response was taken 20 db below the 1% third-harmonic distortion point.

As wavelength is equal to tape speed divided by frequency ($\lambda = ts/f$), in order to reproduce a 15-kc signal at 3¾ ips, the head must resolve a wavelength of 250 μin.

To resolve this wavelength, the effective gap length of the tape head must be 125 μin. or less. The capability of the RCA high resolution head to perform this task is shown in the over-all frequency response in Fig. 5.

CONCLUSIONS

Current production based on the above-mentioned design criteria has yielded a high-quality, uniform, low-cost tape head. Essentially flat response from 50 to 15,000 cps at a tape speed of 3¾ ips is achieved by this high resolution head when the proper record and playback equalization is employed.

THE AUTHOR

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JOURNAL OF THE AUDIO ENGINEERING SOCIETY OCTOBER 1960, VOLUME 8, NUMBER 4

The Multichannel Recording for Mastering Purposes

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In the past, all master recording was done monophonically on full-track, quarter-inch magnetic tape, but today most master recording is done stereophonically on three-channel half-inch tape. This four-part paper emphasizes the solutions to the problems which are peculiar to three-channel recording and multichannel magnetic recorders. First, the basic technical requirements and differences from single channel recorders are outlined; second, mechanical problems of securing ease of operation and flutter and wow are discussed; third, the signal-to-noise considerations of track width and spacing, and equalization are discussed; and fourth, practical operation of multichannel recorders in a recording studio is described.

Contents

1. INTRODUCTION TO MAGNETIC RECORDING FOR MASTERING SYSTEMS

AS THE beginning of a new decade, the year 1960 seems a good point to take stock of our master recording techniques and prepare for the future. During the next ten years we will undoubtedly see stereophonic recordings come of age, both on disks and on magnetic tape. But the initial sensationalism of stereo will be dissipated and the demand will be for stereophonic recordings of genuine worth, those that make a real contribution to listening pleasure.

In this respect, it must be recognized that the quality of the finished product derives from the original master recording, which in turn depends on the equipment and on the methods of operation. This section of the paper and those succeeding are aimed at pointing out the basic characteristics necessary in magnetic recorders for mastering purposes, with the final section showing how the equipment may be efficiently utilized.

Why Magnetic Tape?

With the introduction of magnetic tape equipment, in late 1947, came a drastic change in the phonograph recording industry. Not only was the quality of both master and disk improved but also a hitherto unknown degree of flexibility was presented to the recording industry. No longer was the physical making of a recording strictly a mechanical cutting operation. While the mechanical aspects (of transporting the recording medium past the magnetic heads) remain to this day, the sound storage itself was transformed into a magnetic process—with virtually unlimited technical advantages. The recorded magnetic tape could be edited, pulling together segments of different performances to achieve one near-perfect master recording—and this without an intolerable waste of musicians' time. Selections could be combined in any desired sequence on one disk. And, very importantly, disks of varying sizes and speeds could be made from one master tape.

Since the advent of stereophonic recording, additional flexibility has been provided in that the master tapes of one performance may be released in either the stereo or monophonic versions. In fact, today the recording of one performance may result in release of 33⅓ rpm disks either stereo or monophonic, 45 rpm disks, two- and four-track stereo tapes.

Basic Requirements

The actual basic requirement is that the end result, the disk or tape offered for sale, must satisfy a rather demanding public. This axiom is complicated by the fact that the production master is normally at least one, and perhaps two, generations removed from the original recording. With each generation, of course, there is a slight degradation in quality—and we must still have an acceptable commercial product. The original recording must therefore be as perfect as possible.

What, then, should the magnetic tape equipment offer? What are the primary specifications? Probably you are already answering—high signal to noise, broad frequency response, and low flutter and wow. For stereophonic operation it is necessary to add precise phasing between channels and adequate crosstalk rejection. Each of these primary specifications will now be discussed to arrive at some specific values.

Signal-to-Noise Ratio

At the present state of the art, the signal-to-noise ratio is determined by the magnetic tape, with the actual values determined by tape speed, track width, and the equalization used.

The signal-to-noise ratio will improve with higher tape speeds and wider tracks, but there are practical limitations which must also be considered. For example, as tracks are made wider the alignment problems become much more difficult. Also inherent in wider tracks is the necessity of wider tape, and this entails more expensive transports and an increased cost of magnetic tape.

For each successive re-recording of an original tape the signal-to-noise ratio will deteriorate, with noise rising cumulatively in each generation. At the present state of the art, a three-channel recorder, using ½-in. tape, appears a good compromise between practical engineering and economic considerations on the one hand and adequate signal-to-noise ratio on the other. Such equipment, operating at 15 ips, gives a minimum wide band signal-to-noise ratio of 55 db referred to the 3% distortion level.

Frequency Response

The flattest frequency response possible is required, again because the production master may be generations removed from the original recording. In re-recording, frequency response deviations will probably be multiplied, although it is remotely possible that opposing characteristics in two machines could result in canceling the deviations. An increase of frequency response deviation cannot be accepted, and certainly there can be no dependence on cancellation.

A conservative specification would be ± 2 db from 30 to 15,000 cps because of variation in tapes, but this is unacceptable for mastering purposes where re-recording is involved. The three-channel recorder with ½-in. tape is capable of flatter response when it is aligned very carefully for use with a particular reel of tape, and such a procedure is required for multiple re-recordings. It is possible to achieve a response of $\pm \frac{1}{2}$ db from 50 to 15,000 cps, and ± 1 db from 30 to 18,000 cps.

Flutter and Wow

Flutter or wow is the amount of deviation from a mean frequency, caused by anything in the system that will affect tape motion. The rate of deviation determines whether it is wow or flutter. For equipment with only one flutter component the resultant component in the re-recording could be expected to vary between zero and twice the original value. In practice, however, there is more than a single component, and flutter becomes more or less like a random signal—similar to noise—which adds in an rms fashion during re-recording. This being the case, the minimum acceptable flutter specification at the 15-ips tape speed must be less than 0.1% rms, including all components between 0 and 300 cps. Our mastering recorders typically have flutter of less than 0.05% peak.

Phasing between Channels

The directional quality of stereophonic sound, or of any sound we hear, is dependent on the ability of the brain to distinguish subtle differences in phase and intensity as sound waves arrive first at one ear and then the other. If, in storing and reproducing stereo sound, the normal phasing between channels is not properly maintained, the result is a confusing end product.

When the recording consists of largely independent sources on separate tracks of the tape, phasing is not too much of a problem. When those sources are not isolated —for example, when recording an instrument on two channels simultaneously to achieve a center effect—it becomes more important. And when there are mixing and recombining operations to produce two-channel tapes from a three-channel master, phasing becomes quite critical.

Phasing between channels is a function of the alignment of head gaps and the wavelength involved. Tolerances are more critical at slower tape speeds, where the recorded wavelength is shorter for a given frequency.

At the present state of the art, our multichannel heads are manufactured so that all record or reproduct head gaps would fall within two parallel lines spaced 0.2 mil apart. With the correct azimuth alignment, phase error from channel to channel should be within 30 deg at 15,000 cps when operating at a tape speed of 15 ips.

Crosstalk Rejection

Crosstalk rejection acts the opposite of phasing, in that it becomes more critical as the sound sources on separate channels become more independent. When adjacent tracks are completely independent, crosstalk rejection on the order of 60 db in the midrange is desired. For normal stereophonic mastering, 50-db separation appears more than adequate, primarily because studio acoustics seldom allow greater than 30-db separation from mike to mike.

