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Summary

The Matrix H 2-channel quadraphonic encoding system has been designed to transmit the maximum amount of directional information consistent with mono and stereo compatibility. This report discusses methods of decoding such transmission signals for 'surround-sound' reproduction.

The basic form of decoder is a complex-coefficient linear matrix, but this has an inherent lack of separation between the output signals. 'Logic enhancement' techniques are discussed, which seek to improve interchannel separations for the principal sound-source, at the expense of secondary sources.

As an interim measure, a modified commercial logic-enhanced ('Variomatrix') decoder was studied, which led to the development of a purpose-built logic-enhanced decoder for Matrix H. The latter combines the virtues of both linear Matrix H decoding, and the variable-matrix logic enhancement technique.

All the decoders described are capable of providing a good surround-sound reproduction. In particular a purpose-built Matrix H logic-enhanced decoder has been shown to exhibit a performance very close to a discrete 4-channel system; the failings normally associated with logic-enhanced decoders are almost inaudible.

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QUADRAPHONY: DEVELOPMENTS IN MATRIX H DECODING

Section Title Page

QUADRAPHONY: DEVELOPMENTS IN MATRIX H DECODING

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Terminology

For brevity in this report, abbreviations for directions with respect to the listener are frequently used; these are defined in Diagram A. The loudspeaker positions are sometimes referred to as 'corner locations', and the span between any adjacent pair of loudspeakers is referred to as a 'quadrant'. The four quadrants are specifically defined as 'front', 'back', 'left' or 'right', as appropriate. Signals associated with a particular loudspeaker are similarly designated by the appropriate direction symbol; the origination signals are shown unprimed, whilst the decoded signals are shown primed. Matrix encoded signals corresponding to conventional stereo left and right signals are denoted by L_T and R_T respectively. A list of symbols is given below.

List of symbols

L_F, R_F etc	quad origination signals	
L'_F, R'_F etc.	decoded quad signals	
L_T, R_T	matrix encoded 2-channel (stereo) signals	
f	front	logic control signals
b	back	
l	left	
r	right	
α_{pq}	linear-decode matrix coefficients	
$r\underline{/\theta}$	polar representation of vector, of modulus r and argument θ degrees.	

1. Introduction

The Matrix H 4-2-4 quadraphonic matrix system was designed primarily to overcome the mono and stereo compatability limitations of other proposed 4-2-4 matrix systems,[1] whilst retaining the ability to provide worthwhile quadraphony. In order that the quadraphonic reproduction should provide a significant subjective enhancement of the sound sensation together with a greater sense of realism and involvement for the listener, the decoding system employed must be effective in extracting the directional information contained in the Matrix H coded two-channel signals.

The decoding of Matrix H signals is not limited to one method and it is the purpose of this report to discuss some of the decoders that have been developed to date. It is highly probable, however, that developments will continue to be made in the field of decoding.

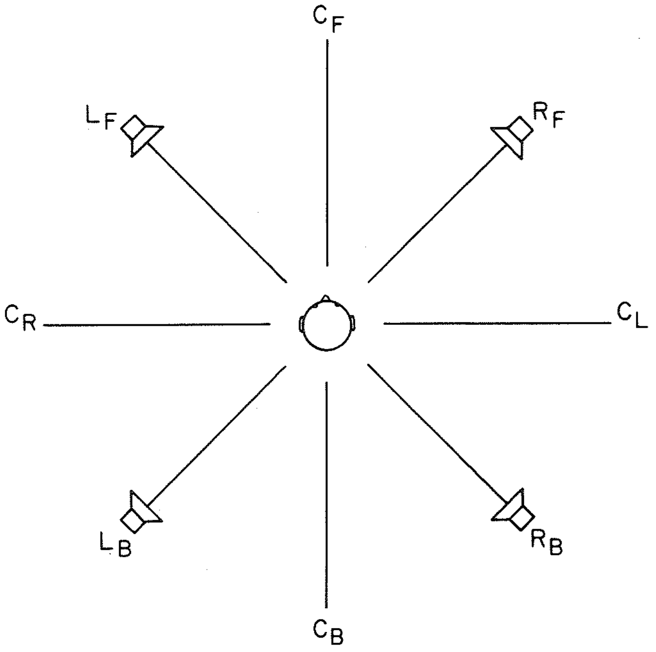

Diagram A - Quadraphonic loudspeaker array for reproduction of surround sound-stage, showing direction abbreviations

C_F centre-front, R_F right-front, C_R centre-right, R_B right-back, C_B centre-back, L_B left-back, C_L centre-left, L_F left-front

Three methods of Matrix H decoding are described in this report, a basic linear matrix decoder, a modified commercial 'logic-enhanced' decoder, and a purpose-built Matrix H 'logic-enhanced' decoder.

2. Matrix H linear decoding

2.1. Basic linear matrix

The fundamental method of decoding employs a basic linear matrix formed by taking the 'complex conjugate'* of the encode matrix thus:-

$$\begin{bmatrix} L'_F \\ R'_F \\ L'_B \\ R'_B \end{bmatrix} = \begin{bmatrix} 0{\cdot}940\,\underline{/{-10^\circ}}, & 0{\cdot}342\,\underline{/65^\circ} \\ 0{\cdot}342\,\underline{/{-65^\circ}}, & 0{\cdot}940\,\underline{/10^\circ} \\ 0{\cdot}940\,\underline{/25^\circ}, & 0{\cdot}342\underline{/{-115^\circ}} \\ 0{\cdot}342\,\underline{/115^\circ}, & 0{\cdot}940\,\underline{/{-25^\circ}} \end{bmatrix} \begin{bmatrix} L_T \\ R_T \end{bmatrix}$$

---

* so called because the column elements in the decode matrix are the complex conjugates of the row elements in the encode matrix.

This results in an overall transfer function for the Matrix H system, expressed in polar co-ordinates, of:-

$$\begin{bmatrix} L'_F \\ R'_F \\ L'_B \\ R'_B \end{bmatrix} = \begin{bmatrix} 1{\cdot}000\ \angle 0^\circ, & 0{\cdot}644\ \angle 55^\circ, & 0{\cdot}791\ \angle -40^\circ, & 0{\cdot}193\ \angle 163^\circ \\ 0{\cdot}644\ \angle -55^\circ, & 1{\cdot}000\ \angle 0^\circ, & 0{\cdot}193\ \angle -163^\circ, & 0{\cdot}791\ \angle 40^\circ \\ 0{\cdot}791\ \angle 40^\circ, & 0{\cdot}193\ \angle 163^\circ, & 1{\cdot}000\ \angle 0^\circ, & 0{\cdot}644\ \angle -90^\circ \\ 0{\cdot}193\ \angle -163^\circ, & 0{\cdot}791\ \angle -40^\circ, & 0{\cdot}644\ \angle 90^\circ, & 1{\cdot}000\ \angle 0^\circ \end{bmatrix} \begin{bmatrix} L_F \\ R_F \\ L_B \\ R_B \end{bmatrix}$$

The response of this system to the eight cardinal stage locations is illustrated in Fig. 1. Each small square describes the decoded output signal-relationships corresponding to the appropriate cardinal position; thus the top-centre square refers to the decoded outputs for a C_F (centre-front) encoded input signal. The numbers in the corners of each small square represent the relative phase-angles (in degrees) of the four output signals, arranged to correspond to the loudspeaker array around the listener (see centre-square). The numbers associated with the arrows indicate the 'separations' (in dB) obtained between the 'wanted' signal output and the 'unwanted' or crosstalk signals from the other outputs. Taking the top left-hand square as an example, this shows the decoded outputs obtained for an input signal encoded at the L_F position. The separation between L'_F and R'_F is 3·8 dB, between L'_F and L'_B is 2·1 dB, and between L'_F and R'_B is 14·3 dB. The relative phases of the crosstalk signals, compared with the 'wanted' L'_F output, are -55° for R'_F, $+40^\circ$ for L'_B, and -163° for R'_B.

It will be seen that low separation figures are obtained between adjacent outputs, and this characteristic is typical of two-channel linear matrix systems, since only two outputs can be completely isolated. However, in the case of Matrix H decoding, greater separation exists in the left/right direction than in the front/back direction. This is intentional since, for a forward-facing listener, it gives a greater accuracy of localisation around the sound-stage than a symmetrical distribution.

