Lateral Feedback Disc Recorder

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How proper use of feedback improves lateral-type recorders.

THE VERTICAL-TYPE FEEDBACK RECORDER introduced in the electrical transcription field about 1938[1] made possible vertical recordings of wider frequency range with reduced distortion and provided a higher degree of uniformity among recorders. This paper describes the W.E. 2A Lateral Recorder, developed around the same general feedback principles as the corresponding vertical feedback cutter.

Although the principles involved are the same for both types, the lateral development presented an entirely new set of problems. For example, in the vertical unit the generated forces are chiefly compressive and tensional and are transmitted from the driving coil to the stylus by means of a thin cone, while in the lateral recorder the member which connects the drive coil to the stylus is subject to forces in shear, and as a result it was found necessary to increase its thickness thirty-fold in order to eliminate spurious vibrations. As will be seen later, it is imperative that the vibrations which are produced by the generated forces be constrained to the mode for which they are intended.

The requirements for an ideal recorder include not only uniform response and low distortion through the audible frequency range, but also the ability to maintain its performance for long periods of time despite temperature and humidity variations and regardless of whether the recording medium is the softest wax or the most resistant lacquer. It can be demonstrated that proper application of the feedback principle to a recorder element will achieve these objectives.

Theory

Assume the recorder element to consist of a vertical member attached to a fixed support by a reed hinge and carrying a recording stylus at its free end (*Figure* 1). The element can be vibrated by means of an attached driving coil as in the dynamic-type loudspeaker. Motion of the element induces a voltage in a second (feedback) coil which is proportional to the velocity of the motion, as in a moving-coil reproducer. The recorder is connected to an amplifier system as shown, the object being to move the cutting stylus with a vibrational velocity V whose wave shape is an exact replica of the wave shape of a signal voltage E.

A general expression for the relation between stylus velocity and signal voltage in an electromechanical feedback recorder system has been previously developed.[1] It is desirable to repeat its derivation here, with the terminology applied specifically to the lateral unit. Let

E = signal voltage
E_2 = output voltage of A-circuit amplifier
V = stylus velocity (inches per second)
E_3 = voltage generated by the feedback coil
E_4 = voltage output of the B-circuit amplifier
$E_1 = E + E_4$ = voltage input to A circuit amplifier (1)

All of the above are complex quantities. Let

$$A = \frac{E_2}{E_1} \times \frac{V}{E_2} = \frac{V}{E_1} \qquad (2)$$

and

$$B = \frac{E_3}{V} \times \frac{E_4}{E_3} = \frac{E_4}{V} \qquad (3)$$

where E_2/E_1 and E_4/E_3 are the voltage gains of the A-circuit amplifier and the B-circuit amplifier, respectively, and V/E_2 and E_3/V are respectively the electromechanical transducer conversion factors of the drive coil and the feedback coil. Therefore,

$$AB = \frac{E_4}{E_1} \qquad (4)$$

The product AB thus defines the transmission around the loop formed by the A-circuit amplifier, recorder, and B-circuit amplifier. Substituting the value of E_4 from this equation in (1), we find

$$E_1 = E\frac{1}{1-AB} \qquad (5)$$

which, with equation (2), gives

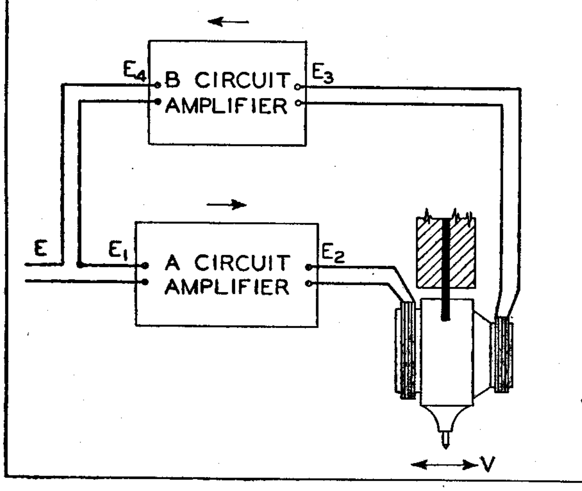
$$V = E_1 A = E\frac{A}{1-AB} \qquad (6)$$

Equation (6) thus determines the behavior of the system (stylus velocity vs. frequency and phase shift vs. frequency) when A and B are known. In particular, when AB is large compared to unity, the condition usually present in the recorder, equation (6) becomes

$$V = \frac{1}{-B}E \quad (AB \gg 1) \qquad (7)$$

which indicates that under this condition the velocity depends only on the signal input E and the factor $1/B$ which can be made very nearly constant.