This discussion will disregard the acoustical properties of the recording studio (which cause crosstalk) and concentrate on the design of the recorder. Here adequate shielding between heads, and maximum track spacing in conjunction with the practical compromises that have already been covered, are the major means of combatting crosstalk.

Number of Channels

One way of visualising a multichannel recorder is to think of it as three or more separate recorders. Each channel is a separate entity, with its own electronic assemblies and heads. The major advantage in recording several tracks on one tape, instead of each on a separate tape, is in the almost perfect time synchronization that be can achieved.

Serious production difficulties might be encountered in trying to record on too many channels. For example, the mixing procedure could become as complex as the original recording session.

The popular three-channel recorder has been accepted as the standard of the recording industry. It offers the flexibility and balance required and is especially useful when making monophonic and stereo releases from the same master.

Tape Width

The minimum track width, in conjunction with the number of channels desired, is again controlled by both practical economic considerations and requirements for extreme quality. Signal-to-noise ratio and crosstalk rejection will both deteriorate as track width is decreased and the tracks are brought closer together.

Again, the three-track ½-in. tape recorder seems a good compromise. Track width on this equipment is 100 mils with adjacent tracks spaced 85 mils apart. This same configuration could be achieved by six tracks on 1-in. tape.

If four tracks are placed on ½-in. tape, or eight on 1-in., approximately 1½-db reduction in signal to noise could be expected.

Head Assemblies

The precise tolerance that must be achieved in aligning the different heads in a stack has already been mentioned. The same careful precision must be taken to insure the straightness of the individual gaps and their perpendicularity to achieve interchangeability of tapes.

In older, sandwich-type heads it was practically impossible to achieve the required tolerances, with the result that master tapes could consistently be reproduced only on the equipment that recorded them—and then not too successfully because of differences in the record and reproduce head stacks. Quoted specifications were thus not achieved in some cases when tapes from one equipment were played back on another.

The introduction of cast-type heads, with tolerances held by mechanical considerations, has alleviated this problem. Today it should be possible to play back a tape from any recorder on any other comparable equipment, and do it within quoted specifications.

The sandwich-type heads were constructed by completely assembling each individual head intended for multichannel use, stacking those heads one on top of the other, then bolting them together. It was impossible to produce heads with consistent characteristics; it can be seen that even a slight difference in tightening the bolts that held the head together could cause gaps to be misplaced with respect to each other or the azimuth of each head to be misaligned.

Cast heads are constructed by assembling, potting, and lapping the two halves separately. The two halves are then placed in a rigid fixture and potted together. Using this technique, all gaps can be aligned within 0.2 mil with a maximum tilt of less than two minutes from the perpendicular.

2. MECHANICAL REQUIREMENTS FOR A MASTERING SYSTEM

General

In analyzing the mechanical requirements of a magnetic recorder, it is not proposed to transform everyone into an expert designer of tape transports. This discussion is intended only as a guide, to point out certain concepts that can be used in determining what constitutes well-designed equipment. The discussion will be divided into nine categories, in each of which the items of importance in mastering equipment will be covered.

Before entering that phase, let us understand that the main difficulties encountered by any designer of magnetic tape transports concern flutter and wow. Differentiating between those two problem children has historically been difficult, but speaking generally we can consider that flutter consists of components above 6 or 7 cps, with wow components falling below that figure. (Normal flutter will extend to approximately 300 cps, but tape scrape flutter is usually above 3500 cps.) Flutter and wow can result from anything that affects tape motion; although the drive system of a transport is most commonly blamed, it is not always the culprit.

Remember that tape transport design is governed mainly by considerations of what is good or bad in relation to flutter and wow.

Drive Requirements

Designing a drive system usually entails a compromise between low flutter requirements and the amount of money we can expect in return. There are ways and means of producing transports that exhibit extremely low flutter; the accomplishment, however, is accompanied by a high price. These ultra-precision drives are usually employed only in instrumentation and data-type recorders, with the cost precluding their use in the audio field.

Capstan Assembly

First, the capstan shaft. A small, round shaft seems quite simple and harmless, but it can be a real troublemaker. It must be rounded within 2/10 of one mil and mounted in its bearing it cannot exceed 2/10 of a mil runout at the tape contact point. The grind pattern, caused in the finishing process, must not be more than 1/100 of one mil. The shaft must be corrosion resistant, and sufficiently hard to withstand wearing (a hardness of 55 Rockwell c is considered minimum).

The diameter of the capstan should be large enough to hold tape slippage and creep to a minimum, with a compromise normally necessary between the diameter and the speed of the shaft. For a given tape speed an increase in diameter demands a decrease in rotational speed, which in turn requires more flywheel.

We generally will use as much flywheel as the drive motor can handle while maintaining sync; this is simply a matter of damping out cogging of the drive motor and ironing out any other irregularities.

Capstan bearings require careful attention. A combination of a sleeve bearing at the top near the tape and a ball bearing at the bottom to provide thrust has proved very satisfactory. A longer distance between the bearings decreases the runout of the shaft, which might be caused by runout of the lower bearing. Long life, low friction, low torque, and uniformity of rotation are the primary requisites for these bearings.

Drive Motor

The drive motor must be of the synchronous type in order to maintain the necessary speed accuracy of $\pm 0.15\%$. Hysteresis synchronous motors are usually employed rather than salient pole (reluctance) types, although the latter is less expensive and provides equivalency insofar as flutter is concerned. The reason for this preference is that the hysteresis motor will sync a greater mass and thus can handle a larger flywheel.

When we refer to direct drive we mean that the capstan is coupled directly to the motor shaft. There are two prevalent types of indirect drive—one using a rim drive and the other a belt drive—in both of which the motor drives the capstan through an intermediate means. In rim drive the capstan flywheel has a rubber rim around the periphery, which couples to a pulley on the motor. The motor itself usually is moved to make and break the coupling between the pulley and the rubber rim. The belt drive is self-explanatory. For this application we must lean toward the indirect-type drive.

There are several reasons for this preference. We can select the diameter for our capstan which will provide optimum operation, with no regard for the speed of the motor; we then design our reduction ratio to provide the desired tape speed. Better mechanical filtering is provided by the intermediate coupling between the motor and capstan, thus decreasing flutter caused by disturbances exterior to the drive system. The unlimited number of reduction ratios we can provide give us much greater flexibility in choosing drive motors to meet varying speed requirements.

The speed accuracy of a direct drive is a function of line frequency and the tolerances maintained in capstan diameter. We must recognize that an indirect drive has an additional possibility of error in that we must take into account the coupling between the motor and the capstan flywheel. But if we use a rim drive we have another advantage, in that we can compensate for small discrepancies in speed by changing the amount of pressure the motor pulley exerts on the rim of the flywheel tire. (The rubber tire on the flywheel also provides some good damping for the drive system.)

Supply and Take-up Assemblies

The motors used in the supply and take-up assembly are usually of the induction type, with high resistance rotors. They produce an inverse torque curve; that is, a straighter line curve (see Fig. 1).

