New Electromechanical Method of Matrixing the Two Components in Stereophonic Disc Recording

HORST REDLICH,* HANS-JOACHIM KLEMP,** and
STEPHEN F. TEMMER***

While the 45/45 stereo cutter can be fed directly from the right and left channels without matrixing, it is equally possible to employ a 0/90 cutter—when designed especially for the operation—to obtain exceptionally fine results.

For the longest time efforts have been directed towards the ability to store stereophonic sound. In magnetic systems, such as tape or film, a satisfactory solution has been found by dividing the available magnetic track width. The modern phonograph record, however, is one recording medium which already has the highest known ratio of playing time to available surface area. Approximately 30 seconds of sound can be stored on one square inch of its surface, while tape at 3¾ ips *twin-track,* requires at least *fifteen* times the surface area to accommodate the same amount of sound. This is one of the reasons why it is nigh onto impossible to apply principles analogous to magnetic recording to disc. As a result, early attempts at recording two channels on disc approached the problem not by dividing the track width, but rather by cutting the available surface area in half.

The Double-Groove Principle

There have been, for example, disc recordings (Cook Laboratories) which are so recorded as to separate the two recording channels into two separate groups of normal microgrooves situated next to each other on the same side of the record. This type of disc must be played back using a double tone arm with two separate pickup cartridges.

This method has two distinct disadvantages. The first is the demand for double the surface area needed for monophonic recordings, and the resulting short playing time available per record. The second, and even more serious, is the extreme difficulty of maintaining the necessary phase synchronism between channels. The degree of accuracy of the phase relationship between the two channels, is dependent on the alignment of the recording and reproducing styli. Aside from this, the phase alignment of the two channels must remain fixed from the outermost to the innermost groove of the record, requiring the same tangential or arc-type motion for both the recording and reproducing mechanism.

All of these problems would be avoided if it were possible to use a single groove, as in monophonic recording, which is recorded with a single stylus and is played back with a single stylus. There are two possible solutions to the problem of how two separate signals can be accommodated in such a single groove.

The Carrier-Frequency Method

This is essentially a method similar to that employed in carrier telephony. Here is one type of carrier system: The first channel is fed directly to the recording cutter through a high-pass filter network of, for instance, 12 kc. A carrier frequency lying directly above the first channel is then used to modulate the contents of the second channel. The upper side-band ($f_c + f_{ch2}$) is filtered out and is recorded together with channel 1 and a synchronizing frequency. The recorded band width, therefore, is somewhat more than twice the width of each channel alone. With a frequency range of 12 kc in each channel, a recorded bandwidth of about 25 kc is required.

The reproduction requires a playback system capable of an upper frequency limit of 25 kc. After preamplification, the first channel is filtered out by means of a low-pass filter. A high-pass filter then isolates channel two, which is demodulated in a ring modulator by addition of the carrier frequency. This frequency is generated by a multivibrator which is triggered by the synchronizing pulse originally recorded on the disk. This synchronizing pulse is necessary in order to achieve flawless demodulation even when the turntable speeds of the recording lathe and reproducing turntable do not agree.

The above described system was developed over a long period of time in the Laboratories of English Decca. Despite the difficult demands on the bandwidth of the recorded disc, the Decca engineers had achieved a very excellent solution to the problem of two-channel recording in a single groove. They achieved a reproducing quality in every way equal to today's highest accomplishments in the electroacoustical field.

The major disadvantage in this system is the relatively high equipment contribution which the consumer must make to achieve demodulation. It is for this reason that another solution to the problem of two-channel, mono-groove recording was sought.

The Two-Component or Vector System

While the foregoing method achieves single-groove recording and channel separation by electronic means, a mechanical alternative to this is possible. The recorded groove contains the two information channels as two excursions lying at right angles to each other (orthogonal system). The actual orientation of this set of crossed motions with respect to the surface of the disc is immaterial, however practical considerations make two particular orientations preferential: one vertical-lateral; the other in which each channel is oriented at 45 deg. to the surface of the disc. The resulting groove may be compared to a street which runs over hill and dale while at the same time winding and curving. The motion of a car on such a road may be analyzed by separation into two components lying at right angles to each other, which may then be in turn assigned to channel one or two.