[Equation (3) shows B to consist of two factors E_3/V and E_4/E_3. For the former to remain constant and independent of the amplitude and frequency of signal voltage E, the feedback coil must meet three conditions: It must be rigidly coupled to the stylus; it must vibrate in a uniform magnetic field; and it must be unaffected by the magnetic field set up by currents in the drive coil. The other factor to be maintained constant, E_4/E_3, represents the



$$E_1 = E + E_4 \qquad (1)$$

$$A = \frac{E_2}{E_1} \times \frac{V}{E_2} = \frac{V}{E_1} \qquad (2)$$

$$B = \frac{E_3}{V} \times \frac{E_4}{E_3} = \frac{E_4}{V} \qquad (3)$$

$$AB = \frac{E_4}{E_1} \qquad (4)$$

$$E_1 = E\frac{1}{1-AB} \qquad (5)$$

$$V = E_1 A = E\frac{A}{1-AB} \qquad (6)$$

$$V = \frac{1}{-B}E \quad (AB \gg 1) \qquad (7)$$

$$V = E\frac{A}{1-AB} + \frac{n}{1-AB} + \frac{d}{1-AB} \qquad (8)$$

Fig. 1. Electromechanical feedback system.

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*Bell Telephone Laboratories, Inc., Murray Hill, N. J.

[1] Recent Developments in Hill and Dale Recorders, by C. F. Wiebusch and L. Vieth. *SMPE Journal*, Jan., 1938.

voltage gain of an amplifier working at low level and presents no problem. It should be noted that these factors, which are responsible for the benefits accruing to the use of feedback, when once embodied in a physical recorder are inherently stable, and consequently the performance of the system should remain fixed over long periods of time.]

If equation (6) is rewritten to include noise and distortion products as well as signal, it becomes

$$V = E\frac{A}{1-AB} + \frac{n}{1-AB} + \frac{d}{1-AB} \quad (8)$$

where *n* and *d* are the noise and distortion, respectively, introduced in the amplifier and recorder without feedback. Hence, when *AB* is large compared to unity, a considerable reduction in noise and distortion is effected. Other forces acting upon the stylus during recording (such as those produced by the turbulent air of suction and blowing equipment and reaction forces due to the mass, stiffness and resistance of the recording medium) may be considered as noise or distortion, and their effect is reduced in like manner when *AB* is large.

Unfortunately, these benefits are obtained only with precision in design and manufacture. Examination of equation (6) reveals that if at any frequency the quantity *AB* becomes equal to $1 + j0$, the denominator becomes zero and the system will sing or oscillate. Nyquist[2] shows that for stability a polar plot of $|AB| \angle \theta$ and its conjugate from zero to infinite frequency must not enclose the point $1 \angle 0$. Bode[3] estimates that for each 10 db of feedback in the useful range one octave must be added to the actual range which must be explored and controlled to insure stability. He aptly describes the limitation as tantalizing—"In typical designs the *AB* characteristic is always satisfactory except for one little point. When the engineer changes the circuit to correct that point, however, difficulties appear somewhere else, and so on *ad infinitum.* The solution is always just around the corner." This frustration is magnified when a mechanical element possessing both mass and stiffness is added to Bode's circuit. A moment's reflection will prove that this is true, for only at the frequency for which the mass reactance is equal to the stiffness reactance will the driving force be in phase with the stylus velocity. As the frequency is reduced, the stiffness reactance increases and the phase between driving force and velocity approaches -90°

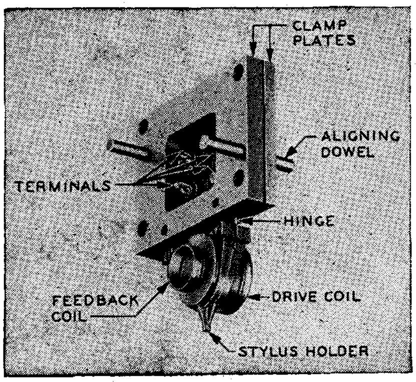


Fig. 2. View of vibrating member.