If the reel motors are used to supply hold-back or take-up tension, they must be as free as possible from cogging. While absolute cog-free operation is unobtainable, it can be approached. Cogging in the hold-back system has been responsible for many flutter problems that have been blamed on the drive system. It would be nice if we could discover a reel motor whose torque would change with the tape diameter on the reel, thus providing a constant tape tension throughout the reel of tape. (Many constant tension de-

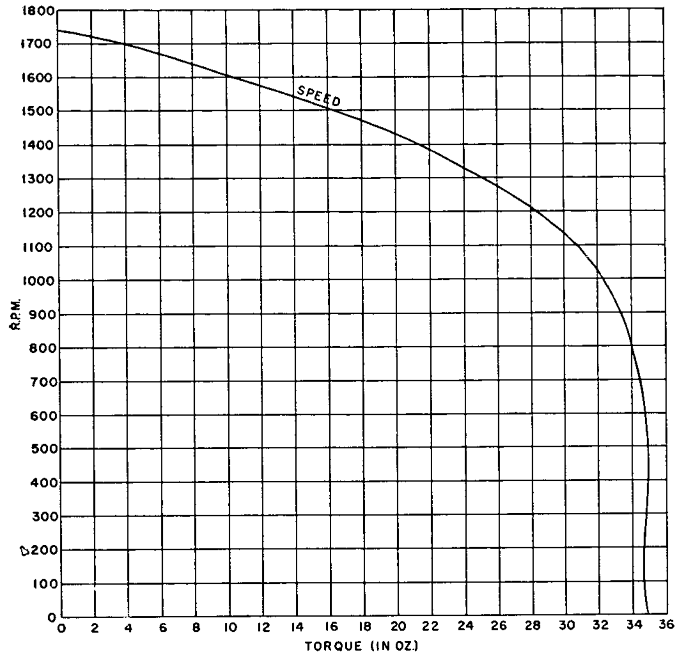

FIG. 1. Typical torque curve for turntable motors.

vices have been used in the past, but those designed for audio equipment have not been too successful.)

The brakes, generally associated with the turntable assemblies, can be either of the mechanical or dynamic type. Our feeling has always been that the mechanical brakes are superior. With mechanical brakes, a self-limiting, or at least a nonenergizing, configuration should be used. Energizing-type brakes that are not limiting will give quite different braking forces as the coefficient of friction changes with variations in temperature and humidity.

Another consideration in designing the brake system is the differential. This differential as applied to magnetic tape recorders means the difference in braking force that exists between the two directions of turntable rotation, with the greater force always acting on the trailing turntable (see Fig. 2). The differential is expressed as a ratio, with a ratio of 3:1 or greater normally used. Such a ratio gives good results in that little tape slack is thrown in the stopping process even from the fast-winding modes of tape motion.

Reel Idlers

The main purpose of the reel idler is to isolate the heads from disturbances originating in the supply motor by tape scraping against the reel flanges or by tape pullers slipping as the reel unwinds. While the reel idler minimizes such disturbances, we must use care or we will create more flutter than we eliminate. Reel idlers should have less than ½-mil runout (total indicator reading), bearings must be selected for low noise and smoothness of operation and low torque and flywheels must be dynamically balanced to close limits. The diameter of the idler and the tape wrap around it must insure positive coupling between the tape and the idler.

Mounting Plate

Mounting plates should be sufficiently rigid to maintain a natural resonance above 300 cps—or notably higher than the 60- and 120-cps exciting frequencies which emit from torque motors and drive motors. This rigidity is most important in the area surrounding the reel idler, heads and capstan; any flexure in this area will cause flutter (Fig. 3).

Of course, another reason for a rigid mounting plate is to hold alignment between the various components that control the tracking of the tape. This is more important on ½-in. tape or 1-in. tape than it is with ¼-in.

Tape Guiding

Next to flutter, our most difficult problem of tape transport design is the tape guiding. All components in the tape threading path must be kept in accurate alignment—this means maintaining exacting tolerance on the perpendicularity and flatness of all such components (turntables, reel, idlers, heads, capstan, etc.).

The capstan idler must hit the capstan squarely, or the tape will be diverted up or down. Tape guides, either rotary or fixed, should not be too small in diameter, and guide widths must be held to close tolerances—normally not more than 2 mils over tape width and preferably less. Tape itself is slit to a tolerance of 0 to 4 mils under the nominal dimension.

Tape guiding problems are multiplied when we use thin base tapes. This is caused by the loss of stiffness at the edge and because we cannot use as high tensions with this type of tape.

All components in the tape path must be kept clean, using a solvent recommended by the manufacturer of the equipment, or all our design work is useless. This means that we must make these components accessible so that the user can easily perform the cleaning chore.

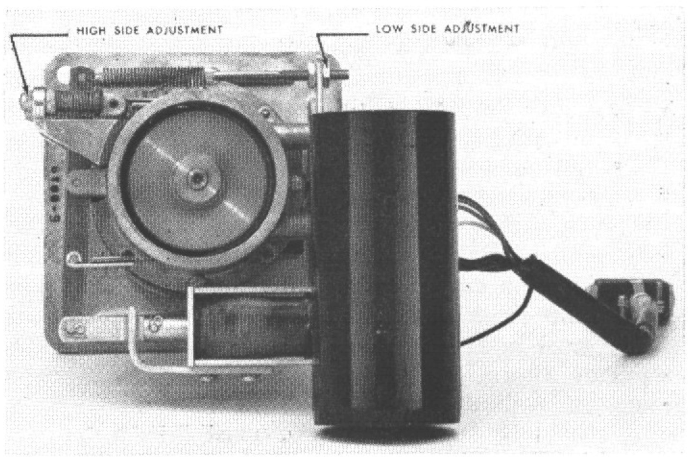

FIG. 2. Typical self-limiting brake assembly.

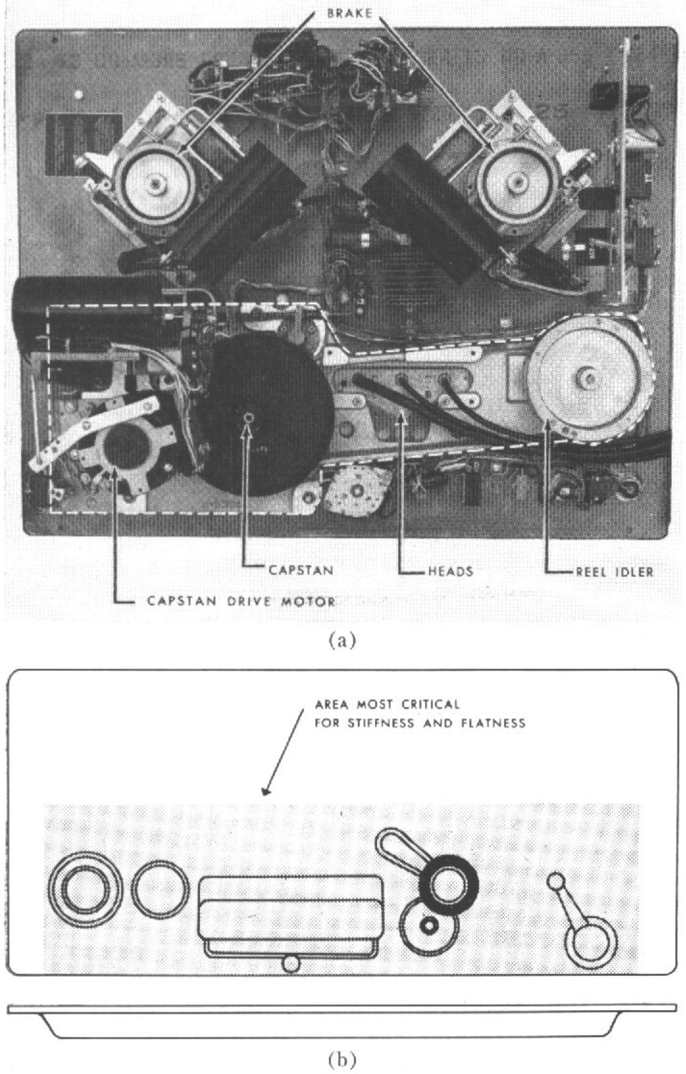

FIG. 3. (a) Area of required rigidity. (b) Bottom view of typical tape transport with dotted lines outlining rigid mounting plate.