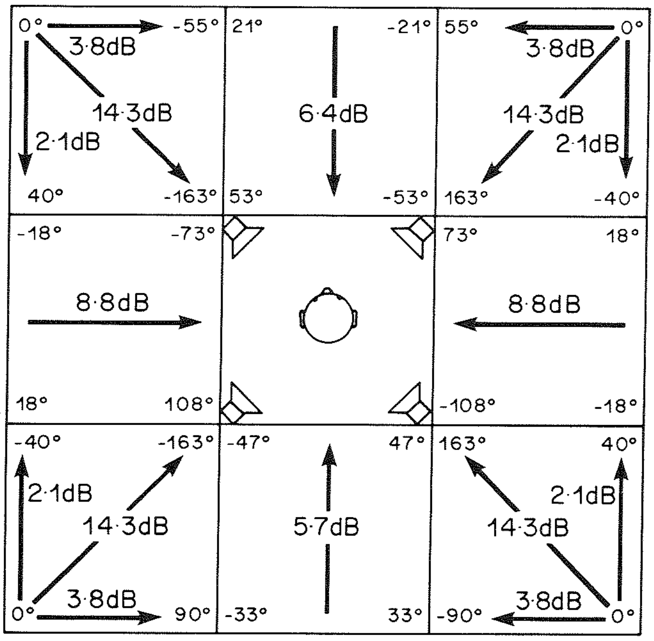

Fig. 1 - Performance chart for basic Matrix H linear decoder (see Section 2)

2.2. Phase-modified linear matrix

Earlier work on the properties of hearing relevant to quadraphonic reproduction[2] showed that the phase relationships between the output signals are also important. The output for a C_F encoded signal in Fig. 1 shows a 42° phase-difference between the 'wanted' signals, which, together with low separation to the phase-shifted rear-channel output signals, causes some diffusion of the C_F image. By phase-shifting the front-channel output signals, this effect can be substantially reduced without significantly degrading the output for other positions; centre-side positions are tolerant of increased phase-difference. In addition, image localisation at the front corners is improved.

The phase-modified linear matrix may be conveniently expressed in polar co-ordinate form:-

$$\begin{bmatrix} L'_F \\ R'_F \\ L'_B \\ R'_B \end{bmatrix} = \begin{bmatrix} 0{\cdot}940\ \angle -20^\circ, & 0{\cdot}342\ \angle 55^\circ \\ 0{\cdot}342\ \angle -55^\circ, & 0{\cdot}940\ \angle 20^\circ \\ 0{\cdot}940\ \angle 25^\circ, & 0{\cdot}342\ \angle -115^\circ \\ 0{\cdot}342\ \angle 115^\circ, & 0{\cdot}940\ \angle -25^\circ \end{bmatrix} \begin{bmatrix} L_T \\ R_T \end{bmatrix}$$

This has a performance shown in Fig. 2. It is seen that the separation figures remain unchanged, but since these are small, the comparatively small changes in the relative phase-angles of the crosstalk signals noticeably improve the subjective performance of the decoder.

The introduction of phase differences between the 'wanted' and the crosstalk signals has the effect of decorrelating the signals and of subjectively increasing their apparent separation. Thus the greatest phase-differences are arranged to occur for crosstalk signals opposite the 'wanted' source direction, although their magnitudes must be carefully controlled. There is an optimum balance between, on the one hand, a 'phasey' oppressive sensation and nasal sound-quality, when too great a phase-difference is employed, and on the other, a close and bass-heavy sound-quality, when too little phase-difference is employed.[2]

In the phase-modified decoding matrix, the various phase and amplitude relationships between the decoded

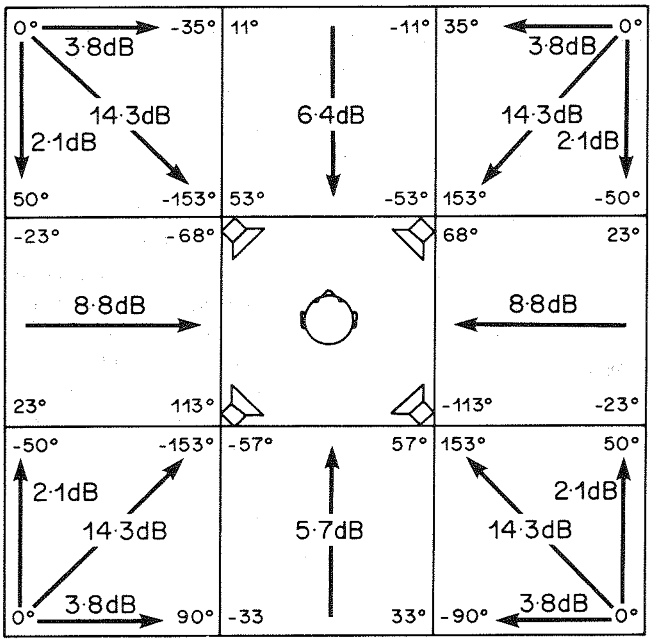

Fig. 2 - Performance chart for phase-modified Matrix H linear decoder (see Section 2)

signals have been optimised, and in analytical, single-source localisation tests this decoder gave accurate image-localisation for a centrally-positioned listener. However, when the listener moved away from the centre-position the directional information became diluted, although the sound sensation was still pleasant. When listening to programme material, listeners commented that, although an extremely pleasant sound sensation was produced, the sounds appeared to be rather close to the listener.

3. Logic enhancement

3.1. Introduction

It is apparent that for a larger usable listening area, signal separations are required which are greater than can be provided by linear matrix decoding. These can be obtained by applying so-called 'logic enhancement' techniques to the decoding process. The decoder is still based upon the linear matrix of the system, but 'logic' circuits are introduced which detect the principal (loudest) sound-source location and vary the decoding parameters to enhance its subjective localisation. In principle, a logic-enhanced 4-2-4 matrix system is capable of reproducing sources at any single location with the same fidelity as a 4-channel discrete system. However, it is a fundamental limitation of such matrix systems that sources at different locations cannot all be reproduced faithfully at the same time. Fortunately, there are ways of masking the deleterious effects of logic-enhancement by exploiting certain insensitivities of the human hearing system.

The overall performance of such a system is characterised by the basic linear matrix and the way in which the logic enhances the principal source. Logic decoders so far developed employ either 'gain-riding'[3] or 'variable-matrix'[4] enhancement; these two techniques will be described briefly.

3.2. Gain-riding logic enhancement

The gain-riding method appears to have been first proposed by Scheiber[3] and many variants have since been suggested. In its simplest form (see Fig. 3), logic circuits vary the gain of the linearly decoded signals to give greater separation between principal-source signals and the associated crosstalk signals; the logic signals are themselves derived from the linearly decoded signals. This process may be expressed as:-

$$\begin{bmatrix} L'_F \\ R'_F \\ L'_B \\ R'_B \end{bmatrix} = \begin{bmatrix} l_f & & & \\ & r_f & & \\ & & l_b & \\ & & & r_b \end{bmatrix} \begin{bmatrix} \alpha_{11}, \alpha_{12} \\ \alpha_{21}, \alpha_{22} \\ \alpha_{31}, \alpha_{32} \\ \alpha_{41}, \alpha_{42} \end{bmatrix} \begin{bmatrix} L_T \\ R_T \end{bmatrix}$$

where l_f, r_f, l_b, r_b are the logic signals and α_{pq} are the linear decode coefficients.

Tests[2] have shown that the minimum audible crosstalk levels for corner and centre-quadrant source locations are about 20 dB and 13 dB respectively. To realise this order of separation with a gain-riding logic system, the crosstalk channels must be attenuated by a similar amount (the basic matrix normally provides about 3 dB of separation). However, secondary sources (quieter than the principal source), at positions different from that of the principal source, will be attenuated similarly. This can lead to secondary-source 'gain-ducking' and 'image movement', although the residual crosstalk signals from the linear matrix sometimes serve to dilute the effect. Careful choice of the attack- and decay-times of the logic action can also help to mask the immediate perception of these effects, but only to a limited extent.

A practical decoder will normally be more complicated than is implied in Fig. 3 with features that attempt to overcome some of the undesirable effects of gain-riding enhancement. Some decoders include a logic-controlled

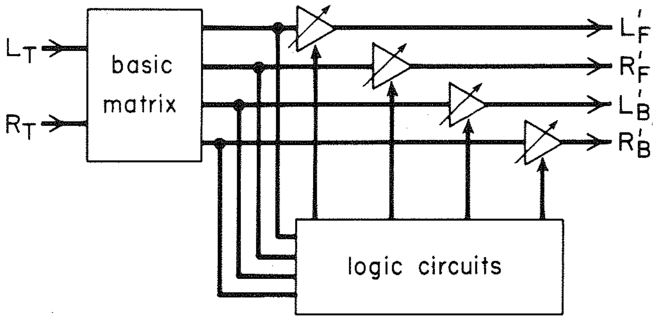

Fig. 3 - Logic-enhanced decoding — gain-riding

blend-circuit between two of the output channels, which operates in a way similar to the variable-matrix technique (described in the next section), albeit after the linear decoding process has taken place. Nevertheless, the overall performance is characterised by the major form of logic enhancement and by the basic matrix.