Similarly, as the frequency is increased above resonance the mass reactance predominates and the phase between driving force and velocity approaches +90°. Introduction of the mechanical element has therefore augmented the original phase shift by 180°.

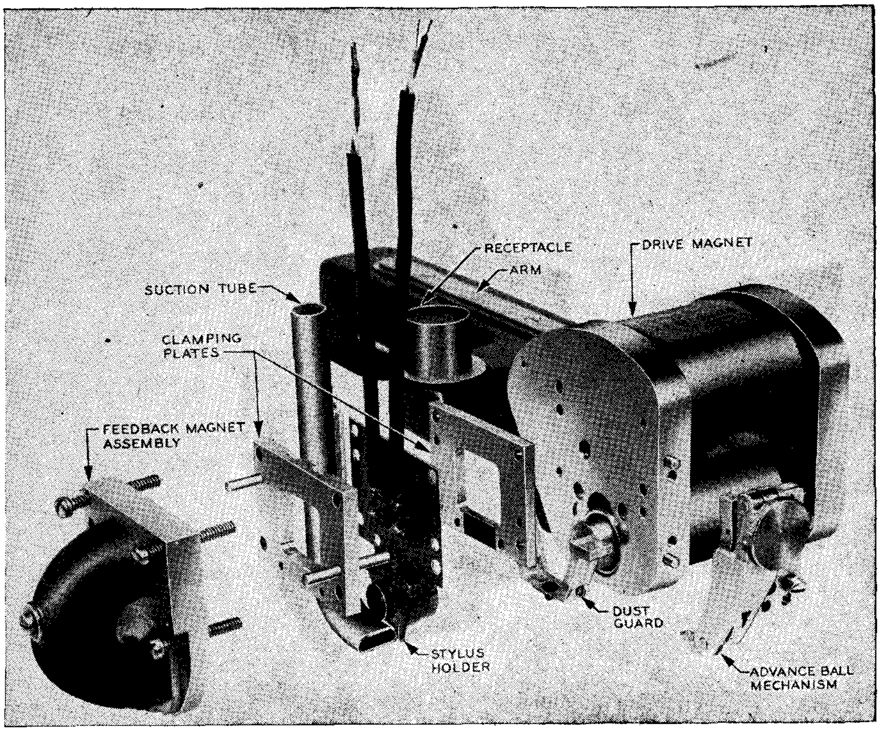
Actually, this simple recorder element, which for convenience has been assumed to be rotating about its hinge in the plane of the paper (*Fig.* 1), will undoubtedly change its mode of vibration as the frequency is increased, and this change will further modify the phase shift. Additional trouble is likely, therefore, when all parts of the element no longer vibrate in unison or when at "one little point" in the frequency spectrum the element vibrates in either or both of the planes perpendicular to the plane of the paper, to say nothing of rotating about each of the mutually perpendicular axes. Vibrations in six distinct modes (some of which may be intercoupled) are possible. several are probable, and all affect $AB \angle \theta$.

Description

The vibrating member as finally evolved is shown in *Figure* 2. It consists of a precision casting of magnesium to which the drive coil and the feedback coil are permanently attached. At the bottom is a cylindrical cavity into which the stylus shank can be cemented and at the top is a flat spring or hinge of beryllium copper. This spring is tightly clamped between carefully lapped plates of nonmagnetic stainless steel which in addition to their clamping function provide facilities for terminating the coil leads. Breakage of leads is no longer a problem since they are supported throughout their entire length on a compliant plastic apron securely cemented to the moving element. When the vibrating member is attached to the magnetic assemblies, the voice currents resulting from a voltage impressed on the drive coil produce forces which swing the member about its hinge. Due to this motion a voltage proportional to the stylus velocity is generated in the feedback coil.

Figure 3 is an exploded view of the recorder showing the assembly in greater detail. Both magnets are covered by plastic jackets to prevent accidental contact with magnetic objects which would otherwise cause the formation of secondary poles with resultant loss in flux. Precisely located dowels automatically align the gaps

Fig. 3. Exploded view of the recorder showing the assembly in detail.



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[2] H. Nyquist, Regeneration Theory. *Bell Syst. Tech. J.*, Jan., 1932.

[3] H. W. Bode, Relations between Attenuation and Phase in Feedback Amplifier Design. *Bell Syst. Tech. J.*, July, 1940.

