FLUTTER AND TIME ERRORS IN MAGNETIC DATA RECORDERS

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Summary Flutter and time errors are critical factors in all instrumentation recording. They become even more so in many current and future applications, especially in the data recovery and reduction processes of various telemetering systems.

This paper presents analytically the relationship between flutter, time base error, and time base error difference (sometimes called jitter), plus the effects of these errors on direct and FM recording. Methods of measuring these quantities are discussed and experimental examples are given. Spectral and probability density analyses and measurements have indicated that these variables are basically random in nature, and as such, they should be specified in terms of a levels, rather than in conventional peak-to-peak figures. Finally, a measurement method for the typical values of interchannel time error is presented, and some trends of correlation among all channels are discussed.

Introduction Flutter studies started way back with audio recorders, and numerous papers dealing with this subject have been written. The flutter problem becomes even more pronounced with instrumentation recorders being developed for wider bandwidths and shorter recorded wavelengths. Flutter causes time base distortion which, though it is not generally realized, sets a limit on the usable data bandwidth of a recorder.

This paper attempts to present a unified picture of flutter and time errors in a multi-channel longitudinal instrumentation recorder. Analytical results are verified by typical experiments. Some techniques are suggested for flutter and time error measurements. A statistical approach for measuring and specifying flutter and time errors is strongly recommended; although, this is probably not the first such suggestion.

It is hoped this material will be helpful from the users' standpoint to provide a better understanding of the performance of a recorder for certain applications. Also, by adding to the already massive collection of flutter and time error data, this material may serve to remind the recording industry that a meaningful and concise standard should be established in this area.

Definitions and Assumptions

Flutter - Variation of tape speed excluding any dc component. For random flutter the distribution is assumed to have a zero mean.

Time Base Error (TBE) - Total time error caused by speed variations measured from a reference point. TBE equals the time integral of flutter.

Time Base Error Difference (TBED) - Time error incurred over successive sample time intervals. TBED is the increment of TBE at two adjacent sample points.

Interchannel Time Base Error (ITBE) - Relative time error between two channels in a multi-channel recorder, including static and dynamic skew.

Some existing terms should be mentioned here for the purpose of comparison and clarification: Time Displacement Error (TDE) has been used for TBE1 and TBED[2], and Jitter is often used in place of TBED. Intrachannel and interchannel TDE are used to distinguish time errors incurred in a single channel or between channels[3,4]. The recording industry should adopt a set of unified terms to avoid needless confusion.

For small variations in tape speed, it is quite adequate to assume that the interaction is negligible between record and reproduce flutter, and that the record and reproduce processes are essentially linear. Under this condition, an equivalent flutter may be considered which is the algebraic sum of record and reproduce flutter corrected for any speed ratio other than unity. Separate calculations may have to be made if the flutter characteristics are quite different between the record and the reproduce processes, especially when operated at different nominal tape speeds, but the linear assumption should still be quite adequate. In our analysis, therefore, a single set of flutter components is used for the combined record-reproduce process to simplify the analytical expressions and yet not lose any generality.

Time Base Error (TBE). -Let

$$F(t) = \sum_{1}^{n} a_n \cos(\omega_n t + \Theta_n) \qquad (1)$$

represent the Fourier components of the flutter where the a_n's are expressed as a fraction of nominal velocity. By definition, the TBE is

$$h(t) = \sum_{1}^{n} \int_{o}^{t} F(t)\, dt$$

$$= \sum_{1}^{n} a_n/\omega_n \sin(\omega_n t + \Theta_n) \tag{2}$$

Equation (2) indicates that the contribution to TBE is inversely proportional to the flutter rate (ω_n). A tape transport with a certain amount of high frequency flutter is actually better than another one with the same amount of low frequency flutter as far as TBE is concerned. In the latter case, the magnitude of TBE may become very large (typically several hundred microseconds over a time interval of a few seconds, and even more if the transport were running without position and speed control mechanism). For transports with a reasonably fast position servo, the TBE is generally small, typically a few microseconds or less, because the low frequency flutter components are largely corrected by the servo action. In this case the residual flutter is nearly random in nature, and it has a rather uniform distribution of power density.