3.3. Variable-matrix logic enhancement

This technique was developed by Ito and Takahashi[5] and has been reported in several papers.[4,6] The principle involved is illustrated in block diagram form in Fig. 4.

It is appropriate at this point to discuss briefly a variable-matrix logic decoder first employed in the QS quadraphonic system. In this form of variable-matrix decoding, front/back and left/right 'directional detection' takes place in the logic circuits, and the decoding equations are given by:-

$$
\begin{aligned}
L'_F &= [\ (1+f)(L_T-R_T) &+& \ (1+l)\sqrt{2}\,R_T\,] \ \underline{/0^\circ} \\
R'_F &= [-(1+f)(L_T-R_T) &+& \ (1+r)\sqrt{2}\,L_T\,] \ \underline{/0^\circ} \\
L'_B &= [\ (1+b)(L_T+R_T) &-& \ (1+l)\sqrt{2}\,R_T\,] \ \underline{/-90^\circ} \\
R'_B &= [\ (1+b)(L_T+R_T) &-& \ (1+r)\sqrt{2}\,L_T\,] \ \underline{/90^\circ}
\end{aligned}
$$

where f, b, l, r are the logic signals.[6] When $f, b, l, r = \sqrt{2}-1$, this expression is identical to the linear decoding matrix for the QS system, and represents the operating point of the decoder. As enhancement takes place, the logic signals vary between the values 0 and $\sqrt{2}$ according to the directional information.

The merit of this technique is that high separation for a principal sound-source is achieved through cancellation of the appropriate pair of terms in the equations and, as a result, the logic signals ($1 + f$, etc.) need vary by only about 8 dB. With the gain-riding system the variation of the logic signals can be 20 dB or more for a similar order of separation. For a variable-matrix system, the variation in level of both the principal and secondary sources should, therefore, be less affected and, more importantly the degree of image movement should be less. Image movement is caused by the decode matrix being skewed to enhance the principal source, and secondary sources can, consequently, be mislocated. The displacement of the secondary image varies with the logic signals and, as the principal source changes, the secondary image is heard to wander.

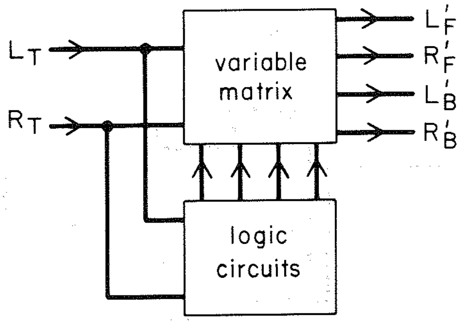

Fig. 4 - Logic enhanced decoding — variable-matrix

As with practical realisations of the gain-riding technique, variable-matrix decoders include features to mask or overcome the side-effects of logic-enhancement. A fast attack-time and slow decay-time are used in the logic circuits, as before, and band-splitting or linear blend-circuits may also be included. However, a brief analysis of the equations describing the decoding process indicates that fewer unpleasant effects may be expected with variable-matrix logic-enhancement than with gain-riding.

3.4. Subjective assessment

In any acoustic study, the performance of a system should be assessed subjectively. During the past few years, many practical decoders have been developed, based on both the two logic-enhancement techniques. Many of these have been assessed at Research Department in extensive subjective investigations. Single-source localisation tests (similar to those described in Ref. 7) were undertaken, and the more successful logic decoders were also assessed using a variety of quadraphonic programme material.

Both the analytical localisation tests and the assessments based on multi-source programme material showed a clear preference for the variable-matrix type of logic decoder.

It should be noted that the basic linear matrix, to which logic-enhancement is applied, also plays an important role in the overall performance of the decoder. The basic matrix of the best decoder of each type was assessed, therefore, in further subjective tests. Although neither was capable of reproducing an effective surround sound-stage, a slight preference was expressed for the basic matrix used in the variable-matrix decoder. This difference is not thought to be significant in accounting for the better performance of the variable-matrix.

The mathematical considerations of the two types of logic-enhancement appear to be fully endorsed by the subjective tests, and the variable-matrix technique should provide the more successful method of logic enhancement for Matrix H.

Two methods of logic-enhanced decoding for Matrix H have so far been investigated. The first was an adaption of a commercial QS–X2 'Variomatrix' decoder, by the addition of a 60° wideband phase-shift, and the second involved the application of variable-matrix logic enhancement to Matrix H linear decoding. These will be discussed in the following sections.

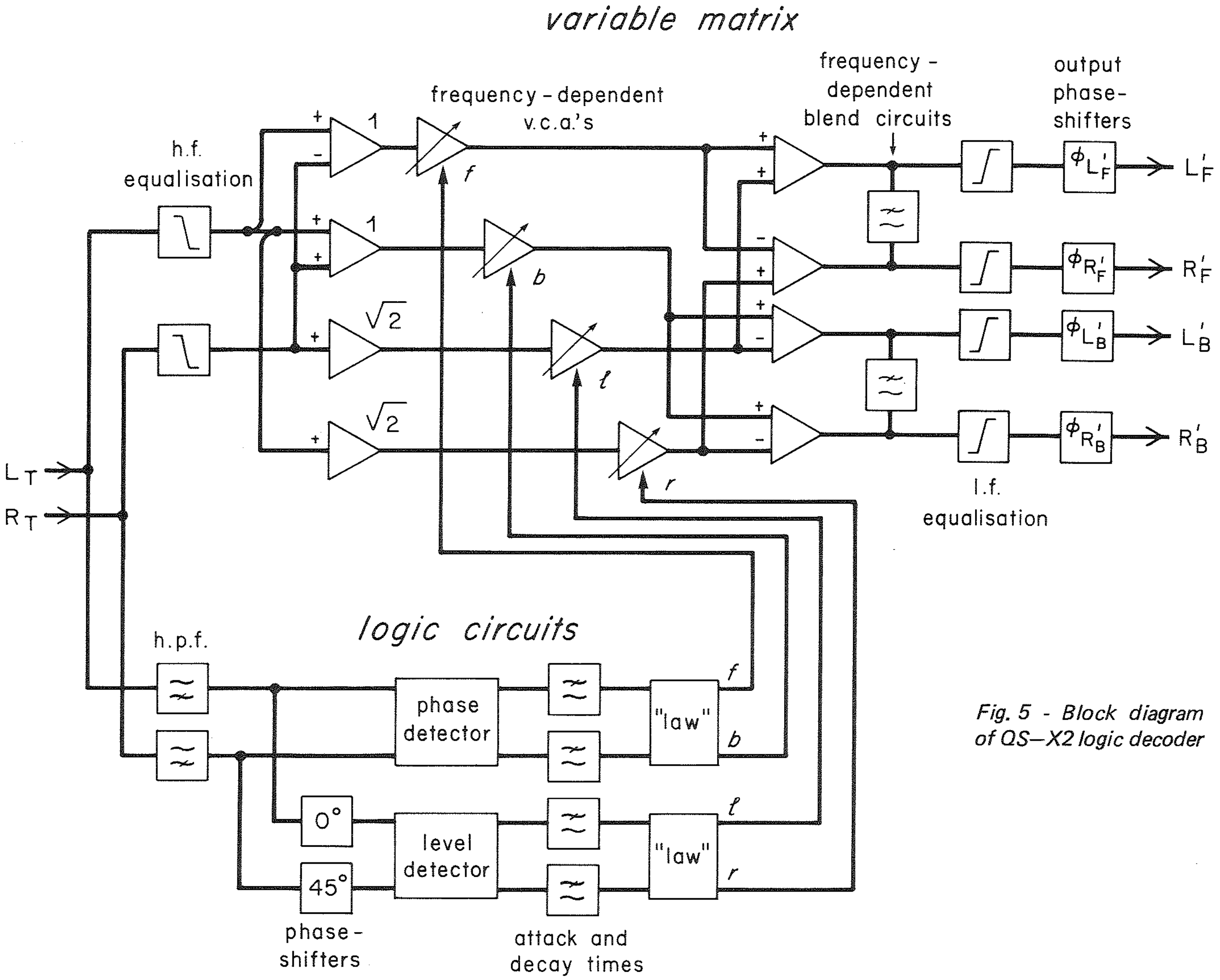

Fig. 5 - Block diagram of QS–X2 logic decoder

4. A commercial logic decoder modified for Matrix H

4.1. General description

In order to approximate the QS decoder (see Fig. 5) to the Matrix H encode, the phase of the R_T input signal was advanced by 60° relative to the L_T input signal, as shown in Fig. 6. In addition the logic action was adjusted to give slightly reduced separation figures. The block diagram shown in Fig. 5 may be considered in two parts, viz the variable-matrix and the logic circuits; these will now be discussed.

