and an x-axis plotted in terms of both time and distance. Fig.2 shows the power cepstra of the 20 units used in the tests. The power cepstra proved to be revealing, as they are very effective in showing reflections. In a conventional pressure amplitude plot, a reflection would show as a comb-filtering effect, but on a complex spectrum, this can be difficult to recognise. On a power cepstrum, however, reflections exist as single spikes along the time-distance axis, and can thus readily be recognised.

In general, what followed from the cepstral analysis was

that the audible similarity groupings from the listening tests could be described in terms of the reflection patterns shown in the power cepstra. The various reflections and resonances produced in the cone of a direct-radiating loudspeaker can give rise to irregularities in the frequency response function that are similar to those due to mouth reflections in short (sub 350mm) horns. This explained the anomalous behaviour of the 'long' Fostex wooden horn in the listening tests. As previously mentioned, the horn was strongly identified as sounding similar to the direct radiating cone, archetype B, but the cepstral analysis showed that the true 'horn' was the 150mm throat section only, with the 140° horizontal wooden flare acting ▶



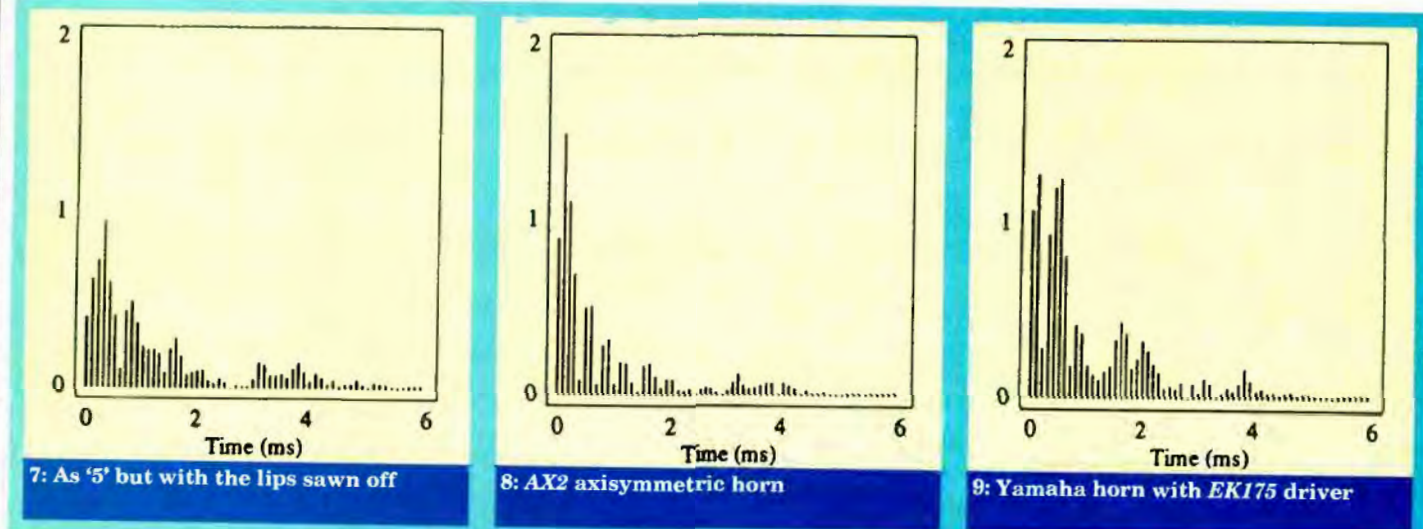


Fig.2.4: Power cepstra of sample loudspeakers

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DL251 Spectral Compressor		Hard/Soft	*	*	2	*	*	*
DL241 Auto Compressor	*	Soft		*	2	*	*	*

only as waveguide 'lips' for directivity control. The unevenness in the throat impedance was largely due to the abrupt, horn-to-lip termination at about 150mm from the driver diaphragm. The horn was consequently reclassified as a 150mm horn with 290mm lips (the shortest horn of all tested), explaining the similarity between this horn and the direct radiators. It should be remembered that there is no absolute dividing line between horns and direct radiators, as a direct radiator can be considered as a 180° conical horn of zero length.