The mean square flutter can be calculated from Equation (1),

$$\sigma_F^2 \triangleq \overline{F^2(t)} = \sum_{1}^{n} \overline{a_n^2(t)}\ \overline{\cos^2(\omega_n t + \Theta_n)}$$

Now, $a_n^2(t) \rightarrow 2P(f)\ \Delta f$ where $P(f)$ is the power density, and $\overline{\cos^2(\omega_n t + \Theta_n)} = 1/2$, because Θ_n is uniformly distributed between 0 and 2π. Therefore, in the limit,

$$\sigma_F^2 = \int_{f_1}^{f_2} P(f)\, df \tag{3}$$

For uniform power density, $P(f) = P_o$,

$$\sigma_F^2 = P_o(f_2 - f_1) \tag{4}$$

where f_1 and f_2 are the lower and upper limit of the flutter bandwidth. The mean square TBE, $\overline{h^2(t)} \triangleq \sigma_T^2$, can be found as follows:

$$\sigma_T^2 = \overline{\left[\frac{F(t)}{f}\right]^2} = \int_{f_1}^{f_2} \frac{P(f)}{f^2}\, df \tag{5}$$

For $P(f) = P_o$

$$\sigma_T^2 = P_o \left(\frac{1}{f_1} - \frac{1}{f_2} \right) = \frac{\sigma_F^2}{f_1 f_2} \tag{6}$$

A direct phase comparison between a reference time marker and a pilot signal reproduced from the tape yields the sampled TBE, which can be converted into a box-car -type function by using a holding circuit. If the position servo is capable of locking-in at such a high rate, the rate of comparison should be several times higher than the flutter rates in order to detect all possible speed variations. Otherwise, a lower frequency must be used (or one must count down from a higher frequency reference) and the TBE contributed by the high frequency flutter components cannot be detected properly.

Figure 1 is a simplified block diagram for TBE measurement, and Figure 2 is the timing diagram. Figure 3 shows some typical TBE signals obtained by this method. Typical spectral distributions of flutter and TBE are illustrated in Figure 4. At the low frequency end of the spectrum, the position servo is effective to its cut-off frequency f_1, approximately between 50 and 100 cps; hence the flutter and TBE diminish quite rapidly below f_1, although occasionally some ripples show up at frequencies corresponding to the fundamentals and harmonics of mechanical disturbances such as once-around motion of the capstan or bearings.

Starting from f_1, the flutter distribution shows a practically uniform spectrum without any pronounced peak. It may be concluded that these flutter components are mostly caused by tape disturbances. Some factors affecting the characteristics of the tape disturbances are the tension, speed, guiding and physical properties of the tape, smoothness of contact surfaces, and tape span (unsupported length of tape). The TBE falls off with increasing frequency starting rather slowly at a poing about $2f_1$ to $3f_1$ and finally approaching a 6 db per octave rate at the high frequency end.

The flutter spectrum may be approximated by a rectangular model as indicated in Equation (4) (See Figure 4). If the upper end of the flutter spectrum, f_2, extends to 10 kc or more, and hence $f_2 >> f_1$, an extension of bandwidth of the position servo would not improve the flutter figure appreciably because the mean square flutter is essentially proportional to f_2. For instance, increasing the servo bandwidth from 100 cps to 1000 cps may improve the flutter by only about 10 percent assuming $f_2 = 10$ kc.

The power density spectrum of TBE may be approximated by a trapezoid with the flat top region extending from f_1 to $2f_1$ or $3f_1$, and a fall-off rate at the high frequency end about 6 db per octave, while the fall-off rate at the low frequency end is about 10 or 12 db per octave depending upon the characteristic of the position servo. The mean square TBE is represented by the area under the trapezoid, which can be evaluated quite readily.

In contrast to flutter, TBE can be reduced very effectively by extending the bandwidth of the position servo (f_1). Many of the current high performance recorders are designed for low TBE, and hence one of the Tlesign objectives is to arrive at an optimum performance of the position servo.

Time Base Error Difference (TBED) By definition, TBED is the time error incurred over successive sample time intervals. Let T = sample interval and g(t) = TBED, then from the flutter expression given in Equation (1), we have

$$g(t) = \sum_{1}^{n} \frac{a_n}{\omega_n} \left[\mathrm{Sin}\,(\omega_n mT + \Theta_n) - \mathrm{Sin}\,(\omega_n \overline{m-1}\, T + \Theta_n) \right] \tag{7}$$

where m indicates the sequence of successive sample intervals. If a holding circuit is used at the output, and letting mT = t, we obtain

$$g_p(t) = \frac{g(t)}{T} = \sum_{1}^{n} a_n \cos\left(\omega_n t + \Theta_n - \frac{\omega_n T}{2} \right) \left(\frac{\sin \frac{\omega_n T}{2}}{\frac{\omega_n T}{2}} \right) \tag{8}$$

where $g_p(t)$ is the TBED as a fraction of T.

1. When $\omega_n T << 1$, the sample rate is much higher than the flutter rates,

$$g_p(t) \sim \sum_{1}^{n} a_n \cos\,(\omega_n t + \Theta_n) = F(t) \tag{9}$$

Equation (9) shows another way of measuring flutter, and it also provides an important relation between flutter and TBED for short time intervals.

2. When $\omega_n T > 1$, the sample rate is comparable to or slower than some flutter rates; then the sin x/x term in Equation (8) diminishes and becomes less than unity. Hence, $|g_p(t)|$ is smaller than the flutter because of partial cancellation between sample points. In general, $g_p(t)$ resembles the flutter function at the low frequency end, while the high frequency components may be attenuated at a varying degree. The location of the transition point depends upon the sample rate. In practice, the sample rate is chosen several times higher than the highest expected flutter rate so that $\omega_n T << 1$.