4.2. Analysis of variable-matrix logic enhancement

The decoding equations for the QS variable-matrix modified for Matrix H may be expressed as:-

$$L'_F = (1+f)\ (L_T - R_T\ \underline{/60^\circ}) \quad + \quad (1+l)\sqrt{2}\ R_T\ \underline{/60^\circ}$$

$$R'_F = -(1+f)\ (L_T - R_T\ \underline{/60^\circ}) \quad + \quad (1+r)\sqrt{2}\ L_T$$

$$L'_B = (1+b)\ (L_T + R_T\ \underline{/60^\circ}) \quad - \quad (1+l)\sqrt{2}\ R_T\ \underline{/60^\circ}$$

$$R'_B = (1+b)\ (L_T + R_T\ \underline{/60^\circ}) \quad - \quad (1+r)\sqrt{2}\ L_T$$

(an overall power-correction factor of 0·654, and also the output phase-shifts, have been omitted). The logic signals, f, b, l, r, may vary between the values 0 and $\sqrt{2}$ about a 'quiescent' or operating value of $\sqrt{2}-1$, at which point the equations approximate broadly to the basic linear decode Matrix H. When logic enhancement takes place, the control signal(s) corresponding to the direction of the principal sound-source increases in amplitude, whilst the control signal(s) corresponding to the opposite direction decreases.

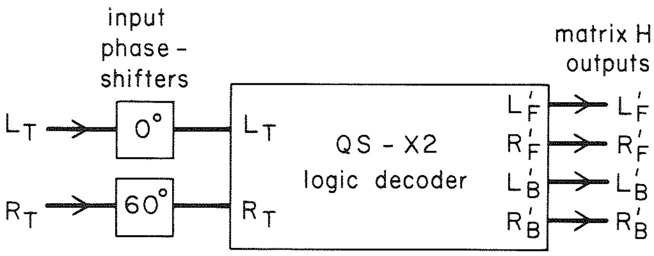

Fig. 6 - Block diagram of QS–X2 logic decoder modified for Matrix H

4.2.1. Single sources

The way in which single or principal sources are decoded will be treated first. Logic enhancement not only increases the desired interchannel separations, but also varies the level of the 'wanted' signals relative to their basic matrix values. Ideally, the overall input/output power law of a source should be constant with azimuth.

With the basic matrix, the crosstalk signals make a significant contribution to the total power (r.m.s. sum) and the power versus azimuth law is constant to within ±1 dB.

With logic enhancement, signal separations are increased and the crosstalk signals contribute only a small amount to the total power. Further, for corner locations, the level of the wanted signal is increased by the logic action by nearly 5 dB above that given by the basic matrix, whilst for centre-quadrant sources, the level remains the same. Nevertheless, the total power law is constant with azimuth to within ±2 dB (c.f. ±1 dB for the basic matrix), and the average power is 1 dB higher than that given by the basic matrix. These differences are small, and the variation in level is unlikely to be audible.

These points may be illustrated by two typical examples (C_F and L_F).

a) A C_F source is coded by Matrix H as

$$L_T = 0{\cdot}828\,\angle 0^\circ, \qquad R_T = 0{\cdot}828\,\angle{-48^\circ}$$

With logic enhancement, the logic signals will be approximately $f = \sqrt{2}$, $b = 0$, $l = r = \sqrt{2}-1$ ($\sqrt{2}-1$ is the quiescent value), and L_F is then decoded as

$$L'_F = (1+f)\,0{\cdot}828\,(1-1\angle 12^\circ) + (1+l)\sqrt{2}\,.\,0{\cdot}828\,\angle 12^\circ$$

giving $|L'_F| = 1{\cdot}67$ with logic-enhancement

and $1{\cdot}65$ with the basic matrix.

The same result holds for R'_F.

b) A L_F source is coded as

$$L_T = 0{\cdot}940\,\angle 0^\circ, \qquad R_T = 0{\cdot}342\,\angle{-75^\circ}$$

and the two logic signals f, l, associated with L_F decoding are both high at $\sqrt{2}$. The L_F decoded signal is therefore

$$L'_F = (1+f)\,(0{\cdot}940-0{\cdot}342\,\angle{-15^\circ}) + \\ + (1+l)\sqrt{2}\,.\,0{\cdot}342\,\angle{-15^\circ}$$

giving $L'_F = 2{\cdot}60$ with logic enhancement.

This level is $((1+\sqrt{2})/\sqrt{2})$, i.e. 4·6 dB, higher than the basic matrix value. The same is true of other corner sources.

These two source positions may also be used as examples to show how high separation is achieved. For a C_F source, the crosstalk to L_B (equal to the crosstalk to R_B) is given by

$$L'_B = (1+b)\,0{\cdot}828\,(1+1\,\angle 12^\circ) - (1+l)\sqrt{2}\,.\,0{\cdot}828\,\angle 12^\circ$$

$$= (1+b)\,1{\cdot}647\,\angle 6^\circ - 1{\cdot}656\,\angle 12^\circ$$

This has a minimum value of 0·173 when $b = 0{\cdot}000$ giving a maximum separation of 19·7 dB.

For a L_F primary source the crosstalk to R_F is given by

$$R'_F = -(1+f)\,(0{\cdot}940 - 0{\cdot}342\,\angle{-15^\circ}) + (1+r)\sqrt{2}\,.\,0{\cdot}940$$

$$= -(1+f)\,0{\cdot}616\,\angle 8{\cdot}3^\circ + (1+r)\,1{\cdot}329$$

If $f = \sqrt{2}$, the minimum value of R'_F is 0·214 given when $r = 0{\cdot}107$ and corresponds to a maximum separation of 21·7 dB.

These two examples show how the two terms on the right-hand side of the equations cancel to give high separation and how it is important for them to be approximately in anti-phase. Having defined the basic matrix it is possible to derive, in a similar way, the maximum separation figures for every principal-source position. In practice it is difficult to arrange the logic circuits so that the derived values of the logic signals, f, b, l, r are able to give these theoretical, maximum separation figures for every source location. However, this has not proved to be a disadvantage for the following reason.

As has been seen earlier, image wandering of secondary sources is caused by the decode matrix being skewed to enhance the localisation of principal sources. By reducing separation, and the range of the logic signals about the quiescent value, the amount by which the decode matrix is skewed, and hence the amount of image wandering, is reduced. In this way, the performance of the modified QS decoder was improved by reducing the separation for a corner source to about 14 dB in the front/back direction and 20 dB in the left/right direction.

4.2.2. Two sources

If two sources are present simultaneously at different locations in the quadraphonic stage, the situation is evidently more complex than for the single-source case. Even if one source is nominally louder than the other, programme signals have a wide dynamic range and the secondary source can often be louder than the principal source for short, but significant, periods of time. For this and other reasons (see Section 4.3.), the logic signals vary at a rate determined by the programme content but limited by the time-constants of the logic circuits.

An extreme case will be considered in which the secondary-source level is low relative to that of the principal source, so that the logic signals are independent of the secondary source. In this example, the principal source is located at L_F and the secondary source at

C_F. The logic signals corresponding to the L_F source are $f = \sqrt{2}$, $l = \sqrt{2}$, $b = 0$, $r = 0$ (nominal values); the secondary source is coded as

$L_T = k$, $R_T = k \underline{/-48^\circ}$ (k being a factor less than unity).

These signals will therefore be decoded to give

$$|L'_F| = k\,|(1+f)(1-1\,\underline{/12^\circ}) + (1+l)\sqrt{2}\,\underline{/12^\circ}| = k\,3{\cdot}40$$

$$|R'_F| = k\,|-(1+f)(1-1\,\underline{/12^\circ}) + (1+r)\sqrt{2}| = k\,1{\cdot}45$$

$$|L'_B| = k\,|(1+b)(1+1\,\underline{/12^\circ}) - (1+l)\sqrt{2}\,\underline{/12^\circ}| = k\,1{\cdot}45$$

$$|R'_B| = k\,|(1+b)(1+1\,\underline{/12^\circ}) - (1+r)\sqrt{2}| = k\,0{\cdot}60$$

Clearly there is an imbalance; the secondary source image is 'pulled' towards the principal source at L_F, the crosstalk signals are increased, and the overall power of the secondary source is increased (3 dB higher than if it had been the principal source). In practice, the logic signals vary with programme content and one may hear the secondary source wandering between C_F and a position between C_F and L_F.