The longer horns, even those with relatively good mouth termination (which is usually easier to achieve in a long horn,) are identified as horns by the temporal spacing of the reflections. Even when the reflections are significantly lower in level than those of the short horns, the greater separation in time of these reflections are recognised by the ear as a pattern which we know as a horn-like sound. The two horns which were not identified in the listening tests as sounding like archetypes B or C, were both shown by cepstral analysis to exhibit minimal mouth reflections. One of these horns was long, and one was short. The long horn, though showing some similarity to C, did not have a particularly strong resemblance, and was considered on some sounds to be similar to archetype A, the Electrostatic. The short horn showed a considerable sonic resemblance to archetype D, the Tannoy dual concentric: both the Tannoy and the Quad Electrostatic have their roots in 1950s design, yet are still in daily use in 'quality control' suites. Furthermore, both of these units had historic 'difficulties' in the low and high-frequency ends of their performance, but both had a clear midrange, suiting them to quality control applications. Apart from reasons of inadequate (woolly) bass, and limitations on maximum sound pressure level, these loudspeakers also lost favour as studio monitors as a result of not sounding representative of other loudspeakers in general. From the cepstral analysis the reason for this is clear, but it poses an interesting philosophical point: should a monitor loudspeaker be rejected because it does *not* possess the midrange problems inherent in most other production loudspeakers?

While the Electrostatic, archetype A, was deemed similar to the sample loudspeakers on a relatively small number of occasions, it was frequently noted that one of the nine test signals (a recording of a waterfall, band-limited 1k-6kHz on playback) sounded more 'wet' on A than on any other loudspeaker, a testament to its reality. ▶

