A NEW CONCEPT IN LOW FLUTTER HIGH ENVIRONMENT RECORDERS

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Summary To improve the performance of tape recorders operating under severe vibration, acceleration, and shock environments, two new flutter reduction design concepts have been developed:

1. Capstan servoing during the recording process to servo out flutter before it is recorded.

2. A new reel drive system in which the reels are coupled together to minimize tape tension variations and eliminate the possibility of throwing a tape loop.

Test data on a prototype spaceborne recorder has proven the validity of the concept. The prototype has shown a capability to reduce flutter by factors ranging from 3 to 10 over conventional high-environrnent recorders.

Typical flutter performance figures on the prototype (which accommodates 600 feet of 0.25" wide tape and operates at 30 ips) are:

0.36% p/p to 5000 Hz - on the bench
1.8% p/p to 5000 Hz - under environment (20 g rms random vibration)
Time displacement errors (TDE) are
± 3 microseconds - on the bench
± 6 microseconds - under environment (20 g rms random vibration)

Introduction Flutter performance in magnetic tape recorders has long been recognized as the single most significant operating characteristic. By definition, flutter in a magnetic tape recorder is a variation between the instantaneous velocity of the tape and its nominal specified velocity. Flutter is normally defined by most recorder manufacturers in either or both of the following terms:

1. Cumulative p/p flutter for a given frequency spectrum; and/or

2. Time Displacement Error (TDE)

Where flutter is specified in peak-to-peak cumulative terms, there are two primary and two secondary factors which must be specified. The two primary factors are the amplitude and the frequency spectrum. The two secondary factors are the attenuation of the filter utilized to measure the frequency spectrum and the percentage of time for which the amplitude measurement is valid. Typically, for the filter, 18 db per octave attenuation is almost universally used as a criteria, although quite often it is not specified. For the percentage of time that the amplitude measurement is valid, the statistical sigma limits are normally used and have the following significance

Random peaks which are outside the specified limits and occur less than a given percentage of the time are excluded from the measurements.

Sigma	Limit Time Percentage
1	32 %
2	5 %
3	0.3%

The conventional way to measure flutter is to record a constant frequency reference on the magnetic tape and then reproduce the reference and feed it into a discriminator tuned to the original reference frequency. Any output from the discriminator represents a frequency deviation and likewise a speed deviation in the magnetic tape. The speed deviations are referred to as flutter amplitude and the rate of these deviations as the frequency spectrum of the flutter. A typical flutter record obtained on a high-quality instrumentation recorder through this technique is shown in Fig. 1. A typical manufacturer’s specification for flutter performance in a high-quality instrumentation recorder is illustrated in Fig. 2.

The second method of specifying flutter, Time Displacement Error, is important in many digital data recording applications and also on certain sophisticated analog applications. This parameter (TDE) specifies the actual position the tape is in with respect to its theoretical position, if it were moving at a constant velocity. Typically, in most specifications, it is given in terms of microseconds at a given tape speed. It is also sometimes referred to in microinches. A sigma time limit should also be attached to the specified TDE value.

Flutter is recognized by magnetic tape recorder users as a critical performance characteristic because it:

(a) Generates both amplitude and frequency distortion in analogtype recording, and

(b) Generates bit jitter in digital recording and TDE in analog.

Technical Discussion In recent years, ground station-type magnetic tape recorders have come a long way with respect to achieving ultra-low flutter performance. Sophisticated high-response servos for the capstans and reel servos to provide constant tape tension have almost reduced flutter to the theoretical limit. Typically, in a high-quality instrumentation recorder operating at a tape speed of 60 ips, cumulative p/p flutter will run 0.25% p/p for a flutter bandwidth of 0.2 to 10,000 Hz using a filter attenuation rate of 18 db per octave and applying the 2 sigma time criteria. For the same conditions, the time base error typically will run ±2 microseconds on a 2 sigma basis. The use of these sophisticated type ground tape recorders, along with electronic flutter compensation techniques, makes it possible to reproduce magnetic tapes which originated on recorders having very poor flutter characteristics and still achieve relatively good data. However, as flutter bandwidth increases, it becomes increasingly more difficult for even the most sophisticated ground station to significantly reduce the effect of flutter on data accuracy. Hence, in many applications, it is necessary or more economical to reduce the flutter at its source, if possible. There are many applications where the original data must be recorded under conditions which are a long way from the ideal laboratory conditions. Further, in a number of these applications, it is not possible to telemeter the data out, such as in certain ballistic reentry situations, and on-board tape recording in a space or airborne vehicle must be employed. In these applications, special problems arise with respect to the on-board recorder in achieving good flutter performance. In these applications, vibration, shock, and acceleration are the principal enemies of low-flutter performance. An increase in flutter by a factor of 10 is not uncommon, even in recorders which are specifically designed to operate under severe environments. Under static environment, the main sources of flutter in a recorder are motor and bearing torque pulsations and pitch line variations due to runouts of pulleys, belts, and idlers. Under a dynamic environment, relative motion of the various elements of the tape recorder system due to acceleration forces introduces additional velocity variations. Relative motion between the head and its mount, between rotating elements and their bearing supports, and tape and belt deflections from their mean path, are typical of the sources of flutter due to a dynamic environment. Reduction of flutter due to these sources lies in reducing the relative displacements of the various elements with respect to the recording head to a minimum.