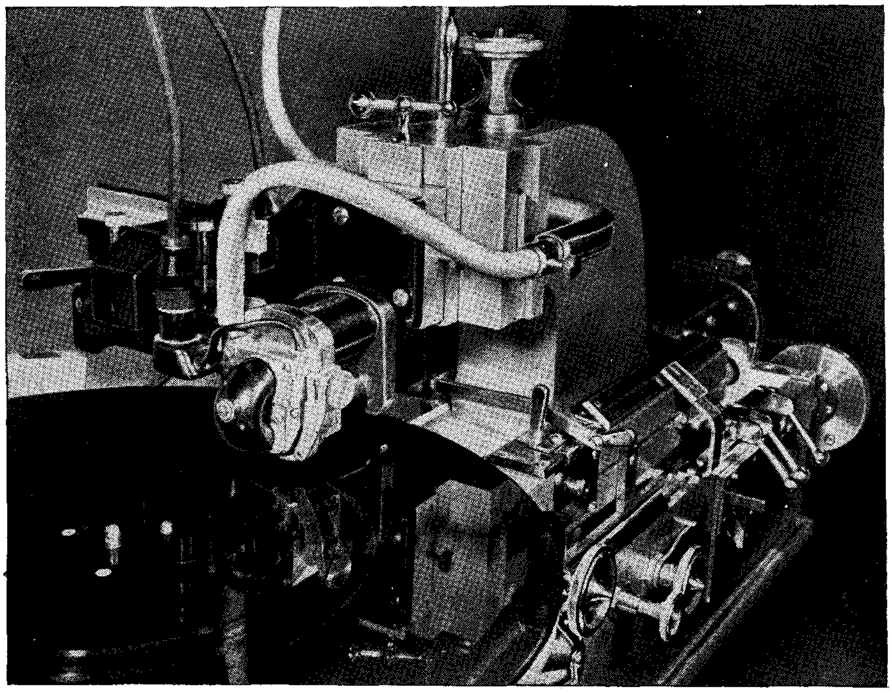

Fig. 4. Western Electric 2A recorder attached to a Scully recording lathe.

of the two magnetic assemblies with the coils of the moving element, insuring adequate and permanent clearance for the vibrating parts. Precision manufacture allows complete interchangeability of components with elimination of trouble generally associated with centering moving parts in a restricted space. After these parts have been assembled, the vibrating element is further protected against dust and magnetic particles by a transparent plastic closure assembly at the base of which is attached a flexible neoprene insert and through which the stylus holder protrudes.

The advance-ball mechanism (*Fig. 3*) is composed of two accurately machined precision castings. The assembly can be quickly positioned for either increasing or decreasing spiral. Adjustment of the depth of cut can be exactly controlled by means of a smoothly running thumb screw which can be locked in position if desired. Either a sapphire ball or a felt pad can be accommodated.

The suction tube extends above the head to allow attachment of a suction hose. It is generously proportioned and so located that it will remove wax or lacquer shavings without danger of fouling.

Figure 4 shows the recorder in operating position. Although the recorder weighs 4-3/4 pounds, the weight on the lathe is no greater than for the feedback vertical recorder, since in the new unit the usual balancing weight is replaced by an adjustable counterspring. The mass and spring values have been carefully chosen to avoid mechanical resonances when recording at either 33-1/3 or 78 rpm.

The recorder is connected to its associated amplifier by means of a cord, nominally 8 feet long, composed of two twisted pairs each individually shielded and with a different lay of the pairs to reduce electrical coupling between them to a minimum. Experimentally, substitution of a 20 foot length of cord showed no detectable deterioration in performance. Conductors, shielding, twist, fillers and braid covering have been chosen to produce a cable as flexible as is consistent with the requirements. The cord terminates in a plug in which the contacts have been sized and gauged to provide adequate contact pressure without requiring excessive pull-out force.

The amplifier with which the cutter must be used is a W. E. 115 type having a two-stage, push-pull, 15-watt, internal-feedback amplifier in the A circuit and a single push-pull stage of adjustable gain in the B circuit of *Figure* 1.