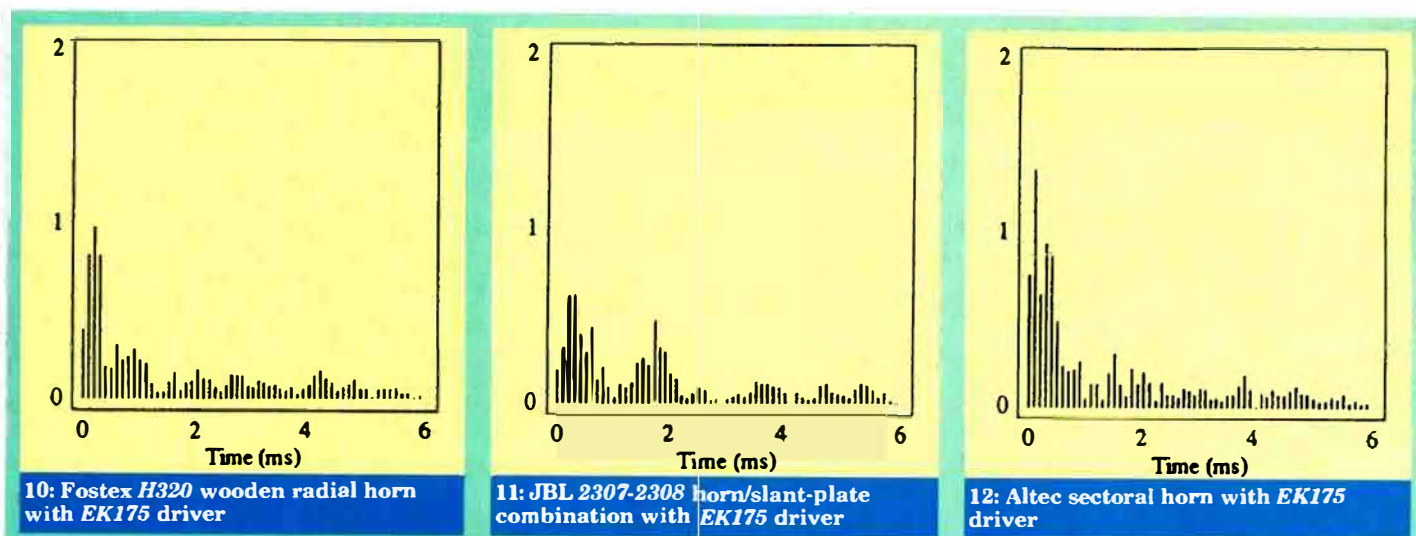


Fig.2.5: Power cepstra of sample loudspeakers

The complete picture

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Design implications

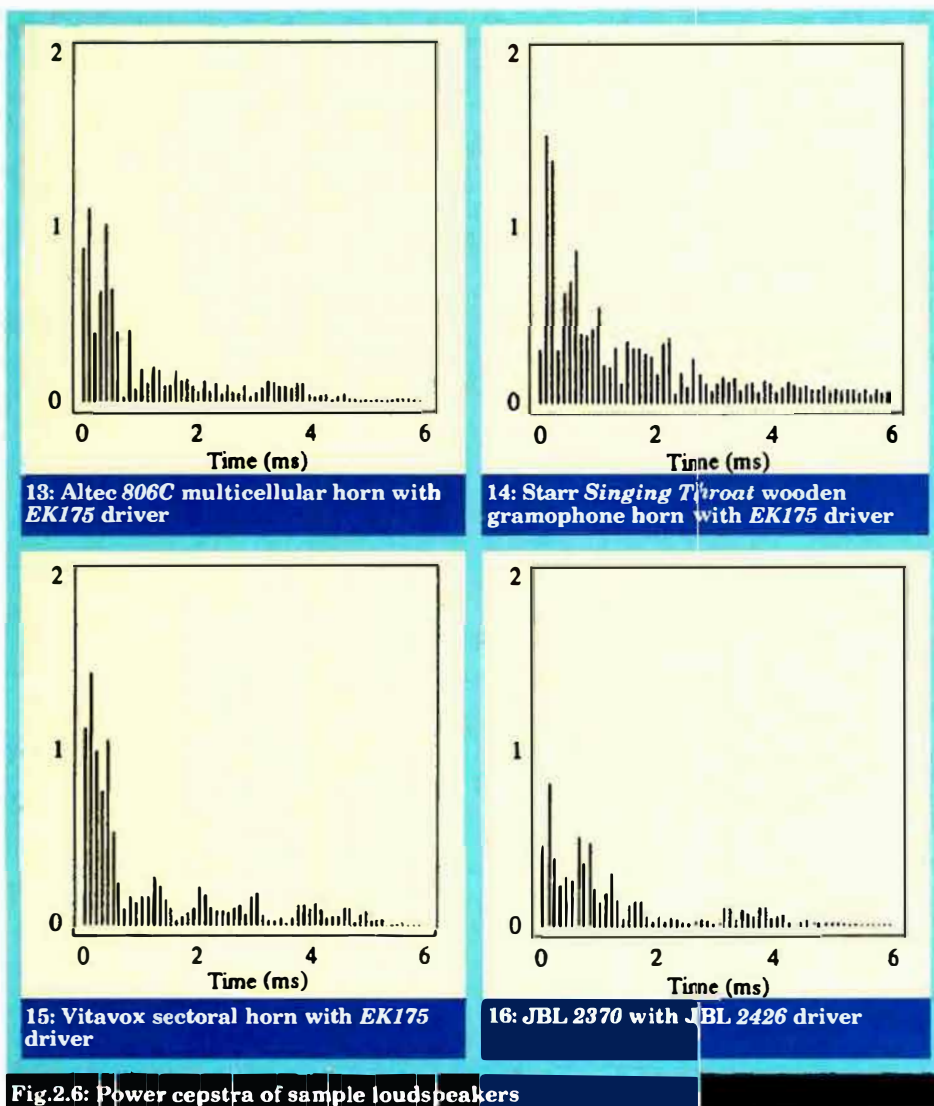
Throughout the tests, a watchful eye was maintained for evidence of the material from which a horn was constructed showing any patterns in the sonic test results. Other than certain materials having specific problems due to bad design or construction, no evidence was found to indicate that any well-damped, solid material could not be used in the manufacture of horns. Obviously, certain materials lend themselves more readily to the manufacture of different shapes, and it could be that some materials have had sonic characteristics attached to them because they are only found on certain generic designs.