The recording of such signals requires a transducer capable of translating the signals of channels one or two into excursions of the stylus in the proper

* *Technical Director* and ** *Development Engineer, (TELDEC) Telefunken-Decca GmbH, Berlin.*
*** *President, Gotham Audio Development Corp., 2 W. 46th St., New York, N. Y.*

direction. The reproducing transducer does the reverse. The complex mechanical motion of the reproducing stylus is resolved into excursions lying at right angles to each other which are then converted into electrical impulses. Of utmost importance is the accuracy of the angle which the "motional cross" has to the surface of the disc in both recording and reproduction, and the true perpendicular relationship which the components have to each other. Only in this manner can maximum separation between channels be achieved.

The first experiments with this type of stereophonic recording were made by A. D. Blumlein, engineer with E.M.I. Ltd., England. Since these experiments and his patent go back to the early thirties, it must be ascertained how this type of recording is adaptable to the present-day microgroove recording techniques. Experiments of TELDEC (Telefunken-Decca) go back to the years 1954 and the first cutterhead utilizing feedback in both channels was built in the summer of 1955.

Quality Considerations in the Vectoral System of Recording

Provided we assume the necessity of preserving the full stereophonic effect in two channels, each of which are of equal quality, then each of them should have a degree of quality, with respect to frequency response and distortion equaling the highest attained level of today's electroacoustical knowledge. Furthermore, we must aim at the highest degree of interchannel separation. The degree of interchannel separation necessary to preserve the full sound-width of the original is subject to much theorizing and discussion. We have conducted numerous listening tests in an effort to arrive at some reasonable figure and on the basis of these tests we feel that the high quality of a stereophonic recording can only be maintained if the separation between channels stays above 20 db. Both the original recording on tape as well as the disc mastering and reproduction separations are included in this figure. The recording alone should be considerably better than the 20 db quoted, in order to allow for a greater tolerance spread in mass-produced reproducing equipment. A separation figure of more than 30 db should be the aim of the disc recording industry. This degree of separation requires of the cutting head a very high degree of motional accuracy. To translate this into concrete figures: the deviation from the prescribed two paths of the stylus by all influences may not exceed 1.5 deg. At higher frequencies, as for instance 10 kc, this is an actual physical displacement of only 0.001 mil. Such magnitudes can no longer be measured by mechanical means. In other words, we demand of a mechanical system degrees of accuracy which cannot be controlled by mechanical or optical means. The only possible approach in our development of such a cutter was to utilize a system of electromotional feedback for the stabilization of stylus motion. This type of feedback control also made possible the other required quality demands for wide frequency response and low distortion, which are favorably influenced by motional feedback. There are, however, further problems of non-linear distortion in such a two-component system, which will be covered in a later paragraph.

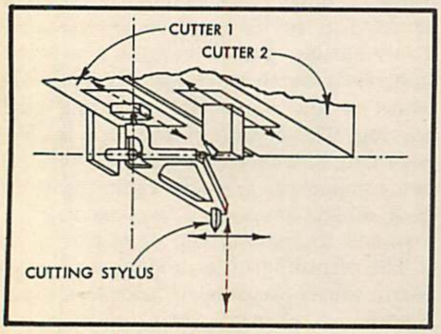

Fig. 1. Mechanically coupled two-component cutterhead.

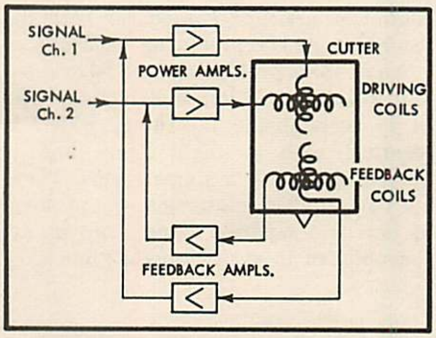

Fig. 2. Diagram of feedback and driving coils in the TELDEC cutterhead.