Consider the case of some of the elements of a tape recorder being set into sinusoidal vibration at a rate f_c Hz and a maximum amplitude X_m in a given plane or degree of freedom. Such motion can be expressed as

$$x(t) = X_m \sin 2\pi f_c t \tag{1}$$

If this motion is introduced as a variation in the velocity of the tape as it passes over the recording head, there will be a change in the nominal velocity between the two of

$$v(t) = \frac{dx(t)}{dt} = 2\pi f_c X_m \cos 2\pi f_c t \tag{2}$$

As an example, suppose there exists a 10 microinch peak (20 microinches p/p) vibration in some element such as the capstan, which transmits directly to the tape. If the vibration is at 2,000 Hz, which is the upper limit of most vibration specifications, the maximum velocity will then be about 0.125 ips. For a tape speed of 30 ips, this constitutes a peak variation of approximately 0.4% due only to vibration of this element. Thus, this motion, which is the equivalent of half a wavelength of yellow light, will result in 0.8% p/p (approximately 0.3% rms) flutter.

From the foregoing, it can be seen that even a micro amount of high frequency displacement can result in significant tape speed variation (flutter).

A tape Flutter versus Vibration Nomograph is included as Fig. 3.

Referring to the Nomograph, it can be seen that the flutter due to dynamic environments can be minimized by keeping the tape speed as high as possible and the resonant frequency and/or displacement rates of the principal mechanical elements as low as possible.

In order to minimize the effect of a dynamic environment on a magnetic tape recorder, the following approaches are normally employed:

(1) Stiffen and lighten all mechanical elements which affect tape motion.

The design concepts employed to stiffen and lighten the mechanical elements which affect tape motion are covered in more detail in Appendix A, “Design Concepts Which Reduce Flutter in a Tape Recorder Operating In a Dynamic Environment”.

(2) Isolate the recorder from high-frequency vibration

To provide maximum isolation from vibration, isolators should have the lowest possible resonant frequency. At the same time, the isolators must be compatible with the shock and acceleration requirements and the available “sway” space. The vibration isolators must, in the available “sway” space, be able to take the shock and acceleration requirements without “bottoming out”. A “bottoming out” condition obviously eliminates the desired function of vibration isolation. Typically, in an actual application, the conditions which would normally cause “bottoming out” of a relatively soft mount represents the time when the data collection is usually the most important. This is a condition which normally cannot be tested in an environmental laboratory since acceleration and vibration must be applied simultaneously. Equipment can show up quite well under either an acceleration or a vibration test and in actual practice operate very poorly when subjected to both environments simultaneously.

In the typical application, the environment (shock and acceleration) and the available “sway” space are given. This information, with the mass of the recorder, determines the isolators which can be used and their resonant frequency. Since vibrations at frequencies above the resonance of the isolators are not transferred into the recorder, the goal is to make the lowest resonance frequency in the recorder higher than the isolator resonance.

(3) Locate the magnetic heads as close to the capstan as possible

A design layout which permits locating the magnetic heads extremely close to the capstan is illustrated in Fig. 7. It is important to recognize that locating the heads immediately adjacent to the capstan is, for all practical purposes, as good as locating the heads directly on the capstan. This is true because dynamic tensions in the magnetic tape as it comes in contact with the capstan are maintained over the arc in which the two are in contact. The non-slip relationship between the tape and capstan maintains these localized stresses which results in micro dimensional variations in the tape - the equivalent of flutter. Hence, even though the capstan rotates with absolutely zero flutter, flutter would be present in the tape on the capstan. This condition is illustrated in Fig. 6.

Employing all of the foregoing techniques and using the best possible design practices still leaves a lot in the way of desired flutter performance under severe environmental conditions. This is particularly true when the recorder is also called upon to reproduce the data, as well as to record it.

In an effort to make a significant step forward in low-flutter, high-environment recorders, a development program was undertaken which, in addition to using the previously described flutter-reducing techniques, involved the following two new recorder concepts:

(1) Capstan servoing during the recording process to servo out flutter before it is recorded.

(2) A new reel drive system in which the reels are coupled together to minimize tape tension variations and eliminate the possibility of throwing a tape loop.

Flutter during the record mode is servoed out through the use of a precision reference frequency prerecorded on a separate track on the tape. Prerecording can be accomplished with the recorder operating under bench conditions or on a high-quality instrumentation-type laboratory recorder. The concept is illustrated in a system functional block diagram, Fig. 8. Referring to the block diagram, the system operates in the following manner:

(1) A precision reference frequency is recorded on tape track 3.

(2) During operation of the recorder, the prerecorded precision reference frequency on track 3 is being reproduced at the same time and in the same head stack used for recording tracks 1, 2, and 4.

(3) While recording on tracks 1, 2, and 4, the reproduced reference frequency being reproduced on track 3 is utilized for servo control of the capstan motor. The precision reference frequency that is being reproduced from the tape is compared with an on-board crystal reference frequency. Phase and frequency differences between the two signals are utilized by the servo to control the the DC servo motor whose shaft is used without any intermediary mechanical couplings, etc. , as the capstan. Servoing at rates as high as 250 Hz is achieved through its extremely high torque to low rotor mass ratio.