Measured Results

Frequency Distortion. Stylus velocity can be determined in several ways. Methods whereby it is calculated from observed values of amplitude and frequency are satisfactory only at low frequencies where the amplitudes are relatively large and can be measured by means of a microscope with calibrated eye-piece. Another method, that of measuring a recorded signal by means of a calibrated reproducer, is satisfactory provided care is taken to correct for all effects introduced by the reproducer itself. The optical method of Buchman-Meyer (the so-called Christmas-tree pattern) is quite popular and the results are dependable for most purposes. However, unless rather exacting precautions are taken, the pattern appears fuzzy and striated as the frequency is increased beyond 10,000 cps and therefore becomes difficult to interpret. Another method for determining stylus velocity is applicable only to the feedback cutter. The voltage E_3 generated in the feedback coil is proportional to the velocity of the coil. If the parts joining the stylus holder to the feedback coil are sufficiently rigid to prevent any relative motion, and no electrical coupling exists between the drive coil and feedback coil, voltage E_3 is also a true indication of the stylus velocity, V.

In *Fig. 5*, curves A and B, the stylus velocity was measured by the feedback coil voltage method, and in curve C the stylus velocity was determined by the Buchman-Meyer optical method.

For the feedback condition a signal voltage E of 0.5 volts applied to the input terminals produces a stylus velocity V of approximately 1" per second maximum velocity and the feedback coil voltage E_3 measures approximately 0.018 volts. The difference between curve B and curve C, starting at 7,000 cps and increasing with frequency, is the result of relative motion between stylus point and feedback coil in this frequency range caused by multiple bending of the hinge, and is responsible for the sharp dip and recovery in response in the neighborhood of 11,000 cps. One remedy has been found to be the addition of mass so distributed that the new percussive center causes no reaction at the hinge. On the other hand, to drive this increased mass would require more current and so reduce the margin against burnout and amplifier overload. The dip and recovery in response in the neighborhood of 11,000 cps has been completely eliminated in experimental models by a generous application of damping material, but the use of sizable damping pads is undesirable for several reasons: necessity for rigid shop control to insure uniformity in results, effect of temperature change, aging over long periods of time, etc. It was decided to forego the use of such "swamping" resistance and, as a result, all mechanical damping is omitted for the useful frequency band. A non-critical damping member reduces a peak in the response at approximately 40,000 cycles. This reduction decreases the phase shift by an amount which is small in itself but which provides added phase margin stability to permit recorders and amplifiers to be interchanged at will. The response at frequencies between 16,000 cps and 20,000 cps is not under the direct control of feedback action but remains fairly smooth; several sharp dips of the order of 10-15 db occur for frequencies between 20,000 cps and 40,000 cps, and definite cutoff occurs in the neighborhood of 50,000 cps, beyond which the response is more than 25 db down.

Physical Limitations

As the recording art is practiced today, the recorded level of the low frequencies will be limited by the *amplitude* of stylus motion in order to prevent cutting into adjacent grooves, the level of medium frequencies will be limited by the *velocity* of the stylus so as to prevent the heel of the recording stylus from touching the groove wall, and the level of the high frequencies will be limited by the *acceleration* of the stylus to prevent the radius of curvature of the groove from becoming less than that of the reproducing stylus. The amplitude limitation depends upon the unmodulated groove width and the groove pitch, while the velocity and acceleration limitations are functions of the linear groove speed. *Figure* 6 shows the maximum level that can be recorded within these limitations for a pitch of 88 grooves per inch with the width of cut equal to the land between grooves, a linear groove speed of 25 inches per second (approximately 6-inch diameter at 78 rpm), and a minimum radius of curvature of .002 inch in the recorded groove. The power required of the 115 type amplifier in order to produce this maximum level recording is also shown in *Figure* 6. As a matter of fact, in actual recording the maximum level is usually made considerably lower than that shown because of tracing distortion of the reproducer.