Operational Requirements

We must provide adequate torque for the fast forward and rewind modes, with the actual torque requirements varying with the tape width. But we must bear in mind that excessive torque might result in our exceeding the elastic limits of the magnetic tape, and hence result in breaking or deforming the tape.

The tape must be stopped without damage. The elastic limit of the tape again determines our maximum braking force. Since a minimum brake differential must be maintained, this factor also determines our lower braking limit.

We must have reasonable start and stop times. One-tenth of a second is usually satisfactory, with of course more time required for high tape speeds, say, 60 or 120 ips.

It should be apparent that we must provide optimum torque and braking force, adequate for fast winding and acceptable start and stop times but which will not exceed the elastic strength of our medium. Typical values for ½-in. tape equipment would be 35-40 oz-in. of torque, with a maximum braking force of approximately 30 oz.

Geometry of Layout

Tape Threading

From the human engineering standpoint, tape threading paths using the wrap-around principle are superior to those utilizing a drop-through-the-slot type. The utmost efficiency in threading tape would be provided by a transport that had a simple wrap-around path from supply reel to take-up reel, with no necessity for threading behind idlers, guides, etc. (see Fig. 4). Unfortunately this perfection is impossible of achievement—although it can be approached—because of the necessity for threading the tape between the capstan and the capstan idler.

Tape Wrap

The amount of wrap around the heads should be held to a minimum because the buildup of tape tension will increase with the degree of head wrap. A wrap of 4 to 6 deg on each side of the head gap has proved quite satisfactory.

Large tape wraps (in degrees) around small diameters should be avoided. This is not only a case of holding tension buildup to a minimum. While there are no qualitative data available *it has been proved that sharp bends around small diameters result in measurable losses of recorded high frequencies during the first three or four playbacks.*

Tape wrap around the reel idler must be sufficient to insure a good, solid coupling between the tape and the idler.

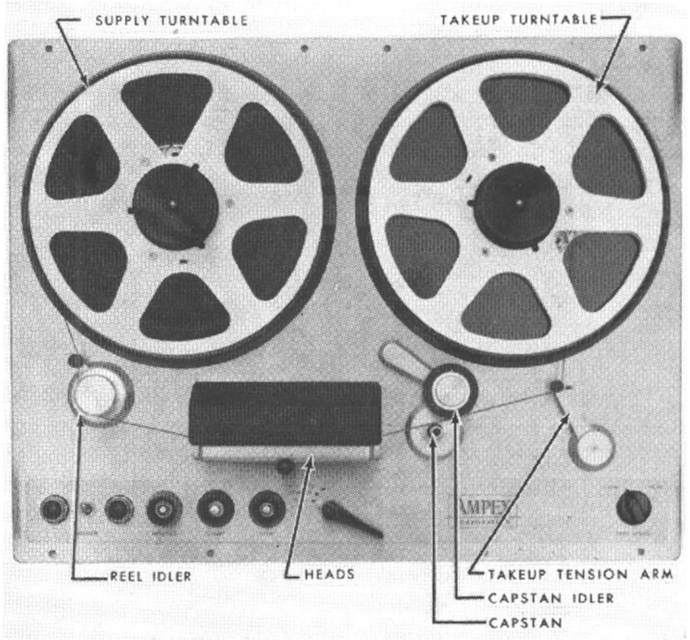

FIG. 4. Over-all view of typical tape transport.

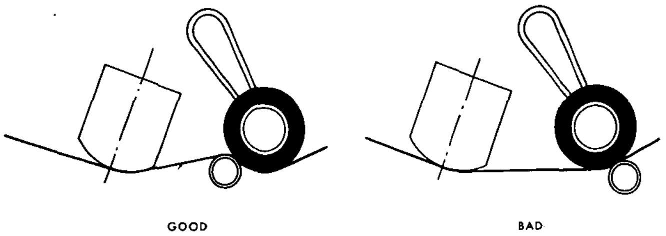

FIG. 5. Relation of capstan, idler, and heads.

On our machines operating at 60 and 120 ips, it has been necessary to groove the tape contacting area of the idler pulley so that the air film is dispelled and good coupling is assured.

Drive Layout

The heads, capstan, and capstan idler should be arranged so that the tape from the heads first contacts the capstan, not the idler (Fig. 5). In those layouts where the tape from the playback head contacts the idler before reaching the capstan, there will be flutter caused by idler runout, by variations in the hardness of the rubber around the periphery, and by bumps or voids in the tire.

Minimizing Tape Scrape Flutter

Tape scrape flutter is defined as the longitudinal oscillation of the tape excited by tape passage over heads and fixed guides. Tape scrape flutter frequency is a function of the unsupported length of tape between the capstan and the reel idler, in conjunction with the modulus of elasticity of the tape. The amplitude of the frequency is a function of the surface condition of the tape and surface roughness of fixed tape guides and heads. Tape scrape flutter manifests itself as modulation noise. It can be seen that we can control tape scrape flutter frequency by the placement of the reel idler with respect to the capstan, but we do not exercise full control over the exciting force. We hope that some day infinitely smooth and well-lubricated tape will be available, thus reducing this problem.*

Number of Components

The number of tape contacting components should be held to a minimum, because every additional part means more buildup in tape tension. Given a certain tension at the supply turntable we will find that we have a considerably higher tension at the capstan; this buildup is a function of the number of tape contacting components, the degree of tape wrap around each, and their surface roughness. The geometry of the layout must eliminate unnecessary guide posts, idlers, etc. Tension buildup can also be reduced by mounting the necessary components on ball bearings or on other types of low torque bearings.

*Further information may be found by referring to articles by Phillip Smaller [J. Audio Eng. Soc. 7, 196 (1959)] and Von E. Belger and G. Heidorn [RTM 3 (1959)].

Conclusion

Careful consideration of every point discussed is necessary in the production of a tape transport for mastering purposes in the recording industry. Sometimes, of course, compromises must be made, necessitated by both engineering factors and by practical economic considerations. The tape transport is the heart of any magnetic tape recorder. The utmost care in engineering, in designing, in manufacturing, and in maintaining the equipment is necessary to achieve desirable results.

3. SIGNAL-TO-NOISE CONSIDERATIONS IN MASTER RECORDING SYSTEMS

This part of the paper will discuss two factors which affect the signal-to-noise (s/n) ratio in a magnetic recorder: track width and spacing as well as equalization, with particular reference to some questions which have been raised concerning the Ampex mastering equalization (AME).

The Effect of Track Width

For mastering purposes, where maximum signal-to-noise ratio is necessary, wide tracks are desirable. But there are limitations to this: economically, the amount of tape used and therefore the cost increases roughly in proportion to the track width. Technically, beyond a certain track width it becomes difficult to maintain accurate azimuth alignment. Minimum track-to-track spacing is desirable for greatest utilization of the tape width, but excessive crosstalk will result if too little spacing is used.

If the signal-to-noise ratio is determined by the medium itself, i.e., the medium (tape) noise is at least 8 to 10 db above the equipment (reproduce amplifier) noise, then the s/n of the system is proportional to the square root of the track width.†

Is the tape noise greater than the amplifier noise? Figure 6 shows the spectral-noise density for system (biased tape plus amplifiers) and equipment (amplifiers, with tape stopped) for a full track Model 351 recorder. This shows

† Let w equal track width, and assume the number of turns on the reproduce head to remain constant. Then the signal output is directly proportional to w; but the noise output, being a random signal, is proportional to the square root of the signal, which is therefore proportional to $\sqrt{w}$. Therefore: signal/noise $\propto w/\sqrt{w} \propto \sqrt{w}$.