(4) Optimum servo performance is achieved by locating the record head stack, which also includes the playback track for the prerecorded reference frequency, as close to the capstan as possible. Referring to Fig. 7, it can be seen that the head gap can be located very close to the capstan - e.g., 0.122". By virtue of this proximity, it is essentially the equivalent of having the record head stack directly on the capstan. This, as previously discussed, is due to tension variations in the tape as it comes in contact with the capstan. Reference Fig. 6. The tension and coefficient of friction between the tape and capstan do not permit tape slippage which would equalize the stresses and result in a uniform strain in the tape section in contact with the capstan. Thus, even though the capstan shaft were to rotate at an absolutely uniform angular velocity and with no runout, flutter would be present in the tape.

(5) During the recording process, the on-board crystal reference frequency is also recorded on track 2 of the tape. This tone is used during reproduce to further servo out any remaining tape speed irregularities which occurred during the recording

process and are occurring during the reproducing process. This, in effect, permits the servo to have two opportunities to reduce the flutter.

Achieving constant tape speed and constant tension across the head area is the purpose of any tape handling mechanism. Most conventional transports do not achieve the latter because while the torque in the supply and takeup reels is essentially constant, the tape pack diameter change s; hence, the tension in the tape as it leaves the reel varies inversely as the diameter of the tape pack. Dynamic environments further compound the problem inasmuch as the torque on the supply and takeup reels can no longer be held constant.

The low-flutter, high-environment recorder developed in this program used the Iso-Elastic* Drive System. This drive system employs an endless Mylar belt to peripherally drive the tape packs. This belt, in turn, is frictionally engaged by two interposed differential capstans. The difference in velocity between the two capstans results in a constant tension between the tape packs and across the head area. Since the tension is only determined by a constant difference in speed between the capstans, it is independent of angular velocity variations of the tape packs. Although this drive system is also affected by a dynamic environment since the belt is, is effect, a stiff spring, it does have the advantage of (1) low mass, (2) provides constant tape tension between reels, (3) simplicity, and (4) a stiff mechanical coupling between the two reels. Coupling the reels together makes it virtually impossible to throw a tape loop even under the most severe environments. Further, under normal conditions, the Iso-Elastic Drive provides constant tape tension independent of the amount of tape on either reel.

Various physical aspects of the recorder which resulted from the development program are shown in Figs. 4, 5, and 9.

Although the prototype recorder is still undergoing evaluation, sufficient test data is available which more than adequately confirms the merit of the original concept. The prototype recorder was designed to operate at 30 ips and have a tape capacity of 600' x 0.25" x 1.1 mil tape (0.92 base, 0.18 mil oxide). The power requirement is 28 ± 4 V dc with a peak power consumption of less than 40 watts. The recorder was designed to record two channels of direct-type data in the bandwidth 350 Hz to 120 kHz ± 3 db. The recording capability, however, could be readily converted-to other types of analog or digital recording. Total weight of the recorder was less than 12 pounds. The environmental capabilities were:

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* “New Concept in High Reliability Recorders for Spaceborne Data Storage:, by D. L. Burdorf, Vice President and Director of Engineering, Kinelogic Corporation

Temperature:	-20°C to + 60°C
Altitude:	Satellite or deep space
Vibration:	
Sine Wave:	5 g peak, 20 to 2000 Hz
Random:	20 g rms, 3 cut-off.
Acceleration:	20 g

Measured performance is shown in the following table:

FLUTTER PERFORMANCE *

Bench Conditions

Wide band	0.09% rms	-	dc to 5000 Hz
	0.36% p/p	-	" " " "
	0.50% "	-	" " 10,000 "
TDE	± 3 microseconds	-	servo optimized for TDE
	± 5 "	-	" " " wide band

5 g Peak Sinusoidal Vibration

Wide band	0.6% rms	-	dc to 5000 Hz
	1.8% p/p	-	" " " "
	2.6% "	-	" " 10,000 "
TDE	± 6 microseconds	-	servo optimized for TDE
	±10 "	-	" " " wide band

20 g rms Random Vibration, 3σ Cutoff

Wide Band and TDE flutter less than for 5 g Sinusoidal Vibration.

*18 db/ octave Filter and 2 σ time limit for p/ p wide band flutter measurements, 2 σ time limit for TDE measurements.

For a given flutter amplitude, TDE is inversely proportional to flutter frequency. Hence, the magnitude of the TDE is principally determined by the low frequency flutter components. Since the capstan servo can be optimized for any given bandwidth, the TDE can be minimized at the expense of high-frequency flutter - this accounts for the two TDEs given in the preceding table.

The flutter attenuation performance of the servo was measured and found to exhibit the characteristics shown in Fig. 1 . From this data, it can be seen that the servo attenuated the flutter 74 db at 1 Hz, 43 db at 10 Hz, and 6 db at 100 Hz.