A Double-Motion Feedback Cutting Head

The integration of the individual components into a resulting double-motion of the recording stylus can be accomplished in two basic ways.

The first way is to use two normal single-motion transducers connected through a lever system as shown in *Fig.* 1. The motion of system 1 leads to motion of the stylus in a vertical direction, while motion of system 2 produces a lateral excursion. Motion of both systems simultaneously produces a vectoral resultant of the two motions, whose direction and amplitude is the resultant of the applicable amplitudes of the two directions as well as their phase relationship.

Experiments carried on with such a system demonstrate its feasibility, as shown by a similar type of drive found in the Westrex Type 3B cutterhead. The required degree of accuracy of motion is, however, extremely difficult for such a system to attain, *even* if the quality and stability of the individual motional components are of the *highest accuracy.* The motional feedback applied to each of such systems cannot include the stylus suspension system itself due to the lever-type connection between the systems and the stylus, whose self-generated interference cannot be compensated. It seemed therefore desirable to devise a cutter in which the armature is of extreme stiffness in itself, and which is so suspended as to permit free motion in only one plane. Only in this way is it possible to use two feedback systems which interact to produce stabilization of motion between the two channels.

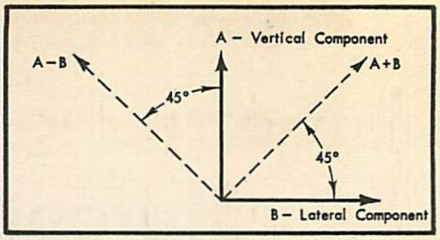

Fig. 3. Transformation of a vertical-lateral recording into a 45/45 recording by sum and difference formation.

The feedback loops are so arranged as to produce at the same time a complete feedback system within each motion (*Fig.* 2). The feedback voltages are produced in two separate feedback coils situated near the stylus itself, and are fed back to the appropriate cutting amplifier. This kind of arrangement produces a linearity compensation within the two loops, and furthermore serves to negate any mechanical outside influence which would tend to displace the stylus motion from its assigned path. Let us take an example where a mechanical resistance diverts the stylus from its intended motional direction. This produces a voltage in the *opposite* feedback loop which is proportional to the diversion. Since this feedback voltage is applied with reversed polarity through the driving amplifier to the drive coil placed at right angles to it, a motion equal and opposite to the mechanical diversion is created which offsets it and maintains linearity.

The result of such a feedback system is the assurance that the two motions of the stylus are maintained accurately perpendicular to each other. Such perpendicularity is absolutely essential, for only in this way can the minimum degree of interaction between channels be assured. The relative position of the "motional cross" should be either vertical-lateral, or at 45 deg. to the disc surface. The selection of one or the other system simply requires a different placement of the driving and feedback coils on the armature of the cutter. It is also possible simply to "turn" the "motional cross" by 45 deg. To do this one must form the sum and the difference of the two driving signals, as in *Fig.* 3.

Positioning of the Driving and Feedback Coils in the Magnetic Field

For distortion-free transduction of electrical energy into mechanical motion, it is desirable to utilize an electro-dynamic system. For a two-motion dynamic feedback system it is necessary to provide one driving and one feedback coil for each motional direction. How

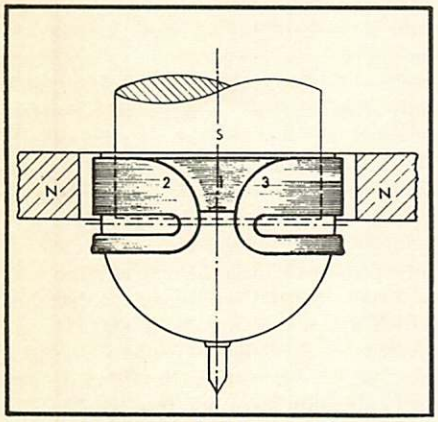

Fig. 4. Diagram of driving-coil arrangement.

such a coil arrangement is placed on a thimble-shaped armature is shown in *Fig.* 4.