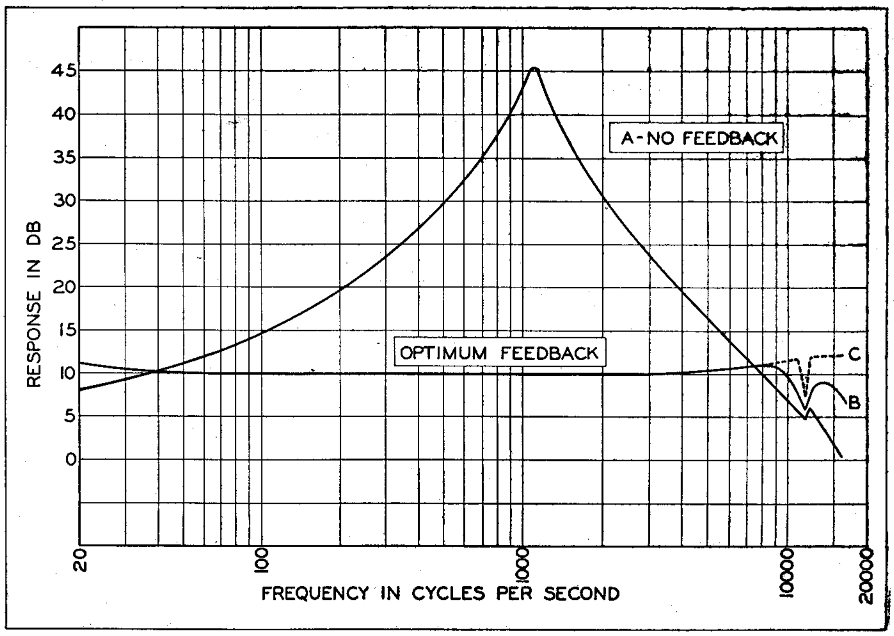

Fig. 5. Frequency response of feedback recorder.

It should be understood that the velocity curve of *Figure* 6 is not recommended as a recording characteristic but only a limit beyond which a recorder should not be required to perform. To arrive at a recording characteristic the limit curve would be modified by the energy distribution curve of the material to be recorded and by a factor which would take into account the manner in which distortion becomes more or less disagreeable with various frequency and energy combinations. This is usually determined by experience in the recording studios and is not properly a consideration in recorder design.

Occasionally, in a preliminary recording of a selection, the distributions of frequency and energy are such that the record, although of average loudness, will possess less than the usual tracing distortion. Because competition is keen among the recording companies to produce the loudest records consistent with distortion which their experience shows to be tolerable, it is common practice to make the final recording of such a selection at a higher level to effect a gain in the signal-to-noise ratio at the expense of increasing tracing distortion. For this reason, the recorder should be capable of meeting the more demanding velocity requirements of *Figure* 6 rather than the less stringent ones which result from a consideration of tracing distortion alone.

It may be argued that the maximum level curve of *Figure* 6 should be based on a linear groove speed of 20 inches per second (approximately 5-inch diameter at 78 rpm) since this speed more nearly represents the condition at the innermost grooves of most records. If this argument is accepted the margin of reserve power increases by a factor of 2.4, or 3.9 db.

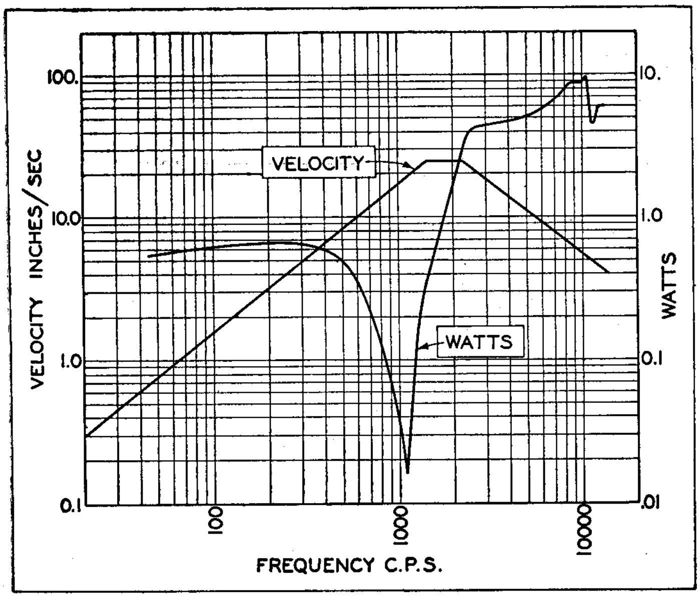

Fig. 6. Physical limitations of a recording system and power required to drive the feedback cutter.