The mechanical transport was designed with a sandwich-type construction using duplex bearing pairs at each end of all rotating shafts. Every effort was made to achieve rigidity of construction of all elements in order to reduce flutter caused by vibration. Flutter tests made during vibration with the transport hard-mounted to the shake table showed the lowest mechanical resonance to be 900 Hz.

An isolation mount was chosen with a resonant frequency of 90 Hz and an amplification of 3 at resonance. This was the softest mount possible with the available sway space between the transport and the case. Maximum flutter under vibration conditions occurred during sine wave vibration at 130 Hz due to a torsional mount resonance at that frequency, caused by a slight unbalance in mount loading. It is expected that redesign of the mount could eliminate this torsional resonance and a further reduction in flutter could be obtained.

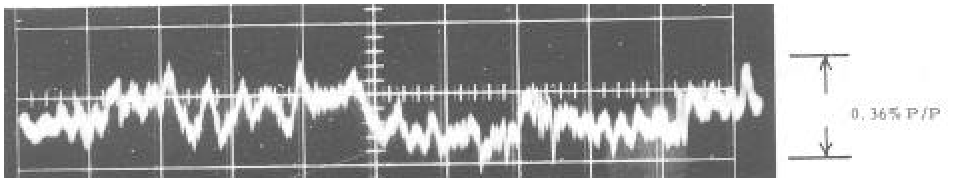


Figure 1 - Typical Flutter Record for Model CH Recorder

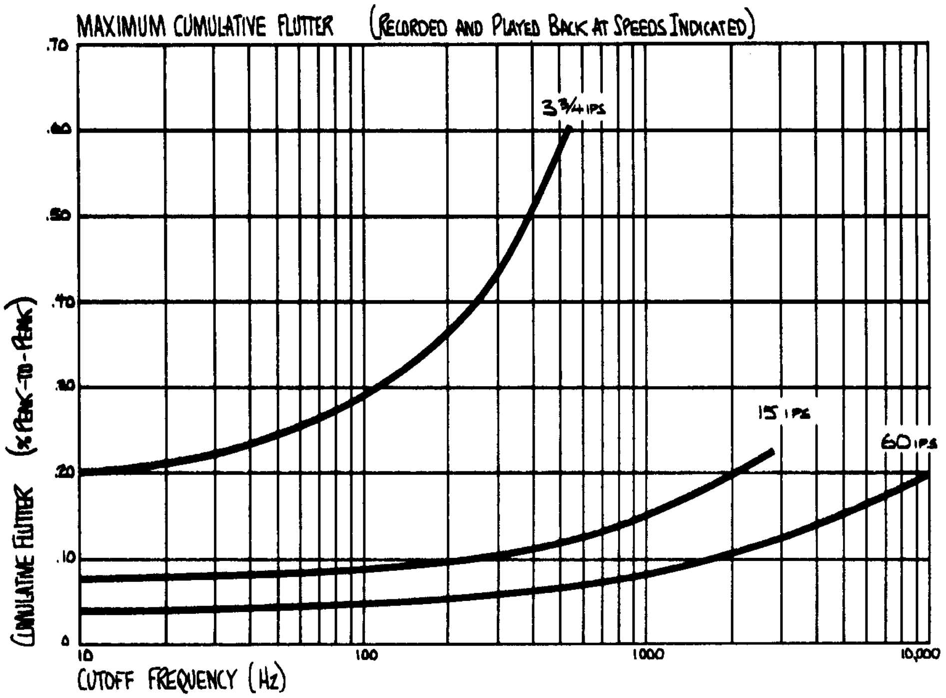


Figure 2 - Typical Flutter Performance Data

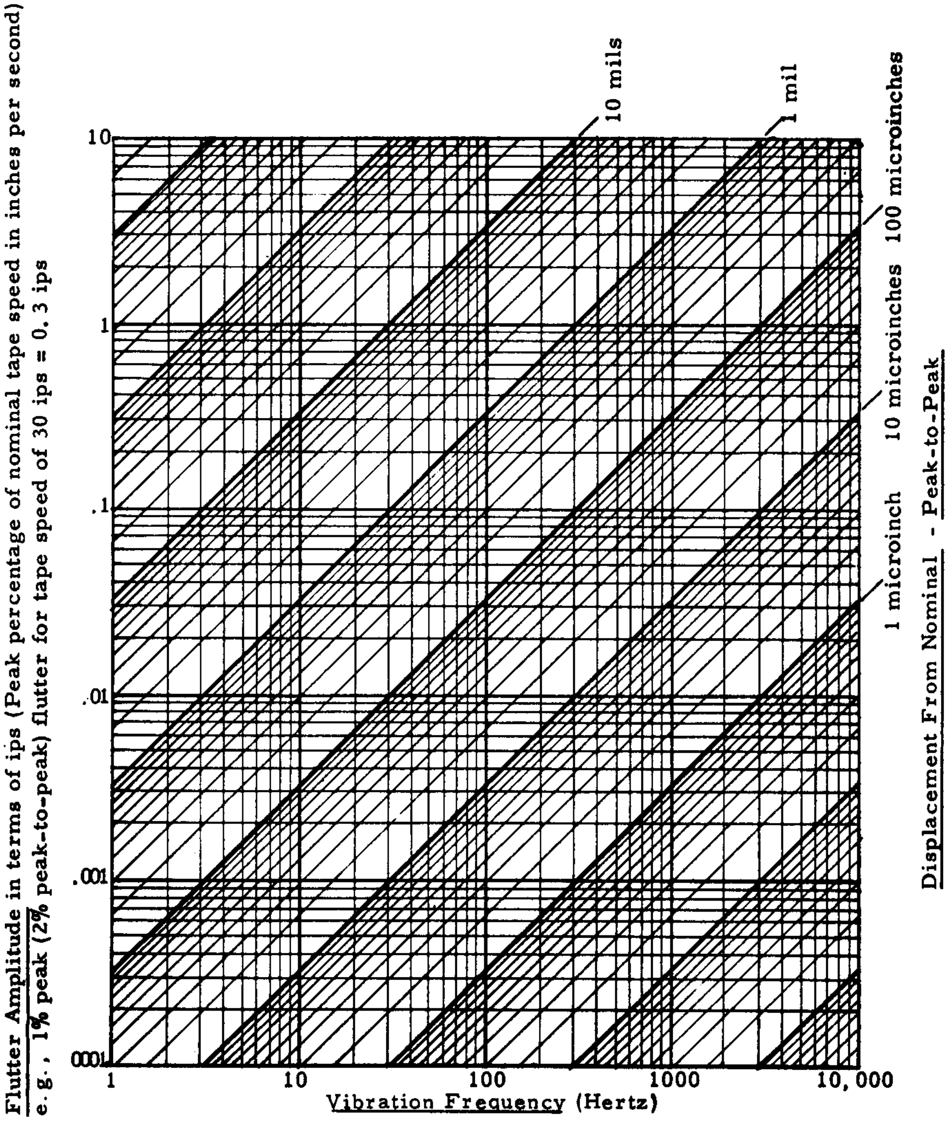


Figure 3 - TAPE FLUTTER versus VIBRATION NOMOGRAPH

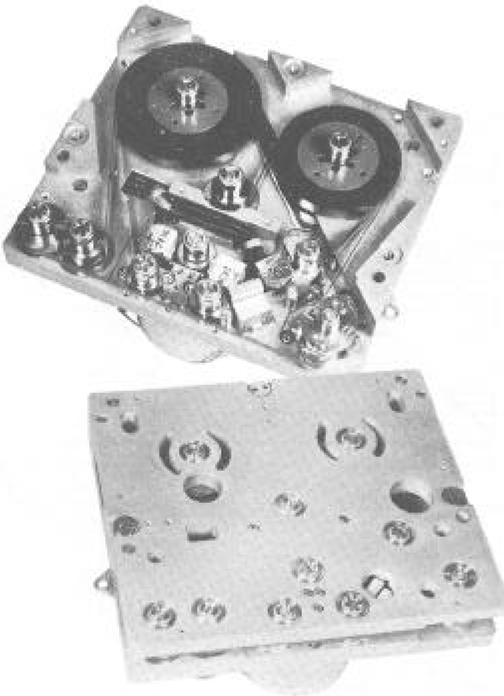


Figure 4 - Sandwich Design Concept used in the Kinelogic Model CH Recorder

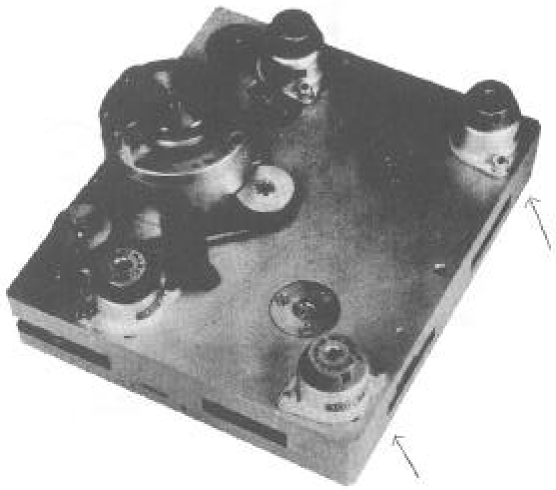
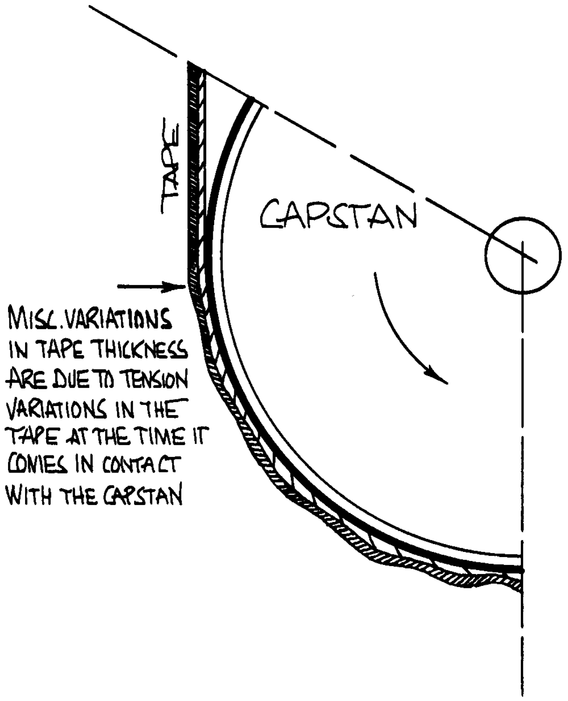