The drive coil 1 (circular shape) moves the armature in a ring-shaped magnetic gap in a vertical direction. The two half-coils 2 and 3, on the other hand, are so interconnected, that the conductive parts of those coils which are situated in the same concentric magnetic field as coil 1, produces a rotational motion of the armature. By selecting the point of rotation, this rotating motion imparts to the stylus, for all practical purposes, a lateral excursion. Therefore the motions resulting from coil 1 and a combination of coils 2 and 3, stand at the tip of the stylus at the right angles to each other. The wiring pattern of a 45/45 cutter consists of a further combination of these two coil windings.

The two feedback coils are located near the stylus end of the armature, since the motions at this end are perpendicular to each other and are not, like those at the driving coil point, composed of a vertical and a rotational motion. At the feedback coil location, therefore, a different magnet structure is necessary. The ring-shaped magnetic gap is so constructed as to produce lines of force running at an angle of 45 deg. to the motion of the armature. One can picture these lines of force as being separated into two components, as shown in *Fig.* 5. Vertical motion of the armature permits its ring-shaped winding, 1 to cut the lines of force shown as dashes. This produces a voltage proportional to the velocity of the vertical motion. Lateral motion of the armature produces a cutting of the dotted lines of force, but an emf of equal magnitude and opposite polarity is generated by the two sides of winding 1 therefore producing no output voltage for this motion. The exact opposite takes place in the figure-eight windings 2 and 3. A horizontal motion produces an emf proportional to lateral velocity, while vertical motion produces cancellation in those windings. All this is true provided complete symmetry is maintained. The potentiometer shown in *Fig.* 5 permits balancing of the coils 2 and 3, thereby insuring motions perpendicular to each other. Channel separation in the stylus motion exceeds 40 db. Should a motional cross of 45 deg. to the record surface be desired, a combination of connections of the feedback coils will also be necessary.

The arrangement just described works with a concentric magnetic system. The ring-windings are always assigned to the vertical motions of the armature, while the bucking half-windings are always assigned to the lateral motions of the armature. This holds true for both the driving coils as well as the feedback coils. Should the concentric placement of magnets be substituted by a transverse one, a reversal of the coil functions will take place. We have chosen the concentric arrangement because of weight considerations. A magnetic field of tremendous strength is necessary (B is greater than 12,000 gauss) and the resulting small dimensions of gap and armature require extreme accuracy in the parts which comprise the magnetic path. It was nevertheless possible to maintain the gross weight of the cutterhead at 12.8 ozs. In a cutter system using a diagonal arrangement of magnets, this weight would be almost impossible to maintain, since the gaps on the left and right must be arranged with alternating *N* and *S* poles, requiring a considerable increase in magnet size.

One of the major difficulties encountered in the design of this double feed-back, two-motion cutterhead was the shielding of the feed-back coil from its driving coil to prevent inductive coupling between them. The close physical location of these coils to each other, the high driving currents and the small order of feedback voltages, made this task very difficult. It is to be noted that the necessary amount of feedback lies somewhere between 40 and 50 db, and that consequently the inductive coupling must be smaller than that. A detailed description of the measures taken to ensure shielding between drive and feedback coils would be too extensive for this article, but the basic difficulty should be noted. Tremendous demands are also made on the heat tolerance of the driving coils and their necessarily tight attachment to the armature. Reason for this are the tremendous acceleration magnitudes (or braking magnitudes) and the driving currents associated with them, especially at high frequencies. Current flow of 200 to 300 amperes per mm^2 under transient conditions are not uncommon.