It is interesting to note that, in practice, reproduce head signal output may also be made proportional to the *square root* of the track width. In this case, noise is again proportional to the square root of the signal output, or $\sqrt[4]{w}$. Then signal/noise $\propto \sqrt{w}/\sqrt[4]{w} \propto \sqrt{w}$.

Let L = head inductance, w = track width, e = head output voltage, and n = number of turns on the head. Since e is proportional to n, we would desire the maximum number of turns. But L resonates with the self-capacity of the head winding, and the cable and input stage capacity (assumed constant). It is undesirable for this resonance to fall into the audio band, as response falls 12 db/octave above resonance; and also since it is difficult to control accurately the amplitude and frequency of the resonance. Therefore, it is desirable to keep the resonance just above the upper end of the audio band. We will therefore assume that all heads would be made to resonate at the same frequency. Therefore, the inductances must be constant. Since $e \propto n$ and $L \propto n^2$, $e^2 \propto L$; since $L \propto w$, therefore $e^2 \propto w$, or $e \propto \sqrt{w}$.

TABLE I. Ampex standard audio head configurations dimensions and relative signal-to-noise ratios.

Tape width, in.	System	Track width, mils	Relative track width	Relative signal to noise, db
½	3-track master[a]	100	1.00	0
½	4-track master or duplicator master[b]	70	0.70	−1.5
¼	Full track	234	2.34	+3.7
¼	Half-track	82	0.82	−0.9
¼	2-track stereo	75	0.75	−1.2
¼	3-track stereo	43	0.43	−3.6
¼	4-track "double stereo"	43	0.43	−3.6

[a] Dimensions of tracks of the 6-track 1-in. system are approximately the same as those of the 3-track ½-in. system.
[b] Dimensions of the tracks of the 8-track 1-in. system are the same as those of the 4-track ½-in. system, except that the space at the edge is 10 mils.

that the system noise is about 15 db greater than the equipment noise in the region of maximum ear sensitivity. (Weighted noise figures reflect this as system noise of −60 db and equipment noise of −75 db relative to "operating level," the nominal 1% distortion level.) Therefore for tracks at least 40 mils wide (output 7 db below full track) the medium noise will be 8 db or more above the equipment noise, and signal to noise will be determined by the medium itself.

Figure 7 is a scale drawing of the standard audio head configurations used by Ampex, and Table I gives the absolute and relative track widths, and the relative signal-to-noise ratios, compared to a 100-mil-wide track.

There is one limit to the practical track width. As track width increases, closer mechanical tolerances must be held to maintain the same azimuth alignment, which affects the amplitude and the stability of the high-frequency response. Azimuth misalignment loss is a function of $w \tan \alpha/\lambda$, where w is the track width, α is the azimuth misalignment angle,

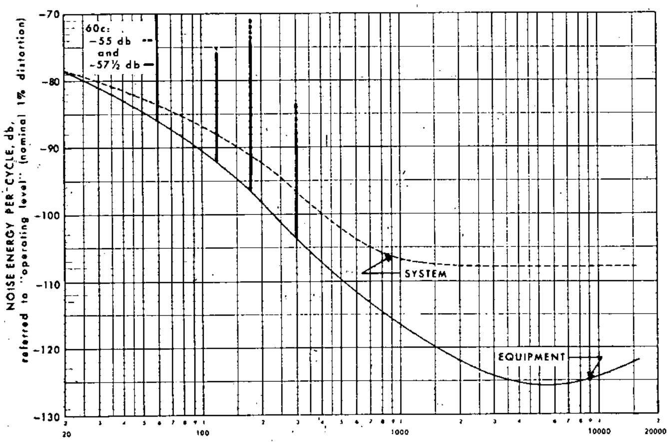

FIG. 6. Spectral-noise density. Full track ¼-in. magnetic tape recorder, Ampex model 351, 15 ips, NAB equalization, Irish 211 biased to maximum sensitivity at 1000 cps.

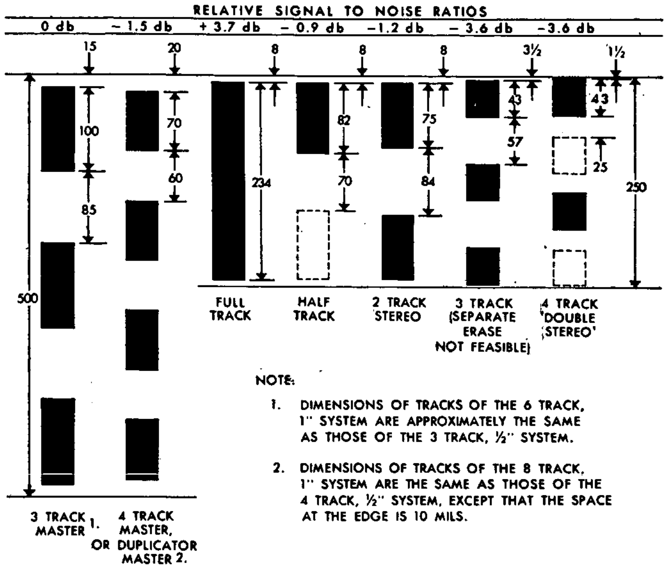

FIG. 7. Ampex standard audio record and reproduce head configurations, and the signal-to-noise ratios relative to a 100-mil-wide track. Dimensions in mils. (Erase heads are slightly wider.)

and λ is the recorded wavelength. For a given loss at some wavelength, the misalignment angle α must *decrease* directly as the width w increases ($\tan \alpha$ is proportional to α for small angles). Experience has shown that for 15-ips recording speed it is practical to maintain azimuth alignment for track widths up to 250 mils. (For lower speeds, say, at 7½ ips, it is difficult to maintain azimuth alignment for tracks appreciably greater than 100 mils.)

So, just how wide should the track be? If tape cost were no object, a one-inch tape with three 250-mil tracks would be the optimum compromise of azimuth alignment stability and signal-to-noise ratio for 15-ips mastering use. Such a three-track recorder, with each track 250 mils (for four-track, approximately 200 mils each track), is to be made available as a stock item by Ampex Professional Audio Department for those users who are willing to double their tape cost for approximately 4 db greater signal-to-noise ratio. A 35-mm sprocket-type film would give the same signal-to-noise ratio at a tape cost of 3½ to 6 times that of the one-inch tape.‡

In most cases cost *is* an object, and a more practical compromise between performance and economy is the one-half-inch tape with three 100-mil tracks.

Crosstalk

The problems of crosstalk have been discussed in a previous paper.[1] Two effects are shown to occur: At long

‡ Based on three tracks: 200 mils each on film, 250 mils each on tape; 18-ips film speed, 15-ips tape speed. Film cost is approximately $42 (net each, one to six rolls) for 11 min (1000 ft); tape cost is approximately $21 to $37 (net each, one to six rolls) for 30 min (2400 ft), the price depending on the particular base material and oxide used.

[1] R. Sinott and M. Sprinkle, J. Audio Eng. Soc. 5, 86-89 (1957).