Wave shapes

Investigations into the actual wavefronts leaving the different horns, showed that the axisymmetric designs generated waves which resembled flattened spherical caps, midway between a true spherical expanding wave and a plane wave leaving the mouth. The waves leaving rectangular horns were of the form of spherical expanding waves which struck the walls of the horn at 90°. Early in the tests, 'bubble-blowing' experiments were performed—wire loops were bent into the mouth shapes of the horns to be tested, and it was noted that only circular, or near-circular mouths would produce complete bubbles; rectangular shapes causing the bubbles to tear themselves apart before they could leave the wire. It was also noticed that rectangular horn designs would produce disturbed responses when listening to them or measuring them from a position 90° to any discontinuity. Such discontinuities include waveguide plates, the top-bottom to sidewall junctions, and any other departures from a smooth surface. The mouth shape and any internal discontinuities tend to produce reflections from the mouth or strange aberrations in the off-axis responses. All of these things were strong pointers in the direction of the concept of axial symmetry being the only viable option for the highest quality reproduction.

Axial symmetry

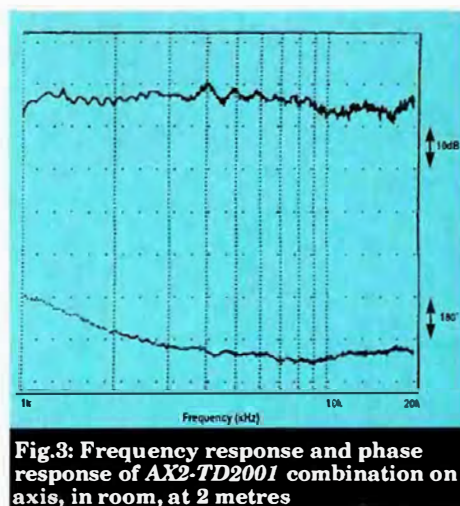
For public address and sound reinforcement applications, directivity is a prime factor in horn design; in studio monitoring, the on-axis $\pm 20^\circ$ response, together with an off-axis response ►



which changes in its frequency balance in a smooth and uniform way, is usually more important. In the above tests, the axisymmetric AX2 horn was driven by an Emilar EK175 compression driver. In the cepstrum plots shown in Fig.2.4 the combination is sample 8, and a small reflection can be seen at a distance of about 50mm from the diaphragm. Investigation showed this to be due to the slightly differing flare rates of the driver throat and the throat of the horn. When mated with the TAD TD2001 compression driver, the flares match exactly and the reflection disappears. The power response of the TAD is also such that its falling high-frequency response is closely matched by the gradually narrowing directivity of the AX2 horn, producing a smooth on-axis pressure amplitude

response, together with an off-axis response where the fall-off of high frequencies takes place in a smoothly controlled manner. These responses are shown in Fig.3.

Monitor systems using the TD2001-AX2 combination are now in commercial use, particularly in control rooms of a very nonreflective nature where the on-axis response is highly important. These monitor systems, especially in inexperienced hands, do suffer from some of the criticisms formerly aimed at the Quad Electrostatics and Tannoys, in that they are not necessarily representative of other loudspeakers, but equally, many experienced engineers praise their ability to pinpoint fine detail. Most studios' use of large and small monitor systems—one



representing 'truth', the other a 'real world' mix—still seems to offer the most viable partnership.

In many ways, the AX2 could be defining the limits of midrange horn design. The axisymmetric shape (Fig.4) seems to be the only one which can produce an output free of the irregularities of response caused by pillars, plates, other obstructions or surface junctions. Horns much more than 300mm in length begin to produce 'horn-like' sounds unless the mouth termination is close to perfect. Given that the rate of flare dictates the throat cut-off frequency, and the mouth size controls the smoothness of the low-frequency termination to the room, then a horn with a low cut-off frequency, possessing a mouth which smoothly flares into the baffle, would be of such great length and mouth size that close coupling to the other drivers in the loudspeaker system could be almost impossible. The AX2 has a cut-off frequency of around 750Hz, but is so smooth in its response that it can be used *through* cut-off. This is the lowest cut-off frequency that can be achieved, consistent with a flare which smoothly blends into the baffle, originating from a 1-inch throat in a diaphragm-to-mouth distance (with TD2001) not exceeding 300mm.