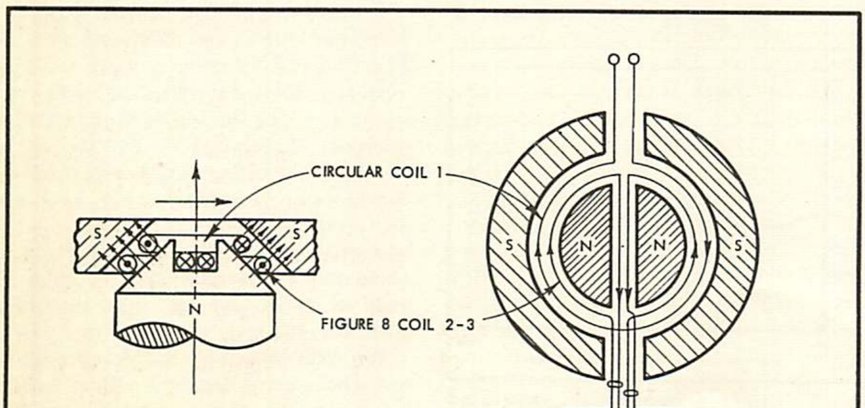

Fig. 5. Feedback coil winding arrangement.

The Armature and its Suspension

In order to permit the recording of vectoral signals in a single groove, the stylus point must be capable of circular motion. Motion in the direction of groove travel is, on the other hand, not tolerable. The armature therefore must be so suspended as to permit motion in only one plane. In the system developed by Teldec, the thimble-shaped armature is suspended using two parallel leaf springs. These two springs are shaped in such a manner as to place the point of rotation at the center of gravity. The design of these springs was further influenced by the consideration of the resonant frequencies of the springs and the desire that their resonances fall into a purposeful frequency range, as well as close to one another. As already described, the armature is so driven as to produce a vertical motion during which the two leaf springs execute a simple bending motion. When driven to a rotational motion, spring A produces a transverse deflection while spring B executes a like deflection in the opposite direction.

Aside from these two motions, an unwanted vibrating motion is also produced. In this third motion, the springs deflect also in the direction of their maximum stiffness. But even this motion has its resonance placed within the maximum feedback range where it is largely corrected. Decisive in the selection of the resonant frequency were two considerations. For reasons of output, the resonance should be placed at the point where the greatest velocities are to be expected. This point has been determined, on the basis of amplitude statistics, to lie near the center of the usable frequency band. This region is also most favorable to electromotional feedback, since in this way the frequency range to be recorded can most readily be stabilized. Feedback in this cutter is effective in a region from 4½ octaves below to 4½ octaves above the resonant point. Besides the two principal resonances which are caused by the elasticity and the mass of the armature, there are also some secondary resonances. It is at the point of these secondary resonances that the feedback coils are no longer in phase with the drive coils and therefore produce positive rather than negative feedback. To avoid this instability, the first secondary resonance must lie well outside the reproduced frequency range; as a matter of fact it should be removed by at least one octave from the highest reproduced frequency. The secondary resonances can be influenced by a choice of material and shape for the armature. We chose a material with a relatively large sound transmission coefficient (K = 33,000 ft/sec.). The use of this material placed the first secondary resonance well above 40 kc. For all practical purposes this produces an extremely stable feedback system, almost wholly independent of the stylus dimensions.

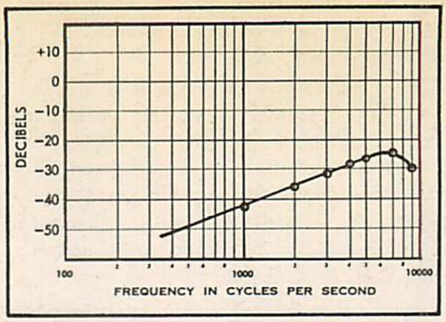

Fig. 7. Distortion in the vertical channel due to pinch effect. Recorded lateral velocity for 0-db reference is 8 cm/sec. Stylus-tip radius, 0.6 mil; high-frequency pre-emphasis, 50 u-sec. Disc speed, 45 rpm; groove diameter, 12 in.