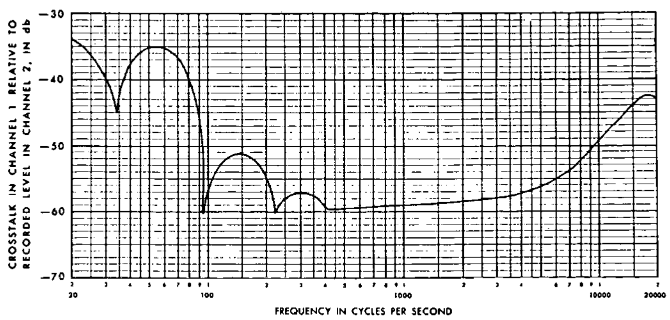

FIG. 8. Crosstalk in channel 1 relative to recorded level in channel 2 vs frequency. Ampex 300-3 (3 channel, ½-in. tape); NAB equalization. Channel 2 recording at operating level (nominal 1% distortion). Channel 1 record head connected and biased normally.

wavelengths (low frequencies) magnetic coupling occurs (in reproduce) between the signal recorded on one track and the reproduce head of the other track. At higher frequencies, the mutual inductance and capacitance between the two record heads cause a small amount of the signal from one record head to be present in the other record head, and therefore to be recorded on that other track. Therefore spacing and shielding between cores is important in both the record and the reproduce heads. Obviously, the closer together the tracks, the more coupling exists (assuming the same shielding). Figure 8 shows the crosstalk for a 3-track ½-in. recorder/reproducer, Ampex Model 300-3. This shows crosstalk for a sine-wave signal recorded at operating level (nominal 1% distortion). In the midrange (400 to 4000 cps) the "transformer" crosstalk is –58 to –60 db; above 4000 cps the coupling increases to –50 db at 10 kc and –43 db at 18 kc. The "long wavelength" crosstalk increases below 400 cps to a maximum of about –51 db at 150 cps, then increasing to –35 db at 45 to 70 cps, and again at 20 to 25 cps. (These data were taken with a 7-cps bandwidth wave analyzer—Hewlett-Packard Model 302A—to eliminate noise; the crosstalk above 100 cps is less than the wide-band noise.) This shows that with the present shielding, the 85-mil track-to-track spacing used for ½-in. three-track recorders is a good compromise—more spacing to reduce crosstalk is unnecessary and wastes space, but any greater crosstalk would be audible above the noise.

Equalization

Two papers[2,3] by one of the authors have discussed subjects related to equalization in magnetic recorders. Several questions which have been received since the publication of these papers will be discussed here, since they may be of interest to other readers and users of AME.

Considerable confusion seems to have resulted from linking together these two papers which were written as two *entirely independent* studies, *neither depending on the other.*

Design for Minimum Noise (AME)

"There are two limiting criteria for designing equalization in a recording system. One criterion is that of making a post-emphasis which will minimize the audible noise from the system." This was the approach discussed in the first (January) paper.[2] The basic data from which this type of equalization is designed is the frequency sensitivity characteristic of the ear; the post-emphasis is designed to minimize audible noise, and the pre-emphasis to make the over-all system flat. The data in that paper show that the new equalization will be quieter. (Energy distribution is not involved in this approach—it is entirely irrelevant.)

Does AME result in increased audible distortion? This is a moot point. The purpose of AME is to trade overload margin for lower noise level. The first paper[2] proposes this equalization on the basis that one really should use a meter which indicates actual tape overload. The vu meter makes no pretense of this; we have hypothesized that an equalized peak-reading volume indicator would do the job, but we have not yet proved it. Since the NAB equalization has a great deal of usually unused overload capability at the vu "zero" level, many operators have got into the bad practice of operating at "pinned" levels. The AME will put the maximum level on the tape with the meter operated as the ASA Standard proves—*"needle pinners" will very likely get distortion with AME.*

Since the second (April) study[3] was done using recorded samples, a question has been raised as to whether the AME tests were done with live or recorded material. Live program sources were used for all tests, with a variety of types of music and studio setups. The listening tests were performed using an Ampex Model 350-2 (two-channel) recorder, so modified that one microphone input fed a preamplifier and recording gain control. The signal was then split into the two recording channels, which were essentially identical except for the record/reproduce equalizations used. One channel was NAB, the other the test (AME); in each case the over-all response of each channel was flat plus or minus ½ db from 60 to 15,000 cps. Then a switch would select one channel or the other to feed the power amplifier and speaker. In this way, we were able to make *A/B* comparisons of noise and distortion, for a standard NAB equalized channel, and for the test (AME) equalized channel. (This equipment was demonstrated at the convention, but its description was inadvertently omitted from the Journal paper.) We felt that the listening tests made rather severe demands on the new equalization, and that it performed very satisfactorily, as none of the listening jury was able to determine which equalization he was listening to, even though he was allowed to operate the *A/B* switch himself.

Was the loudspeaker used of high quality, and the listening jury representative? The loudspeaker was an Ampex theater-type system, which we equalized to 12 kc. One could not defend this as being *the* ultimate loudspeaker, but it seemed to produce a satisfactory sound quality. The

[2] J. G. McKnight, J. Audio Eng. Soc. 7, 5-12 (Jan. 1959).
[3] J. G. McKnight, J. Audio Eng. Soc. 7, 65-71, 80 (Apr. 1959).

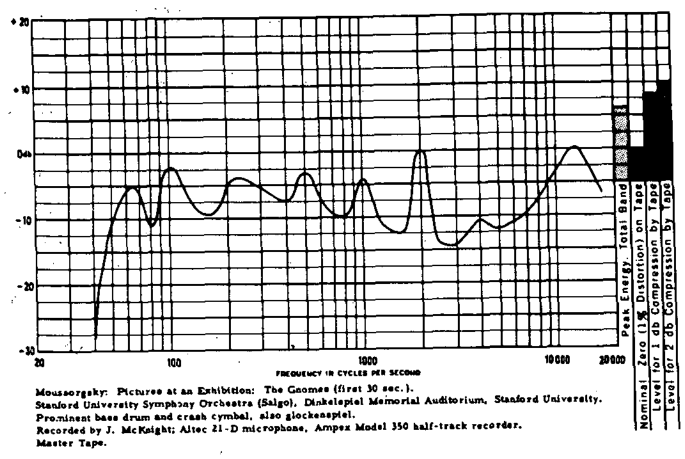

FIG. 9. Spectrum analysis of recorded music. Ratio of peak energy in one-third octave bands to vu meter reading.

listening jury was representative of *critical* listeners; it included design and research engineers, musicians, and recording engineers.

The Ampex master equalization, then, was designed specifically to minimize audible noise—we have purposely traded overload margin for lower noise level. There is no doubt that AME lowers the noise level; and if levels are held to zero level on a vu meter, overload distortion should not be audible.

Design for Equal Probability of Overload at All Frequencies

The second criterion is that of designing the pre-emphasis so that the system will have equal probability of overload at all frequencies; then the volume indicator may be designed primarily for *balancing* levels. For *this* purpose, we are primarily interested in the distribution of peak energy.

In the energy distribution study,[3] was the reference vu meter against which peak levels are determined a *standard* vu meter? A Weston Model 862 meter was used, connected with the specified building-out resistor, across a terminated 600-ohm source; while we did not ourselves test this meter, these Weston meters are usually accepted as meeting the ASA Standard, C16.5-1954, for volume indicators.