The pulling of secondary sources towards the principal source is a general feature of this type of logic enhancement and constitutes perhaps its most serious limitation. The worst example of image wandering conceivable is probably that which can occur when two sources of a similar level are located diametrically opposite one another; however such situations occur infrequently. Moreover, the ear appears to be relatively insensitive to secondary source movement, particularly if the attack- and decay-times of the logic action are judiciously chosen. Normally, image wandering is not found to be seriously objectionable.

Although emphasis has been placed on image wandering, the level of secondary sources also changes as a function of the logic action. It is found that, in most cases, the total power of the secondary source does not vary by more than about 3 dB.

4.3. Logic-enhancement circuits

The logic circuits are shown in block diagram form in Fig. 5. The encoded two-channel signals are high-pass filtered before being applied to interchannel level- and phase-detectors,* both of which incorporate high-gain, limiting-amplifiers and phase-discriminators. In the level-detector a phase-detector is preceded by a 45° phase-shifter together with sum and difference amplifiers. (The interchannel level (ratio) can then be estimated, independently of the absolute levels of the signals, by measuring the phase-difference of two derived signals; these are formed by taking the sum and difference of the encoded signals, after one has been phase-shifted by 45°). The combination of the limiting-amplifiers and the input filter prior to the detector gives an effective cut-off frequency of about 100 Hz. However, this is level-dependent since, for very small input signals, the limiting-amplifier has insufficient gain to drive the phase-detectors, and the output level of the detector falls to its quiescent value.

Both the level- and phase-detectors provide balanced d.c. outputs proportional to the phase-difference (90° representing the quiescent value). These constitute the logic signals and represent the principal-source location in the original quadraphonic stage. They drive voltage-controlled, variable-gain amplifiers, (v.c.a.'s) via filters that determine the attack- and decay-times of the logic action. The frequency content of the logic signals is related to the dynamic characteristic of the principal source, the relative levels of different sources, and the movement of a source around the stage. However, it is necessary to band-limit the frequency spectrum to mask the onset and decay of logic enhancement

The gain of the amplifiers in the matrix circuits varies with the d.c. level of the logic signals. Circuits prior to the v.c.a.'s determine the 'law' of the logic signals so that f, b, l, r excurse between the values 0 and $\sqrt{2}$ about the quiescent value of $\sqrt{2}-1$.

The v.c.a.'s themselves are frequency dependent. At low audio frequencies they have constant gain so that the decode matrix is independent of the logic action and reverts to its basic form. At high frequencies the logic action is partially bypassed and the separation is reduced, but still to a figure greater than that given by the basic matrix.

As has been seen there are three frequency-dependent stages in the logic circuits, i.e. the input-signal high-pass filtering, the logic-signal time constants, and the frequency dependence of the v.c.a.'s. All of these are mutually dependent and need to be carefully matched. The attack-time of the logic signals should be fast enough for a new principal source to be correctly located without transient mislocation or wandering. At the same time, the phase- and level-detectors require at least a few cycles of audio in order to derive the logic signals accurately, and at low audio frequencies, the necessary period is longer than the attack-time. The input signals are therefore high-pass filtered. Even so, the pass-band largely includes those frequencies where the energy of average programme material is at a maximum (i.e. about 100 Hz to 1 KHz),[8] and a fair estimate is made of the location of sources. Further equalisation of the input signals may improve this estimate.

Since the logic signals may vary up to a frequency determined by the attack-time, audio signals below this frequency must not be subject to the logic control, otherwise severe intermodulation distortion may occur. For this reason, the v.c.a.'s have constant gain at low frequencies. At higher audio frequencies, the modulating frequency (i.e. that of the logic signal) is only a small fraction of the audio frequency and the distortion under these conditions is almost inaudible,

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* In this context interchannel level means the ratio of the levels of two signals, and interchannel phase means their phase-difference.

being transient in nature.

4.4. Output circuits

4.4.1. Blend and equalisation

Following the decoding stage, frequency-dependent blend-circuits are inserted between the corresponding left and right channels of the four audio output channels (see Fig. 5). At very low frequencies (less than 100 Hz) blend is almost total; thus low frequencies are localised on the front/back centre-line. With increasing frequency, left-to-right separation rises to a maximum at 1 KHz, but is again reduced at higher frequencies by the h.f. roll-off of the v.c.a.'s. Typical response curves are shown in Fig. 7. Because of the frequency-dependence of the v.c.a.'s, it is necessary to apply high and low frequency equalisation to maintain a uniform overall power response. An h.f. attenuation of 1·5 dB is effected at the input to the variable-matrix, and an l.f. attenuation of 3 dB is effected at the output.

4.4.2. Output phase-shifters

Finally, a phase-shifter is added to each output channel. These are simple, single-pole, all-pass networks that introduce constant phase-differences for only a relatively narrow band of frequencies around 700 Hz. They attempt to reduce the rather unpleasant sensation of 'phaseyness', but also appear to cause image blurring.

4.5. Subjective assessment

In subjective tests, the higher signal separations of this decoder afforded a more open sound than that given by the basic matrix, with sharper definition of the sound-stage. However, criticisms were made of image movement and mislocation of transient sounds, such as speech sibilants. Also ambience at the rear of the stage was too narrow, giving the effect of a 'tunnel of sound'. Nevertheless, the quadraphonic performance of this decoder, together with that of the QS system, was judged to be significantly better than that of other 4-2-4 matrix systems so far tested.

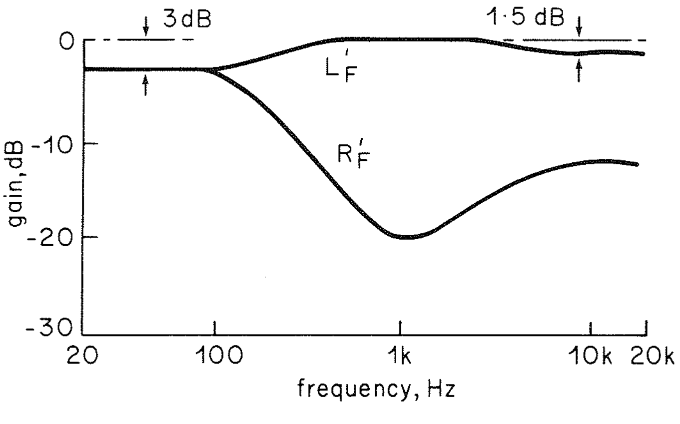

Fig. 7 - Typical separation curves for a L_F source given by the modified QS decoder

5. Matrix H logic decoder

5.1. Mathematical analysis

Although the quadraphonic performance of the modified commercial decoder was good, it still had limitations which it would be desirable to overcome. The design of a new decoder was therefore undertaken, in which logic enhancement was applied directly to the basic linear Matrix H.

The Matrix H decoding equations may be written as:-

$$L'_F = [\ \ 0{\cdot}940 f\ (L_T - R_T\ \underline{/75^{\circ}}) + l\ 1{\cdot}282\ R_T\ \underline{/75^{\circ}}]\ \underline{/-20^{\circ}}$$

$$R'_F = [-0{\cdot}940 f\ (L_T - R_T\ \underline{/75^{\circ}}) + r\ 1{\cdot}282\ L_T\ \ \ \ ]\ \underline{/-55^{\circ}}$$

$$L'_B = [\ \ 0{\cdot}940\, b\ (L_T + R_T\ \underline{/40^{\circ}}) - l\ 1{\cdot}282\ R_T\ \underline{/40^{\circ}}]\ \ \underline{/25^{\circ}}$$

$$R'_B = [\ \ 0{\cdot}940\, b\ (L_T + R_T\ \underline{/40^{\circ}}) - r\ 1{\cdot}282\ L_T\ \ \ \ ]\ \underline{/-65^{\circ}}$$

where, for linear decoding, the logic signals f, b, l, r are at their quiescent value of unity. By varying the logic signals in a similar way to that described for the modified commercial decoder, high separation for a principal source can be achieved.

These equations are realised in the decoder shown in block diagram form in Fig. 8. This decoder is similar in many ways to the modified commercial decoder and makes use of the same integrated circuits. The logic circuitry, however, incorporates a number of improvements, and more logic outputs are provided to drive extra variable-matrix circuits. The audio channels have been more extensively modified, not only to realise the exact basic Matrix H equations, but also to improve other aspects of the decoding.