However, a high-efficiency horn system, usable from below 1kHz to over 20kHz, with a mouth diameter of 12½ inches, capable of producing very high fidelity and a maximum output of 125dB at 1 metre is certainly a useful tool. What is more, it definitely is not 'horn-like' in its sound. Clearly, when the many variables are fully understood and appreciated, horn systems *can* be produced which do not possess any typically horn-like vices. Attention to detail is a prerequisite, as is a comprehensive knowledge of the caveats.

Two further aspects of horn design are called into question as a result of this research, both requiring further investigation. Firstly, given the extreme sensitivity to small disturbances in the throat region, can the Tannoy concept of having an actual gap in the horn, (the voice-coil gap of the bass cone) ever be expected to produce optimal results? More particularly, when that gap is modulated by high levels of bass driver movement, can a variable length, variable flare, gapped throat ever be expected to produce optimal results? Secondly, the results show that any abrupt flare-rate changes within the horn, can, do, and will cause reflections which will superimpose themselves on the transfer function. As the whole concept of constant-directivity horns relies upon flare-rate changes of no subtle nature, then can the best results ever be achieved from constant-directivity horns?¹⁰ Fig.5 shows the measured throat impedance plot of the AX2, ►

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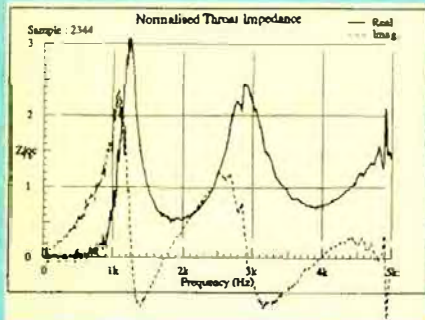


Fig.5a: Throat impedance plot of a typical constant-directivity horn

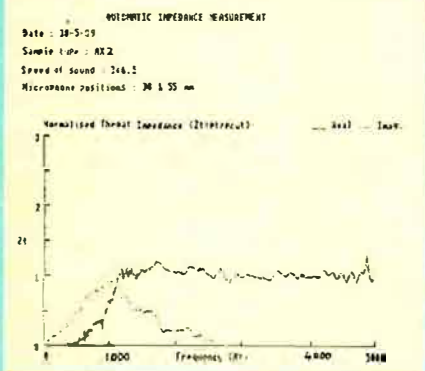


Fig.5b: Throat impedance of AX2 axisymmetric horn

compared to that of a widely-used constant-directivity horn of reputable manufacture and of similar dimensions. However, this should

not overly concern manufacturers of constant-directivity horns, as the bulk of their sales are in the PA/SR field, where their smooth coverage of a desired area far outweighs the sonic subtleties discussed here. For studio purposes though, constant-directivity horns would not seem to be the ultimate solution. ■

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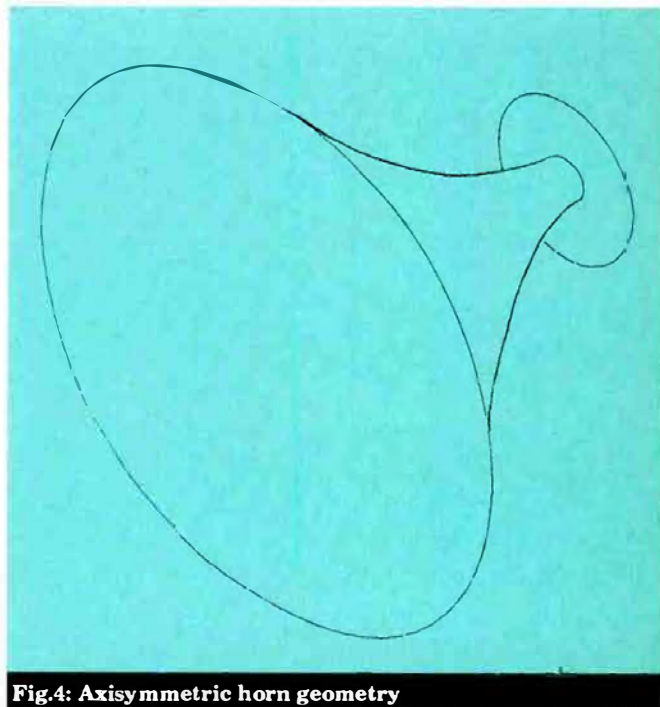


Fig.4: Axisymmetric horn geometry

A2

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