Amplitude Distortion

The realization of a flat response curve fulfills but one requirement of an ideal recorder. Increasing importance is being attached in the audio engineering fields to amplitude distortion and intermodulation distortion. Harmonic and intermodulation measurements on disc recorders are seldom, if ever, published. For this reason, few recording men know whether a criterion of a good recorder is 5%, 10% or 20% inherent distortion. One reason for this lack of information is the difficulty of performing the measurements, the customary procedure being to cut a test record and measure the distortion generated in a reproducer when the

MEASURED INTERMODULATION DISTORTION

RECORDER USED	LOW FREQUENCY COMPONENT FREQ.	AMPLITUDE	VELOCITY	HIGH. FREQUENCY COMPONENT FREQ.	VELOCITY	% INTERMODULATION DISTORTION MEASURED IN OUTPUT OF W. E. 9B REPRODUCER
2A	40	.0025"	0.63"/SEC	2000	0.16"/SEC	1.0
	60	"	0.94	"	0.24	1.0
	100	"	1.57	"	0.39	1.0
W.E. D90946	40	.0025	0.63	2000	0.16	9.5
	60	"	0.94	"	0.24	9.2
	100	"	1.57	"	0.39	9.0
CONTEMPORARY	40	.0025	0.63	2000	0.16	52.0
	60	"	0.94	"	0.24	53.0
	100	"	1.57	"	0.39	52.0

TABLE I. Intermodulation measured with the aid of a reproducer.

record is played back. The measured distortion necessarily includes that of the reproducer, and if the linear velocity of the recorded groove is not sufficiently great, added distortion due to the finite size of the reproducer point (tracing distortion). Measurement of harmonic distortion is particularly difficult with a sharply tuned wave analyzer unless the turn-table has negligible wow or flutter. On the other hand, intermodulation measurements of the two-frequency modulated carrier method[4] in which the sum of the intermodulation products is indicated on a meter are not greatly affected by small changes in turn-table speed. For this reason the intermodulation method is becoming increasingly popular for measuring distortion in disc recorders. Apparatus suitable for performing these measurements is available in commercial form.[5] Table 1 shows intermodulation distortion measured in the output of a Western Electric 9B reproducer when reproducing records cut by a 2A recorder, a W.E. balanced-armature, rubber-line recorder, and another commercially available recorder (also of the balanced-armature type.) In each recording the velocity levels were so chosen that the low-frequency component fully modulated the groove of an 88 grooves per inch record in which the width of cut equaled the "land" between grooves. The velocity of the high-frequency component was then adjusted to be ¼ (—12 db) that of the low frequency. The same cutting stylus (.002″ radius, 87° included angle) was used successively in each recorder. The linear velocity of each record was sufficiently large to eliminate tracing distortion in the reproducer output. It was found necessary to employ a moving-coil-type reproducer in order that the distortion introduced by the reproducer would not mask that generated in the recorder. In fairness to the third recorder, it should be mentioned that when the input was reduced 6 db the intermodulation distortion decreased to the more reasonable values of 21%, 24%, and 23%, which is probably comparable to 6% on a harmonic basis.

The limitations in measuring technique due to the inclusion of a reproducer and varying turn-table speed are eliminated by the feedback cutter provided the feedback coil voltage E_3 is a true replica of the stylus velocity V. For then the feedback coil may be considered as an ideal reproducer following the contour of the recorded wave even as the stylus is engraving it. Obviously, distortion products measured in the output E_3 of this reproducer are independent of variations in turn-table speed and contain no tracing distortion. Table II is a tabulation of intermodulation distortion products in a 2A recorder measured by this means. For each measurement in Part A the intensity of the low frequency was adjusted to produce full groove modulation as in Table I. The results of this test compare quite closely with those of the preceding method if allowance is made for the rather small distortion contributed by the reproducer in obtaining the data of Table I. Part B shows the intermodulation distortion produced by fixed frequencies at several intensities. The intermodulation test presented in Table II was repeated using 7,000 cps and then 12,000 cps in place of 2,000 cps, with almost identical results.