Analysis of the variable-matrix can be performed in the way described for the modified commercial decoder, and maximum separation figures have been predicted. This has shown that adequate separation can be achieved for most source locations, but for a corner signal the maximum front-to-back separation is relatively low (13·6 dB) and this may displace the image slightly. Separation can be increased by slightly altering the front and back phase-angles of the R_T signal from their values of 75° and 40° respectively. With this modification, a better overall performance can be expected; this approach is under further investigation.

5.2. Input phase-shifters

Accurate wide-band all-pass networks provide appropriate interchannel phase-shifts at the input of the decoder. R_T is phase-shifted by 40° and 75° (relative to L_T) for the decoding matrix, and by 67° and 22° for the logic detection circuits.

5.3. Frequency-dependence of the variable-matrix

As already discussed, in the modified commercial decoder, the matrix is independent of logic action at low

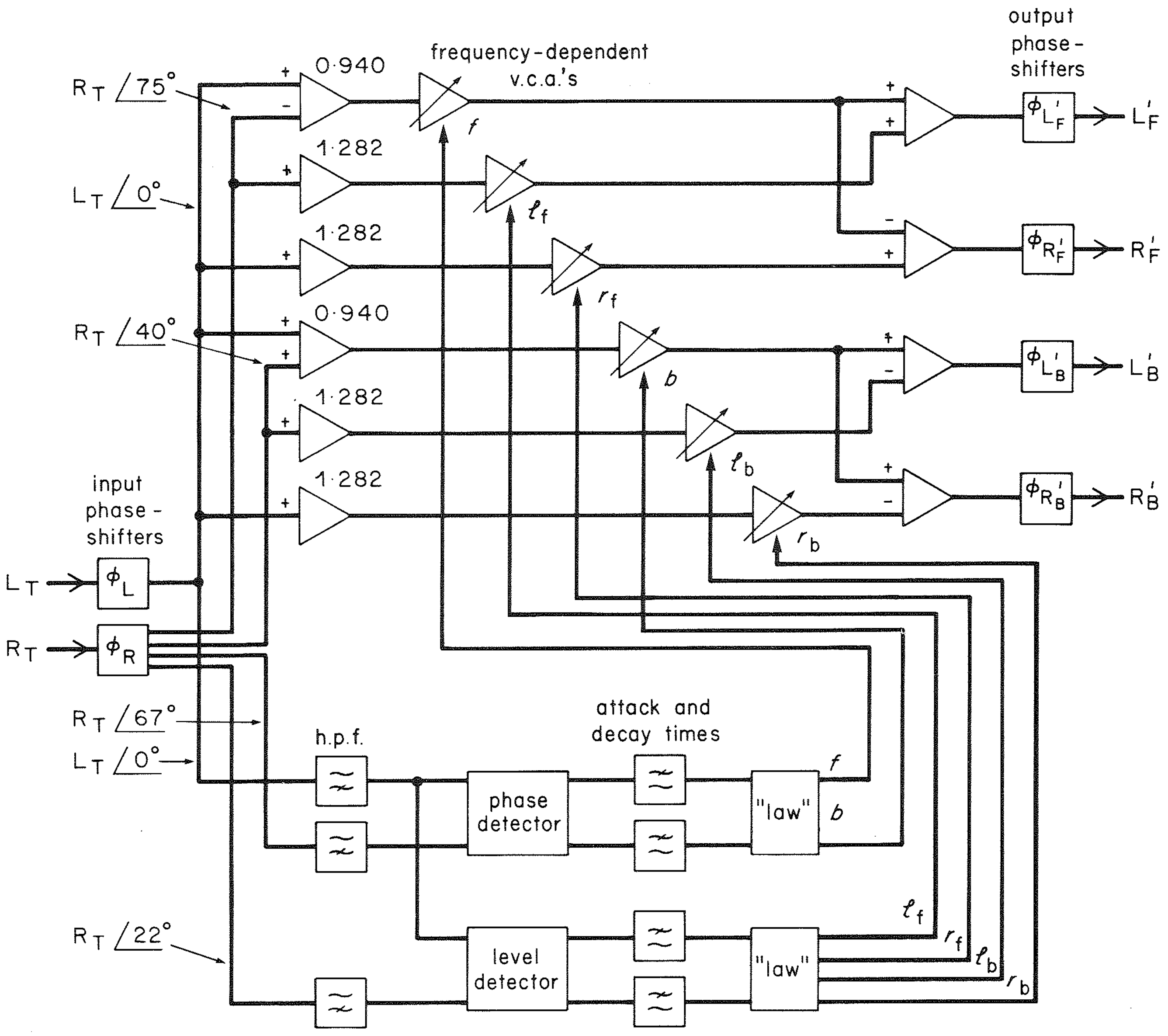

Fig. 8 - Block diagram of Matrix H logic decoder

frequencies and reverts to the basic matrix. However, at these low frequencies, the basic matrix is distorted by the left-to-right blend-circuits in the output channels, which localise low-frequency sounds on the front/back centre-line. No such blend-circuits are included in the Matrix H decoder, since basic Matrix H is capable of accurately localising sounds without logic enhancement.

This has the added advantage of maintaining high separation to a lower frequency (see Fig. 9) and as a result, the total energy of the crosstalk signals is less for the same maximum separation figure (at 1 KHz). This permits a reduction of the logic action so as to reduce image wandering, whilst still maintaining adequate separation.

The logic signals modulate the audio signals and the removal of the blend-circuits might be expected to result in audible intermodulation distortion (see Section 4.3.). However, in practice no evidence of this has been found, possibly because the distortion is of a transient nature.

At high frequencies (above 1 kHz), the high separation of mid-band frequencies is maintained by not restricting the high-frequency response of the v.c.a.'s in the variable-matrix, as in the commercial decoder (see Fig. 9).

5.4. Phase-correction of the output signals

Work on the effects of interchannel phase-differences on the localisation of quadraphonic images[2] has shown that even small phase-differences (of the order of 20°) can sometimes displace or blur an image. There is also evidence that adverse phase-differences can increase the audibility of image wandering in the following way. If a large phase-difference exists between two principal-source signals (for a C_F source, say), the image is displaced and

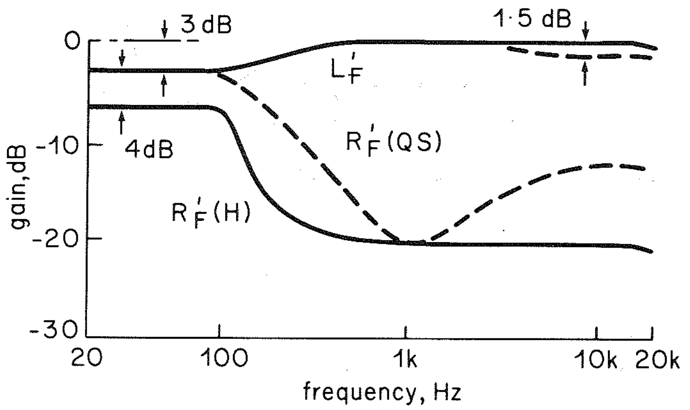

Fig. 9 - Typical separation curves for a L_F source with logic enhancement

▬ H (see Section 5)

▬ ▬ ▬ modified QS (see Section 4)

even small additional variations of phase can cause the image to wander. If, on the other hand, the phase-difference is small, the same variations will have a negligible effect.

Great care was taken, therefore, in the design of the output phase-shifters, to ensure that the proper phase relationships exist between two principal-source signals, and between a principal-source signal and a crosstalk signal. The phase-shifts used were slightly different from the basic matrix values (shown in the equations of Section 5.1.) in order to account for the logic action and the higher interchannel separations produced. They are accurate up to a frequency of about 4 kHz, it being unnecessary to maintain stringent tolerances at higher frequencies (unlike the input phase-shifters in the decoder). With the Matrix H logic decoder, images were found to be much sharper and better defined than those given by the modified commercial decoder; further, slightly less image wandering was also noted, although the sharper images might have been expected to emphasise this effect.

5.5. Discussion

On a brief subjective assessment of this decoder, significant improvements were found as compared with the modified commercial decoder. The principal improvements consisted of sharper images, a greater sense of 'openness' and better overall perspective, fewer sibilant mislocations, and a much greater tolerance to listener position.

As mentioned earlier, it is thought that this type of decoding, which uses different interchannel phase-angles for decoding the front and back channels, could be optimised by slightly altering the phase-angles from those used in the basic Matrix H decoding equations. Further developments can also be envisaged, for example, using more complex forms of logic-enhancement, or the incorporation of delay-lines in the audio channels to overcome low-frequency localisation and transient problems.