Figure 5 - Vibration Isolators used in the Model CH Recorder



MISC. VARIATIONS IN TAPE THICKNESS ARE DUE TO TENSION VARIATIONS IN THE TAPE AT THE TIME IT COMES IN CONTACT WITH THE CAPSTAN

Figure 6 - DYNAMIC TENSION EFFECTS on Tape on the Capstan

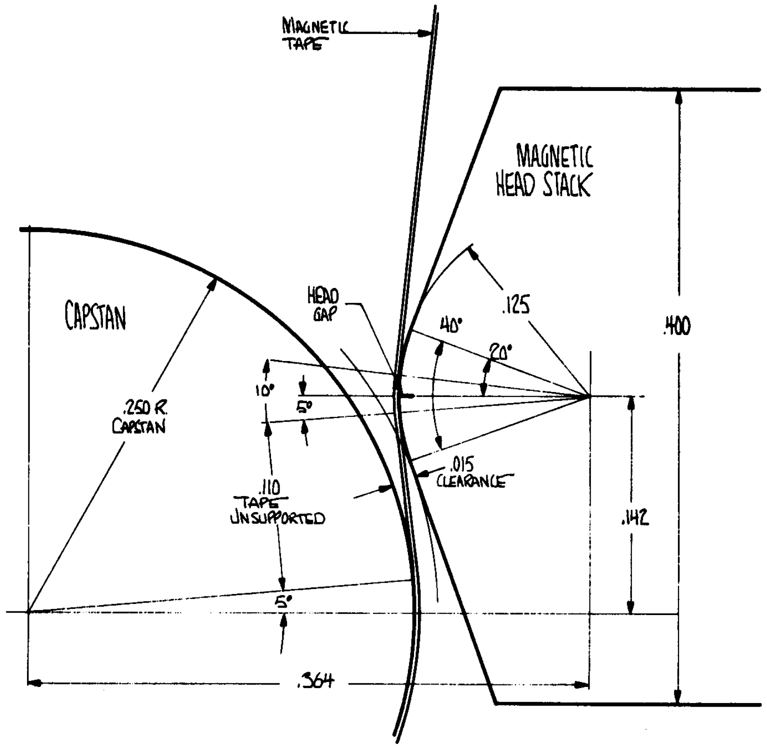


Figure 7 - Capstan and Head Layout

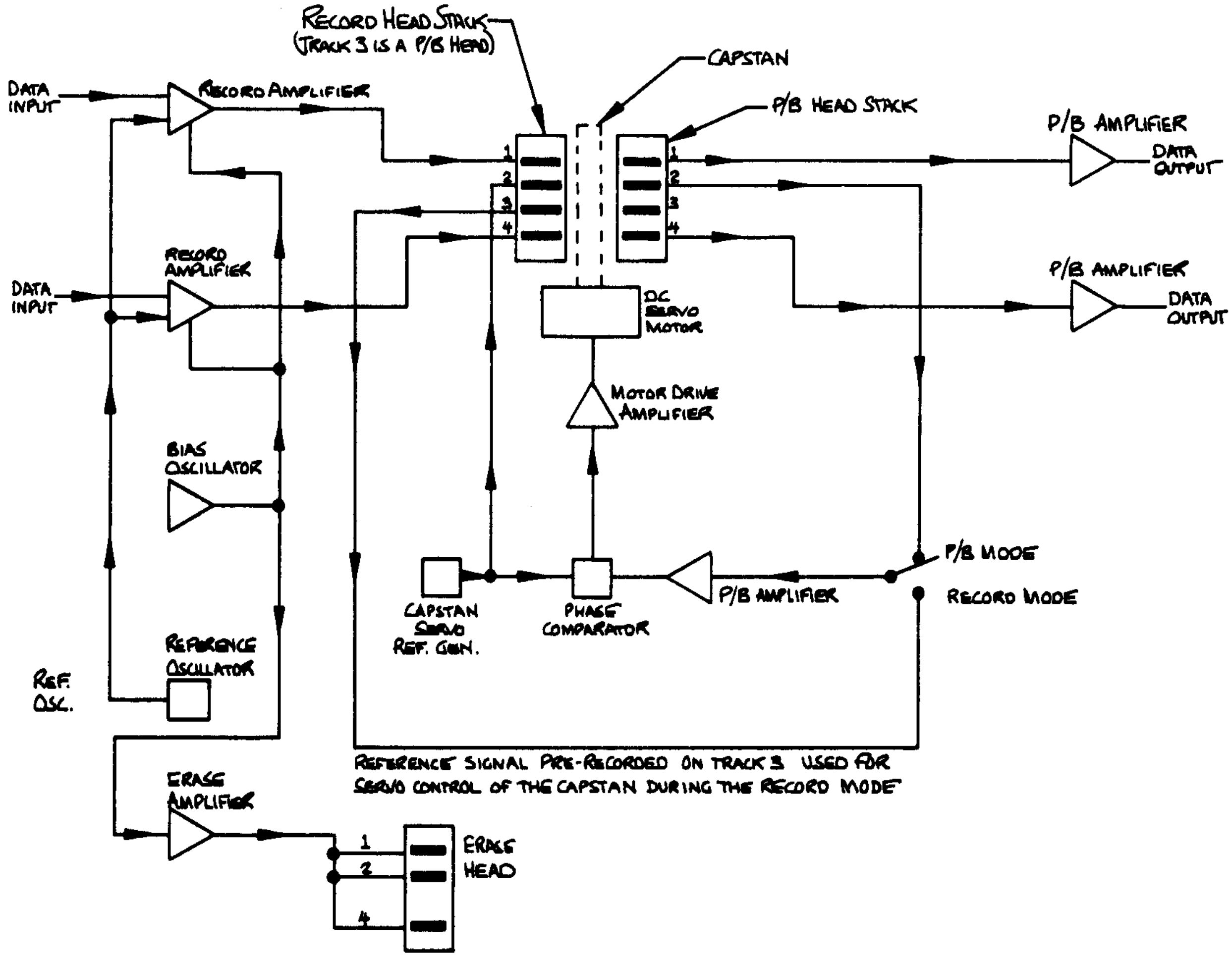


Figure 8 - Model on Recorder System Functional Block Diagram

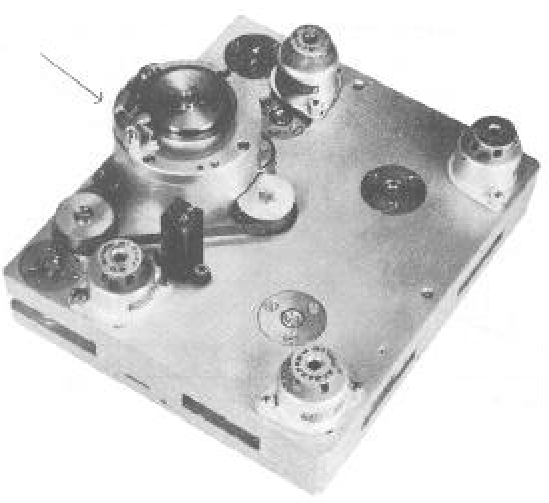


Figure 9 - DC Servo Motor and Associated Optical Tachometer

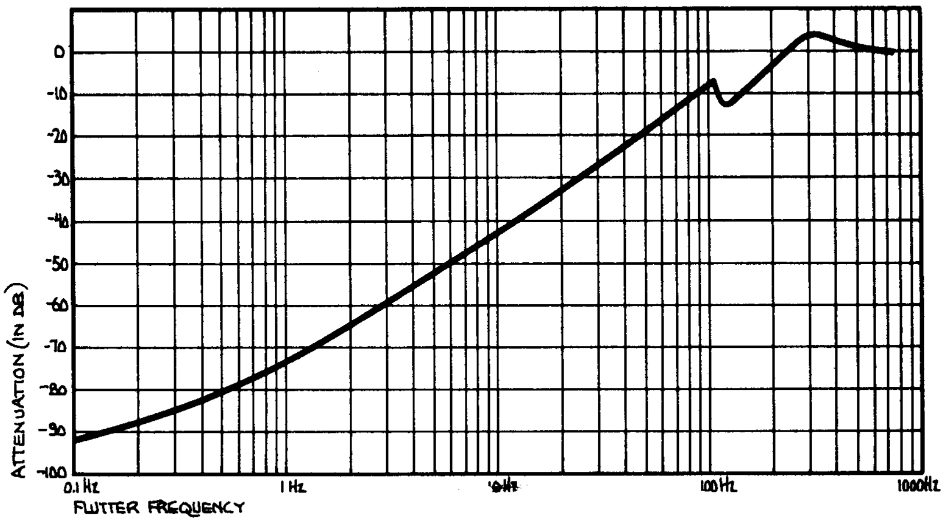


Figure 10 - Flutter Attenuation Characteristics

Figure 11 - Model CH Recorder

APPENDIX A

Design Concepts Which Reduce Flutter In A Tape Recorder Operating In A Dynamic Environment

Rotating Components Rotating components present the most difficult problem in reducing displacements. The drive capstan or capstans are the most difficult of the rotating elements. Since the capstan is the element which establishes tape speed, any displacement of the capstan relative to the recording head will usually show up directly as flutter. However, to establish constant tape motion under static conditions, it is normally necessary to add inertia to the capstan shaft to attenuate torsional disturbances generated by motors or bearings. Hence, it would appear that a set of conflicting requirements arises since mass is required to obtain inertia, but absence of mass is necessary to reduce displacement.

The bearings to support the rotating components for use in a dynamic environment must have low friction variation under dynamic load, as well as maximum stiffness. These requirements rule out all bearings except ball bearings for miniature, low-power recorders. The bearing in effect acts as a spring coupling between the supporting structure and the rotating element. Generally, shafts and other elements can be designed to be relatively stiff compared to ball bearing supports. Applying ball bearings to obtain maximum stiffness of support requires consideration of elastic deformation versus load relationships in bearings.