Is it valid to assume that the energy distribution in recordings is representative of that in live programs? We are concerned with two possible distortions that may occur in the record/reproduce process: amplitude distortion and phase distortion. The first paper[2] shows that, for a 15-ips recorder, a signal whose amplitude is 9 db above the zero (nominal 1% distortion) level will be compressed 1 db, and be reproduced as +8 db; likewise, +12 db will be compressed 2 db, and reproduce as +10 db. Therefore, if we know that the reproduced total peak energy did not exceed +8 (or +10) the original signal did not exceed +9 (or +12), and the compression was no greater than 1 (or 2) db. (This only applies for the "master tapes"; in the case of the "copies," we do not know what compression might have occurred in the "master.")

This information on tape compression was shown in each of the energy distribution graphs.[3] Figure 9 reproduces one of the "spectrum analysis of recorded music" graphs to show the peak energy in the total band (+6 db, in this case) and the level required for 1 and 2 db of tape compression (+8 and +10 db, in this case). In only one of the eight master tapes used was the total level great enough to cause 1 db of compression by the tape. None of the six copies of master tapes reached the 1-db compression level. This is typical of all of the 76 recordings used—the recorded levels were low enough so that no appreciable amplitude distortion occurred.

The question of phase distortion was not studied. We are aware that phase distortion does occur in our recorders. Therefore, it is quite possible that the peak energy, total band data[3] may be in error due to the phase distortion. However, the distribution should not be affected as this is measured in small bands, which would not be affected by phase shift.

Therefore, we believe that the distribution of peak energy, as determined from these recordings, is also representative of live music.

The second paper[3] shows that if we are to design a pre-emphasis strictly in accordance with maximum energy distribution, *we are not justified in using any pre-emphasis at all.* The present NAB curve[4] essentially fulfills this requirement.

Conclusions

We have shown that the one-half-inch three-track tape recorder provides a good compromise between signal-to-noise ratio and tape cost. If tape cost were no object, a one-inch tape would give 4 db additional signal-to-noise ratio. The Ampex master equalization gives approximately 7 db lower noise level at the expense of overload capability; if the level is not allowed to rise above the nominal zero level, with peaks to +2 or 3 db, the distortion should not be increased noticeably.

4. APPLICATION OF MULTICHANNEL EQUIPMENT IN THE RECORDING INDUSTRY

In the operation of the recording studio, the techniques of multichannel recording offer many advantages: in flexibility, in insuring quality at minimum cost, and in providing masters which can be used again and again as our requirements change with the demands of the industry.

Let us first consider the need for flexibility of operation (see Fig. 10). This need is apparent at the start of any recording session when the engineer must set up the orchestra. Using the multitrack recording technique the precise placement of the different musical instruments is unneces-

[4] J. G. McKnight, J. Audio Eng. Soc. 8, 146 (July 1960).

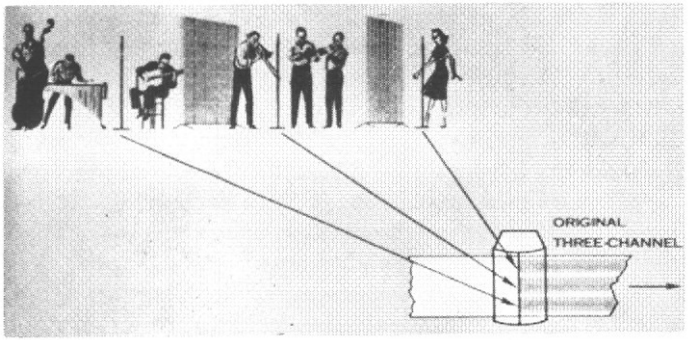

FIG. 10. Recording session.

sary. The engineer can arrange the various sections in any configuration he desires, with his only consideration that of achieving adequate isolation for proper separation, while maintaining audible contact between the musicians.

He then proceeds to record each section on a separate track of the magnetic tape. Using professional quality equipment, he does not have to worry too much about phasing problems in the final mix. He may also check the stereophonic and monophonic balance during actual recording by combining the monitor circuits. During the subsequent re-recording procedure he can rebalance, equalize, and add reverberation as necessary. The re-recording procedure actually affords him a second opportunity to achieve nearly perfect results.

The multichannel recorder also allows the engineer to add a soloist or vocalist to an original recording. Perfection by the orchestra is probably the most time-consuming (and expensive) part of any recording session, while the solo artist is usually very sensitive to interruptions and multiple retakes. If we remove the mistakes and rehearsals of one from those of the other, we will thus most efficiently utilize time and money while producing an over-all better product.

In multitrack recording it is necessary to record only one master. This master can then be mixed and balanced to produce both stereophonic and monophonic ¼-in. master tapes. This flexibility eliminates the need for duplicate equipment and personnel to operate and maintain it.

Now let us take a look at how multichannel recording can insure quality at minimum cost. This characteristic is best emphasized in the re-recording process, where the engineer rebalances, re-equalizes, and adds reverberation. Many a session which would normally have resulted in a poor record has been saved by the judicious use of these three tools during re-recording. It is interesting to note here that the engineer in multichannel recording is no longer simply the man we look to for technical achievements, he is fast approaching the importance of the orchestra director in attaining artistic results.

The flexibility we have already discussed also is an aid in securing quality at less cost. Surely, as we decrease the pressure inherent in any recording session we can expect better results, and this is exactly what our flexible approach allows. Certainly, the pressure on the orchestra is less if a slight unbalance between sections can be corrected; if technical perfection and artistic perfection do not have to be achieved simultaneously. A solo artist is much more apt to be relaxed and thus give a better performance if he knows he can take as much time as he desires without adding excessively to the orchestral expenses.

With the ever-changing demands of the record industry we must have some way of insuring that any future requirement can be met. This is best done by editing the original multitrack masters. These edited masters may be re-recorded (with appropriate equalization) for use as ¼-in. monaural masters, and ¼-in. stereophonic masters for use in lacquer channels or for high-speed duplication. We can thereby maintain our original recording on file.

Such a file is a near priceless possession. It can be used again and again to produce working masters for any type of recording at any speed. Imagine their value if we had the best of Caruso, John McCormack, or Galli-Curci available on master tapes today.

If Mylar-base tapes are used for these studio masters, the durability and storage life will be further improved.

With this general picture in mind, we can now proceed to a more specific plane.

As previously mentioned, the first thought of the engineer in multichannel recording is the proper separation of the sound sources to be recorded on the different tracks. This starts with the studio itself. For popular-type repertoire, probably the best results are achieved in a dead studio, where unwanted reverberation and acoustic coupling between microphones are eliminated. This is achieved by physical properties—acoustic tile, perforated transite, polycylindrical panels, etc. Flats, or separators, with acoustic tile on one side for absorption and a hard material on the other side for reflection, can be inserted between groups. Isolation booths are also frequently used, especially when vocalist or soloists are to be recorded with a full orchestra.

One way to achieve instrumental separation is to use unidirectional microphones with back-side cancellation in the order of 25 to 35 db. It is also possible to use acoustic devices such as a bass separator. Drums and traps are sometimes isolated by putting a rug or heavy blanket over them to prevent the sound from spreading through the studio.

As shown in Fig. 11, proper separation depends on the physical placement of properties.