6. Simplified Matrix H logic decoder

The Matrix H decoder described above is a fairly complex device, as Fig. 8 shows. Methods of simplifying the circuits and of overcoming some of the residual impairments were investigated. This work continues, but a simplified decoder has already been developed with a performance comparable with, if not better than that of the Matrix H logic decoder described above.

A block diagram of this decoder is shown in Fig. 10. The logic circuits used are the same as those incorporated in the Matrix H logic decoder described in Section 5, but the basic matrix is modified to decode using a single phase-angle for both front and back channels. The decode equations become:-

$$L'_F = [\ 0{\cdot}940\,f\,(L_T - R_T\ \underline{/67^{\circ}}) + l\ 1{\cdot}282\ R_T\ \underline{/67^{\circ}}]\ \underline{/-20^{\circ}}$$

$$R'_F = [-0{\cdot}940\,f\,(L_T - R_T\ \underline{/67^{\circ}}) + r\ 1{\cdot}282\ L_T\ ]\ \underline{/-50^{\circ}}$$

$$L'_B = [\ 0{\cdot}940\,b\,(L_T + R_T\ \underline{/67^{\circ}}) - l\ 1{\cdot}282\ R_T\ \underline{/67^{\circ}}]\ \underline{/25^{\circ}}$$

$$R'_B = [\ 0{\cdot}940\,b\,(L_T + R_T\ \underline{/67^{\circ}}) - r\ 1{\cdot}282\ L_T\ ]\ \underline{/-95^{\circ}}$$

where the basic matrix is given when $f, b, l, r = 1$.

Since R_T is phase-shifted by the same angle for the front and back channels, the variable-matrix circuits are reduced in complexity. At the same time, separations for corner sources are improved without significantly sacrificing other locations.

Although the basic matrix has been altered, it can be seen from the chart shown in Fig. 11 that its performance closely resembles that of the phase-modified linear Matrix H shown in Fig. 2. Moreover, the two linear matrices were compared subjectively using programme material and there was little apparent difference between them.

With the different basic matrix, the output phase-shifts are slightly changed from those used in the Matrix H logic decoder of Section 5. The values used give good phase-correction of the output signals, with both the basic matrix and logic enhancement. Fig. 12 shows a typical performance chart for the decoder, applicable to frequencies in the logic-enhanced band, and Fig. 11 represents the performance at low frequencies where logic

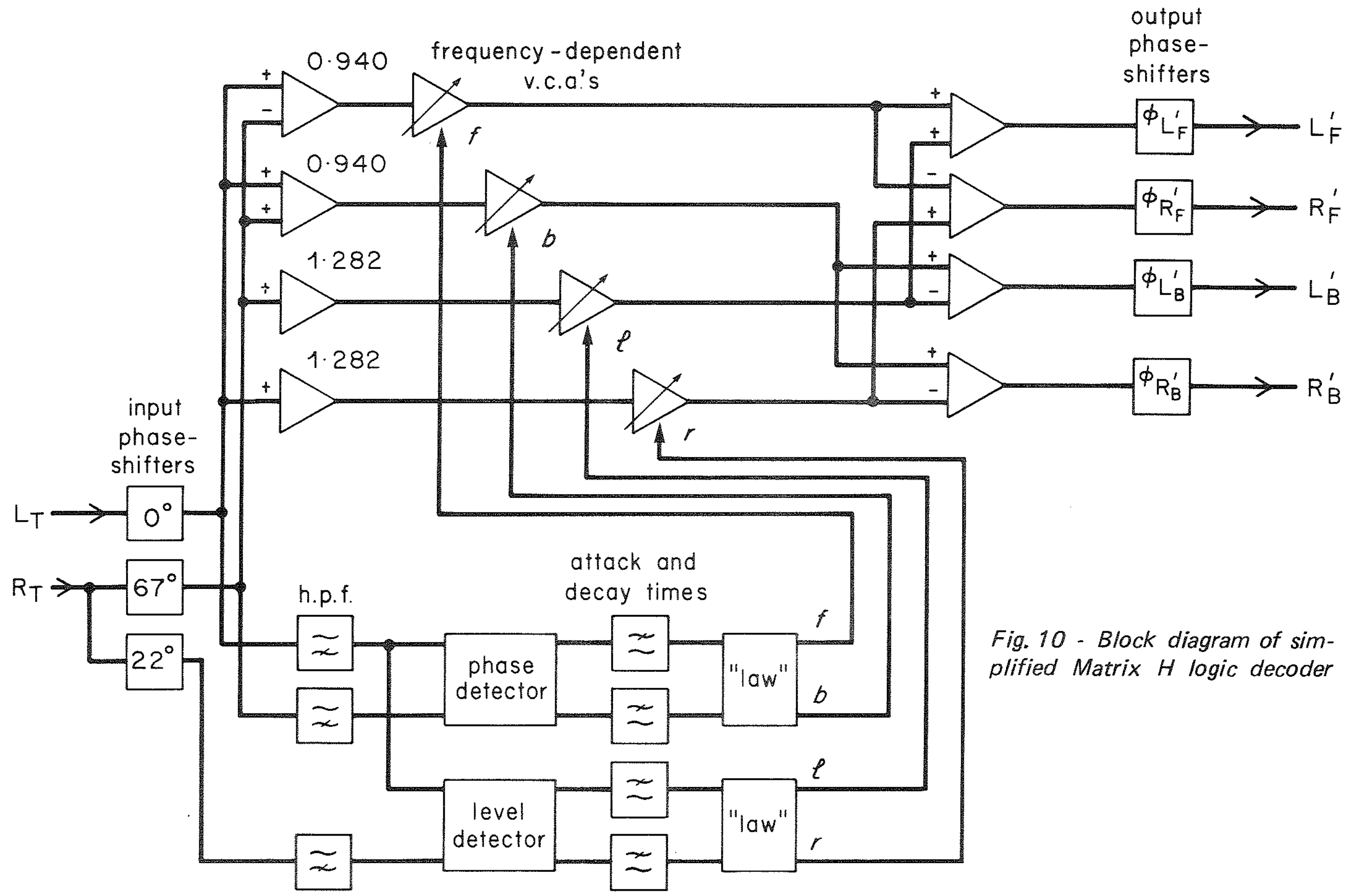

Fig. 10 - Block diagram of simplified Matrix H logic decoder

is not operative.

Subjectively the performance of the decoder was found similar in many ways to the Matrix H logic decoder of Section 5, with the addition that corner signals were better defined. Since the favourable qualities of the more complex decoder are also exhibited by the simplified version, more comprehensive subjective assessments were undertaken and these are discussed in the next section.

7. Subjective appraisal of Matrix H decoders

7.1. General

Throughout the development of the Matrix H quadraphonic system a considerable number of subjective tests have been conducted in order to assess the performance of this and other proposed matrix systems. These have included simple analytical tests, designed to examine the basic properties of the system, and programme listening tests to examine the qualitative performance and the ability of the system to reproduce complex source-signal arrangements.

7.2. Localisation tests

One highly informative and analytical set of tests involves single-source localisation, as described in Reference 7. The listener is asked to estimate the position and spread, or diffusion, of a sound-image produced by the system, with a source-signal encoded at any one of sixteen azimuth positions.

In such tests the basic Matrix H decoder was found to give good overall positional accuracy but the images were more diffuse than those of discrete 4-channel quadraphony. However, unlike most other systems, when decoded using a basic linear matrix the images were not unpleasant or 'phasey' in quality, and were reasonably stable with head movement. Some comments of 'closeness' of images were made, but otherwise the subjective results were found to be quite acceptable.

The commercial decoder modified for Matrix H gave better overall positional accuracy and considerably sharper images than the linear decoder, to the extent that the results were not significantly inferior to those of a discrete system. The 'closing-in' effect of the linear decoder was absent, but some comments were made that sibilants were localised at positions different to that of the main image. This is probably due to limitations in the transient performance of the logic enhancement.