For a typical angular contact bearing

$$\delta r = .0021 \sqrt[3]{\frac{Q^2}{D}} \tag{1}$$

where δr = radial deflection

Q = load

D = ball diameter

It can be seen that the deflection increases as the 2/3 power of the load. This gives a typical free bearing deflection versus load curve as shown in Fig. 1.

Providing preloading by means of duplexed bearings shifts the noload running point up along the curve, such as to the 2 lb. preload point shown. The resulting no-load stiffness is now twice the stiffness (due to 2 bearings in series) of a single bearing at the 2 lb. load point, resulting in the load versus deflection curve shown for the duplexed pair.

Adding more preload would further increase the stiffness; however, running friction will also increase and mill be a limitation in low-power recorders. Addition of more bearings will also increase stiffness of the bearing support. Referring to Equation 2, the bearing deflection is inversely proportional to the ball diameter to the 1/3 power. If, for any given bearing O. D. , the number of balls can be increased by reducing ball diameter, an increase in stiffness will result, as deflection varies inversely as the number of balls.

for example, if $r1 = \frac{1}{ND^{1/3}}$ for bearing #1 (2)

and bearing #2 has 2 N balls of $\frac{D}{2}$ diameter

$$\delta r2 = \frac{1}{2N(0.5D)^{1/3}} = \frac{1}{2 \times .794D^{1/3}} = \frac{.63}{ND^{1/3}}$$

$$\text{then } \frac{\delta r2}{\delta r1} = .63$$

Bearing supports should be located at either end of the rotating mass to be supported instead of using a cantilevered arrangement. This allows each supporting bearing to take an equal part of the load and provides maximum stiffness.

Care must be taken to maintain alignment of the two sections as misalignment will give the same effect as runout.

Tape and Belts Unsupported lengths of tape and belts will generally have low resonances and must be kept as short as possible. The behavior of an unsupported length of tape or belt will be similar to a vibrating string, and the frequency in vibration per second can be expressed as

$$f = \frac{n}{2L}\sqrt{\frac{S}{m}} \qquad (3)$$

where

n = number of nodal loops

L = length (in feet)

S = tension (in pounds)

m = mass per unit length (slugs per foot)

where

$n = 1$ lowest mode of vibration

$f = 2500$ cycles per second

$S = 0.25$ lb. tape tension (for 0.25 inch tape)

$$m = \frac{252 \times 10^{-6} \text{ lbs/ft}}{32 \text{ ft/sec}^2}$$

Substituting in Equation 3 gives an unsupported tape length of L = .428 inch

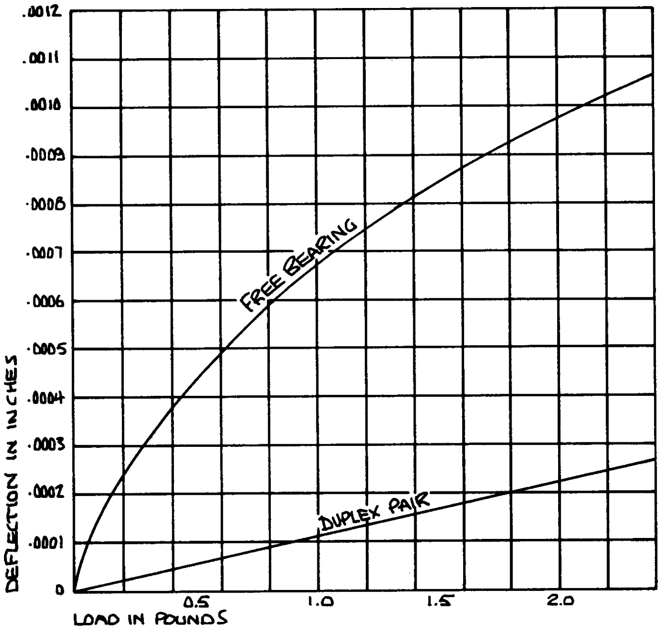
Higher tape tension increases this value as the square root; thus, doubling the tension only increases L to 0.606 inches.

If we assume an unsupported tape length of one inch, vibrating with a peak-to-peak amplitude of 0.030 inch, the arc length at the peak of the cycle will be 0.001" longer than the chord length. This is typical amplitude of vibration for such a length. This 0.1% change in tape length causes tension and velocity which will result in tape flutter.

Reduction of the effects of vibration on tape and belts can be accomplished by

(a) reducing unsupported length to a minimum
(b) providing support or guiding by means of fixed supports with large radius area. This will eliminate unsupported length with low sliding friction because of the small tape wrap around the large radius.
(c) increasing tension
(d) vary unsupported lengths to shift resonant frequencies eliminating effects from adding. Where long unsupported lengths cannot be eliminated, such as between an almost empty reel and the first roller, isolation of the resonance disturbances from the recording head area must be introduced.

Conclusions Although the foregoing is only a synopsis of the major considerations involved in the design of miniature high-environment tape recorders, it serves to point out the complexity of the problem. A thorough understanding and analysis of the problems, however, permits optimization of the bearings, materials, shaft dimensions, location of mass, etc.



Appendix A - Figure 1 - Ball Bearing Deflection Underload