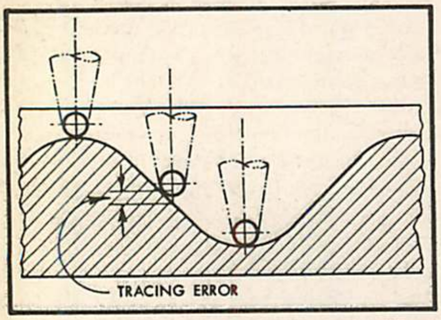

Fig. 6. Section of vertically modulated groove to show how tracing error is caused.

The Double-Component Cutting Method

The mechanical recording characteristic of a two-component system differentiates itself sharply from the normal lateral method, in that the ever-present vertical component produces an ever-changing cutting mode of the stylus. Distortion referred to the motion of the stylus itself nevertheless stays extremely low due to the large amount of motional feedback employed. Care must be taken, however, to ensure that no plastic changes (spring-back) occur in the groove. This requires great care in the grinding of the stylus itself and in the selection of lacquers for mastering. The stylus burnish must be selected as the optimum for the mechanical properties of the acetate material used, and the temperature of the heated sapphire becomes more critical.

If we now play this recording with a reproducing sapphire which has a ball-shaped tip, we meet up with further causes of distortion, some of which are not found in lateral recording. The main cause of this distortion is the pinch effect, which produces second harmonic distortion in the vertical channel caused by excursions in the lateral direction. A second distortion-producing problem results from the vertically recorded component. Since the reproducing stylus has a finite size, an exact tracing of the vertical groove component is impossible (*Fig.* 6). Here as well, the second harmonic is produced with effects in the same direction as the excursion, i.e. in the vertical direction.

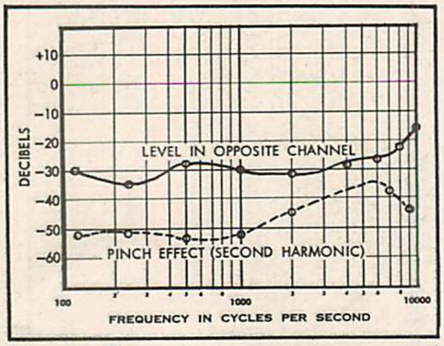

Fig. 8. Channel separation measured with a double-dynamic pickup, 0.6-mil tip radius. Recorded velocity, 2.5 cm/sec. for 0-db reference.

These distortion figures are symmetrical only if the modulation-cross is inclined at an angle of 45 deg. to the record surface. The amplitudes of the vertical component then assume a magnitude in each of the 45-deg. directions of only 0.7 or a reduction of 3 db. In a vertical-lateral system, on the other hand, only the vertical channel is adversely affected by this distortion although in the full measure. If a reasonable relationship is maintained in the dimensions of the groove, recorded level, groove velocity, and reproducing stylus, these interferences can be held to a minimum, and reproduction can attain the demands which are made in today's state of the electroacoustical art. *Figure* 7 shows a plot of the distortion imparted to the vertical component by the pinch effect as related to frequency. The curve reaches its maximum around 7.5 kc. The reason for this is the dropping playback equalization curve (RIAA) which tends to suppress this form of distortion at higher frequencies. Furthermore, the second harmonic of 7.5 kc lies already at 15 kc where reproduction falls off rapidly in most systems. These data were obtained using a Neumann "DST" double-dynamic reproducer. *Figure* 8 shows the channel separation. Here again we can see the typical interference of the second harmonic caused by the pinch effect.

These quality limitations, when examined in the light of the above factors, produce the limit of the innermost groove diameter.

Conclusion

The transducers described here were developed in the Laboratories of TELDEC (Telefunken-Decca) in Berlin, Germany. They have been in use for over a year now for the purpose of providing practical knowledge in the cutting of stereophonic disks. As a result of this considerable experience it has been proven that stereophonic recordings may be transferred to disc in such a manner as to make differentiation between the original tape and the disc impossible even for trained ears.

We wish especially to acknowledge the contributions of Georg Neuman Laboratories, Berlin, whose practical construction of the cutting head have made our developments possible. Æ