The Matrix H logic decoder described in Section 5 has not yet been tested fully, but the simplified version (see Section 6) gave a further small improvement in overall positional accuracy compared with that given by the modified commercial decoder, and the overall performance closely matched that of a discrete system. In

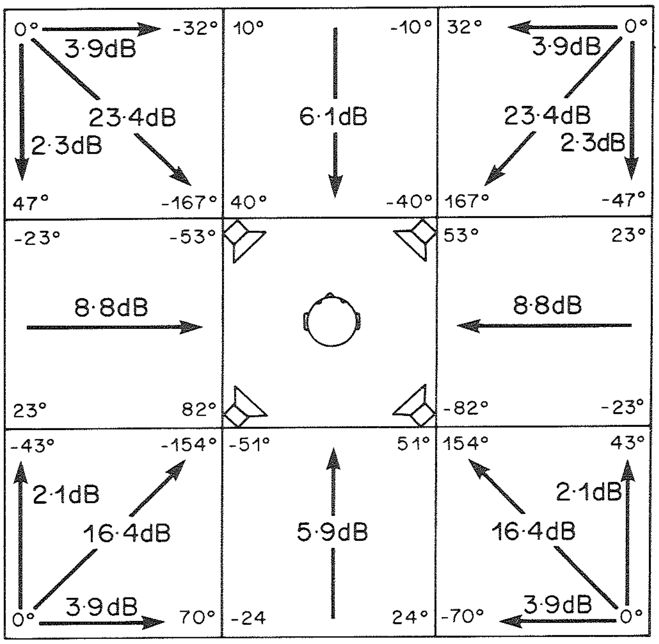

Fig. 11 - Performance chart for basic matrix in the simplified Matrix H logic decoder (see Section 6)

particular, although sibilant effects were not completely absent, they were much less noticeable than those for the modified commercial decoder.

7.3. Programme assessment

A wide selection of programme material, including serious music, light music, pop, comedy, and drama, has been used in assessing various 4-2-4 matrix systems. For assessments of this nature, a complete encode/decode combination is sometimes used when balancing the original programme material (obtained from, say, multi-channel recordings). By monitoring the encoded stereo signals and the decoded quadraphonic signals, the performance of the particular system can be optimised. In such circumstances, the four inputs to the encoder may not be the most suitable for a discrete 4-channel system. Further, and perhaps more importantly, a 4-2-4 matrix system balanced in this way may not provide optimum encoded signals (L_T, R_T) for an alternative form of decoder. Thus in tests assessing the subjective performances of the various Matrix H decoders, the programme material was balanced only for discrete quadraphony, and encoded by Matrix H. Given the same encoded signals, the decoders were then compared using discrete quad as a reference.

The basic linear Matrix H decoder gave good positional accuracy with multi-source material and good tonal quality. It gave an overall pleasing sound sensation that was, however, somewhat blurred and 'closed-in' when compared to discrete quad. Some instability of the sound-stage was apparent with considerable head movement about the listening position and, when the listener moved out of the central listening area, the sound-stage collapsed to the nearest loudspeaker more noticeably than with discrete quadraphony. Even so, a pleasing unoppressive sound was maintained, unlike most other 4-2-4 systems when decoded linearly.

With the modified commercial decoder a much more spacious sound was produced, generally with good tonal quality. Its performance was more similar to discrete quad than that of the linear decoder. Occasional sibilant mislocations were noted, mainly on speech, but these were not too objectionable. However, with serious music the ambience was often found to be too narrow at the rear of the sound-stage, and a narrowing of the front-stage also occurred when the main body of sound was located in the centre-front region of the stage. It was also found that, for complex programme material, sound-images seemed to be less clearly defined than with discrete quad, and there was an apparent excess of low-frequency energy in the centre of the stage. This was almost certainly due to the left/right blending in the commercial decoder at low frequencies. Some image movement was detectable, and in particular a dominant front sound-stage tended to pull forward secondary sound-images, located at the rear corners, to appear at the sides of the quad stage; however, this was seldom seriously objectionable. Some secondary image wandering could occasionally be detected by experienced listeners, but none of these deficiencies appeared to be severely detrimental to listener's appreciation of the quadraphonic sound. This decoder was more tolerant to off-centre listening positions than the linear decoder, but uncomfortable 'phasey' effects could be detected in some locations for some image positions, largely due to the limitations of the phase-correction circuits employed.

The simplified Matrix H logic decoder again produced a spacious sound of good tonal quality similar to discrete quad. The sound gave the impression of being significantly clearer, with a more 'open' perspective than that of the

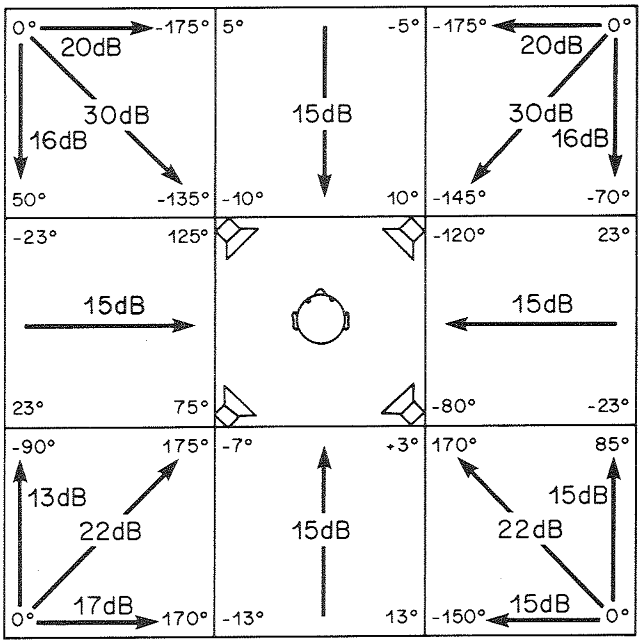

Fig. 12 - Performance chart for simplified Matrix H logic-enhanced decoder (see Section 6)

modified commercial decoder, and was judged to be very close to the discrete quadraphonic sound. Ambience-spread in the rear-stage was substantially improved, and had a more natural tonal quality. In addition, compression of the front-stage was much less obvious than with the modified commercial decoder. Sibilant effects were hardly noticeable, although occasional image movement could still be detected. The lack of low-frequency energy in the centre-stage region, using complex source material, was considerably preferred with this decoder, and this point was significant when listening for extended periods; a more 'comfortable' sound sensation was commented upon. Tolerance to off-centre listening appeared to be particularly good, very much like discrete quad, and the unpleasant 'phasey' sensations observed with the modified commercial decoder were absent.

A 3-way comparison test between the modified commercial decoder, the simplified Matrix H logic decoder, and discrete quad (used as a reference) was arranged after the initial assessment period. Nine studio managers from BBC Radio Broadcasting Groups were asked to assess and rate the two decoder performances on a continuous 0—100% quality scale, with discrete quad as a reference, necessarily defined as having a 100% rating. The listeners were unaware of the decoder options being used. They listened to a 30-minute tape containing a wide selection of programme items mixed for discrete quad. Overall, the simplified Matrix H decoder was rated at 77% as compared to discrete quad, and the modified commercial decoder was rated at 47%. However, this result pertained to tests where small differences in performance might be expected to be magnified; it should be noted that, in some earlier tests, where the original programme material was balanced for the Matrix H system using the modified commercial decoder, a much closer match was obtained to discrete quad. This match was considerably better than that for other matrix systems.

8. Conclusions

The Matrix H 4-2-4 quadraphonic system permits the use of a number of different decoding options, all of which are capable of producing worth-while quadraphony, but with different limitations.

The basic linear Matrix H decoder produces a pleasing surround-sound; it is simple and has the advantage of time invariance, but it cannot produce sharply-defined sounds, and gives a somewhat restricted listening area.

The application of logic-enhancement techniques to Matrix H decoding can provide a sharply-defined and more spacious sound-stage, similar to discrete quad. However, since the 'logic' circuits can only produce ideal decoding for one sound-source direction at a time, much of the success of this technique depends upon effective deception of the human hearing mechanism.

The variable-matrix technique of logic enhancement has been found to be most successful to date and, as an initial expedient, a commercial ('Variomatrix') decoder was modified for Matrix H decoding. This gave generally good results, although limitations due to the instrumentation of the decoder were apparent to the experienced listener.

The Matrix H logic-enhanced decoder combines the advantages of a good linear decode matrix with those of the variable-matrix enhancement technique, but is rather complex. However, a simplified version, which is comparable in complexity with the commercial decoder, and is based upon a slightly modified form of the basic matrix, has been shown to provide the best quadraphonic performance to date from a 2-channel matrix system. Although the limitations of logic enhancement still exist, their adverse subjective effects are, in general, well masked.

It is considered that the limit of the performance of Matrix H decoders has not yet been reached and, as discussed in this report, some aspects of decoding have yet to be optimised. In addition there are other techniques that may be applied to future decoders. Nevertheless, it has been shown that a high standard of quadraphonic reproduction may be achieved with the decoders discussed in this report.

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