During re-recording sessions, special types of equalization are used to accentuate or attenuate certain frequencies. This is done under controlled conditions, in contrast to the regular recording sessions where one is usually limited to the conventional boost or dip-type equalizer. The judicious use of equalization can change the characteristics of a voice or an instrument quite drastically, depending upon the particular need of the moment. The re-equalization process is thus a means of achieving the desired frequency response under

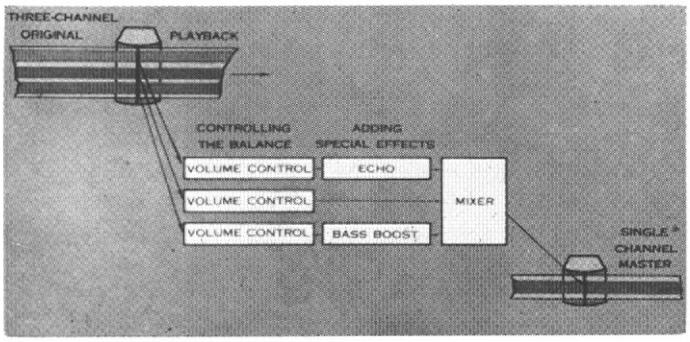

FIG. 11. Transferring session.

highly controlled conditions. It is much easier to obtain in the re-recording process than in the original session.

It can prove advantageous in other ways. For instance, it is very helpful when a certain instrument or voice has been lost during an original recording. The application of special equalization on a separate channel sometimes will make it possible to pull out this certain instrument from a group—thus saving, or at least improving, the recording.

There are three types of *reverberation* commonly used in the recording industry today: room, electronic, or tape. Rooms may be designed with polycylindrical columns, nonparallel walls, and ceilings, etc. They are made of concrete, tile, plaster, etc. The reverberation times will vary from 1½ to 5½ sec.

Reverberation may be included in the original recording; however, certain companies prefer to add this effect during the re-recording process. At that time, the signal is reproduced from the original tape and fed to the mixer. If room-type reverberation is used, part of the signal is routed through amplifying circuits to a reverberation chamber, where it is fed into a loudspeaker. The signal is then picked up by a microphone. The mike circuit is fed back to the mixer and recombined with the original signal.

A few years ago a company in Germany introduced an electronic reverberation unit, consisting of a pair of transducers mounted on a large steel plate. The signal is fed from the mixer to an amplifier which is used to excite the steel plate through one transducer, when the plate vibrates the other transducer picks up the signal and returns it to the mixer. Reverberation time can be varied from ½ to 5½ sec; damping is used to change the reverberation time.

Probably everyone is well aware of tape reverberation, or at least the sounds that are obtained by tape reverberation. We have all heard commercials where there actually seem to be two voices—one on top of the other. These are produced by taking the signal off the tape and feeding it back into the recorder. An example of equipment for this application is a tape reverberation unit which utilizes a loop of tape about three feet long. The loop runs continuously over a series of playback heads. The signal is fed from the mixer to the single record head on the unit. The operator can select the proper playback head to give him the desired time delay.

In adding a vocalist or soloist to a previously recorded tape, the engineer has a choice of two procedures. He can use either selective synchronization or use two machines to dub voice and music to another tape.

Selective synchronization (sel-sync, for short) is simply a switching arrangement which allows selected record heads to act as playback devices during a voice-over session. This allows reproduction from other tracks, from heads in the same stack and thus in precise alignment, to be recorded in synchronism with previously recorded music. Inherent in this procedure is the necessity of having one track for the exclusive use of the soloist, so that he can record, erase, and record again until he is satisfied with the performance. Its great advantage lies in the fact that only one recorder is necessary.

When the two-recorder method is used, the master is played back using headphones or loudspeakers, and a new tape is recorded. An additional generation is involved, with a subsequent increase in tape hiss. However rebalancing, re-equalizing, and adding reverberation can be accomplished during the over-dubbing process. If equipment is available, both a two-track stereophonic and a monophonic master can be produced during this voice over session. This eliminates another re-recording process and still gives a multichannel protection.

There are always questions with respect to the deterioration of signal to noise when multichannel tapes are rerecorded to produce two-track stereophonic or monophonic masters. If the equipment is maintained to professional standards, the slight increase in noise will not affect the end product to an appreciable degree. In fact, most companies re-record and change the balance on their ¼-in. single- or two-track tapes. Bearing this in mind, any change in signal to noise which occurs when we re-record three-track tapes will not be appreciably different from the change in a rebalanced ¼-in. tape.

Most multichannel master recorders use ½-in. tape or wider. To obtain the best high-frequency response, 1-mil base magnetic tape is used. This is due to the better head wrap (i.e., contact) obtained with the thinner, more flexible base. Most professional recorders will hold reels containing 3750 ft of 1-mil base tape, cutting reloading time to a minimum and allowing the artists to perform a complete work without interruption. One-mil tapes ½-in. wide are also less likely to be damaged by tearing or stretching, thus minimizing one of the constant problems when using original masters in production channels.

THE AUTHORS

John G. McKnight, who was born in Seattle in 1931, studied at Stanford University, and received his B.S. in electrical engineering there in 1952.

In 1953, he worked for the Ampex Corporation on the development of cinemascope-stereophonic sound equipment. He spent the years 1953-1956 in the U. S. Army, assigned to the engineering staff of the Armed Forces Radio Service in New York. During this time, he also worked as development engineer for the Gotham and the Narma Audio Development Companies. He returned to Ampex in 1956, where he was a senior engineer in the research division; in 1959, he became manager of the Advanced Audio Section of the Professional Audio Division. He has always been interested in the problems of magnetic recording, specifically as they concern music, and has published several papers on this subject.

Mr. McKnight is a member of the Audio Engineering Society, and an affiliate member of the Institute of Radio Engineers.

W. M. Fujii

W. M. Fujii received his B.S.S.E. in 1952 from the Illinois Institute of Technology. He joined Ampex in 1955. He has worked on high-speed duplicating equipment, high-fidelity audio systems, custom design, and modification of standard equipment. Mr. Fujii was in complete charge of design and development of a portable recorder/reproducer for government use where tape speed was held constant despite wide variations in power line voltage and frequency. He is presently in charge of the design and development of a miniature recording and reproducing equipment, also under government contract. Prior to joining Ampex he was employed by RCA in the broadcast equipment section. There he worked with transcription turntables, magnetic tape recorders, studio consoles, magnetic strips, and military TV equipment.

Mr. Fujii is a member of the IRE and AES.

George Rehklau attended the Air Mechanics School, Aeronautical University, Chicago, and Aircraft Electrical and Propeller Specialist courses at Chanute Field, Illinois. He served in New Guinea during the war years.

From 1945 to 1949 he worked for United Air Lines as a design draftsman. During this period he was a night student at the Institute of Design, Chicago.

George Rehklau

He has been with Ampex Corporation since February, 1949. He did mechanical design work on the Ampex Models 300, 400, 400A, 500, and 600, with the industrial design of the last-named model also his responsibility. He was project engineer, and did all the mechanical design for the Ampex Model 350 tape transport. He was in charge of mechanical design on the Navy's UNQ-7 shipboard recorder and the AR-102 airborne unit, and received a patent for the capstan assembly on these machines. He was project engineer for Ampex precision reels, containers, and hold-down knobs used on the instrumentation equipment, and patents are now pending as a result of this work.

He is now engaged as a project engineer working with the Ampex line of professional audio recorders.

W. H. Miltenburg

William H. Miltenburg was born in Los Angeles in 1918, and attended the California Institute of Technology. He worked as a sound engineer for several major motion picture studios, i.e., Warner Bros., Columbia, Universal International, and several major independent studios. In 1947, he joined RCA in Hollywood as a recording engineer for RCA's film studios, and later transferred to the RCA record division. In 1954, he was transferred to New York and promoted to chief engineer and manager of recording for the RCA Victor record division. In 1960 he joined the Ampex Corporation as operations manager of the newly formed United Stereo Tape Division of Ampex Audio Company.

Mr. Miltenburg is a Fellow of the Audio Engineering Society, a member of the SMPTE, and National Academy of Recording Arts and Sciences.