Effect of Record Material on Recorder Response

The use of voltage readings E_3 to measure stylus velocity and distortion also makes it possible to compare the behavior of the cutter when recording "in air" to that when recording in the most resistant lacquer medium. It is important in all types of disc recorders that this difference in behavior be made

[Continued on page 44]

MEASURED INTERMODULATION DISTORTION

A

LOW FREQUENCY COMPONENT FREQ.	AMPLITUDE	VELOCITY	HIGH FREQUENCY COMPONENT FREQ.	VELOCITY	INTERMODULATION DISTORTION PERCENT
40	.0025"	.63"/SEC.	2000	.16"/SEC	0.61
60	"	.94 *	"	.24 *	0.62 *
100	"	1.57	"	.39	0.61

B

*WITH THE ABOVE VELOCITY VALUES OF 60~ AND 2000~ AS A REFERENCE, THEIR LEVEL TO THE RECORDER WAS VARIED IN 2 DB STEPS:

INPUT TO RECORDER	INTERMODULATION(%)
-6DB	.47
-4	.49
-2	.55
0	.62
+2	.83
+4	1.14
+6 (60~ SINGLE AMPLITUDE = .005")	1.70

TABLE II. Intermodulation measured by output voltage of the feedback coil.

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[4] Analysis and Measurement of Distortion in Variable Density Recording, by J. G. Frayne and R. R. Scoville. *SMPE Journal*, June, 1939.

[5] An Improved Intermodulation Measuring System, by G. W. Read and R. R. Scoville. *SMPE Journal*, February, 1948.

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as small as possible to insure that the frequency response of the cutter will not vary with discs of differing hardness nor change as the diameter or depth of cut of the recorded groove changes. The expanded scale of *Figure* 7 shows the stylus velocity of the 2A recorder in cellulose nitrate relative to that in air as measured by readings of feedback voltage E_3. This relationship was found to be independent of the linear groove speed.

Perhaps one of the most important yet least appreciated factors in recorder performance is its response to a suddenly applied impulse, or its transient response. Speech contains many transients, and in music many instruments are more readily identified by their characteristic transient attack than by their harmonic content. It is important, therefore, that these transients should undergo as little change as possible in the recording process. In general this requires a wide frequency band of uniform response and a phase shift which is linear with frequency throughout the band, not only to prevent degradation of the components of the transient itself, but also to insure that individual elements of the recorder do not vibrate independently at their own natural frequencies when subjected to this form of shock excitation and so introduce extraneous frequencies which help mask the original impulse. The transient response of the feedback cutter system was studied by observing the oscilloscope tracing of voltage E_3 while the stylus was recording a square wave of 400-cps repetition rate. The record was then played back with the reproducer output connected to the scope. Both patterns showed steep sides and fairly sharp corners, indicating satisfactory high- and low-frequency response with linear phase relationship. Superposed on the horizontal top of the patterns was a transient wave of approximately 11,000 cps with a small initial amplitude and having a decrement sufficient to reduce the amplitude of the wave train to substantially zero in 1/1600 second (¼ cycle of the 400-cps repetition rate). It seems reasonable to assume that such a transient will not seriously affect an otherwise high-quality recording.

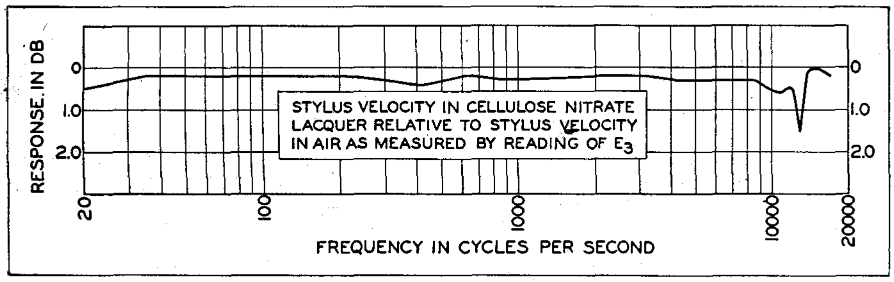

Fig. 7. Effect of record material on recorder response.

That the behavior of the recorder would be satisfactory when subjected to a sudden impulse or transient could have been predicted by a consideration of data taken under steady-state conditions. *Figure* 5 shows the response to be flat over a wide frequency band. The phase shift corresponding to the no-feedback-condition curve can be calculated and then modified according to equation 6 (feedback results in improved phase linearity as well as improved response). Phase calculated in this manner checks quite accurately with measured results over the frequency band where feedback is controlling and indicates a favorable condition for transient response.

Conclusion

The data presented above on frequency response, reserve power, intermodulation distortion, effect of varying record material, phase and transient response attest to the benefits of properly controlled feedback in a disc recorder; benefits which are permanent and independent of temperature and humidity