3. If only a few flutter components are predominant, it is possible that $\omega_n T = 2k\pi$ (k is an integer) and, hence, $g_p(t) = 0$, or is very small. Here, positive and negative error neutralize each other over the sample period T. Although this situation rarely occurs in practice, it does illustrate a pitfall which deserves some attention.

For random functions, the mean square TBED can be derived as follows:

$$\overline{g^2(t)} = T^2 \int_{f_1}^{f_2} P(f) \frac{\sin^2(\pi f T)}{(\pi f T)^2} \, df \tag{10}$$

For $P(f) = P_o$ = constant (rectangular power density spectrum for the flutter), and assuming $f_1 = 0$ and f_2 becomes the flutter bandwidth, Equation (10) becomes

$$\overline{g^2(t)} = \frac{P_o T}{\pi} \left[\frac{\cos(2\pi f_2 T) - 1}{2\pi f_2 T} + \mathrm{Si}(2\pi f_2 T) \right] \tag{11}$$

where Si(x) is the sine integral, which is tabulated. A plot of Equation (11) is shown in Figure 5; point A, where $Tf_2 = 0.5$, may be considered as a dividing point. For $Tf_2 < 0.5$,

$$\overline{g^2(t)} \sim P_o f_2 T^2 = \sigma_F^2 T^2 \tag{12}$$

Equation (12) indicates that the rms TBED is directly proportional to T, and this checks out with Equation (9) for the case of coherent flutter. For $Tf_2 > 0.5$,

$$g^2(t) \sim \frac{P_o T}{2} = \frac{T}{2} \frac{\sigma_F^2}{f_2} \tag{13}$$

Here the rms TBED is proportional to the square root of T because of partial cancellation of time error within each sample period T.

TBED measurement can be implemented by using the arrangement shown in Figure 6. Referring to the timing diagram shown in Figure 7, a pilot pulse initiates the period gate, which is pre-set at a fixed duration and embraces a specific number of pilot pulses. The trailing edge of the period gate starts a ramp function which in turn is sampled by the next pilot pulse. The sample voltage is stored in a capacitor. The cycle is repeated for the next group of pilot pulses.

A staircase function is obtained which represents the TBED, as shown in Figure 8. Again the pilot frequency may be scaled down to a lower value if necessary.

As mentioned earlier, $g_p(t)$ is essentially the flutter, F(t), if the sample period T is much smaller than the flutter periods. This was verified experimentally by comparing the spectral distribution of F(t) and $g_p(t)$, as shown in Figure 9 where the two curves practically coincide with each other, and the minor differences are quite negligible.

TBE and TBED are equally important from a practical standpoint, and one can be derived from the other. TBE can be measured when a transport is equipped with an adequate position servo as this implies that the low frequency flutter components are already compensated for and the TBE is bounded in a small range. TBED can be measured on any tape transport to determine the amount of jitter for many critical applications.

Effect of TBE on Direct Recording Direct recording is defined as the normal baseband recording where high frequency bias is applied for the purpose of improving linearity and sensitivity of the record process.

When a signal e_s (t) is passed through a magnetic recorder, the output, affected by time-axis distortion, may be expressed as

$$e_o(t) = e_s \left[t + h(t) \right]$$

Consider a single tone input, $e_s(t) = E \sin \omega_s t$, and a single flutter component, $a_f \cos \omega_f t$, then $h(t) = (a_f / \omega_f) \sin \omega_f t$ (neglecting any integration constant which introduces a constant delay but no frequency distortion). From FM theory, the modulating index m = $\omega_s a_f / \omega_f = a_f f_s / f_f$ = flutter magnitude (as a fraction) times the ratio of signal to flutter frequency; the value of m could vary widely depending upon the transport and signal parameters.

For instance, assuming a transport with a 10-cps flutter component which has a peak value of 0.05 percent, then $m = f_s x\ 5 \times 10^{-4}$. Figure 10(a) and (b) illustrate the distribution of sidebands for f_s = 2 kc and 100 kc respectively. Notice that the ‘frequency smearing’ effect becomes more pronounced at higher signal frequencies and the band spread is close to $2(a_f f_s + f_f)$, which increases linearly with the signal frequency.

By investigating various combinations of signal frequency, and flutter amplitude and rate, some general conclusions may be drawn as follows:

1. The modulating index is directly proportional to signal frequency. For a given transport, higher frequency signals would tend to spread out more than lower frequency signals; although in terms of percentage of the carrier the spread is about the same.

2. m is proportional to a_f/f_f which is 2π times the TBE. Therefore, large TBE is objectionable. As mentioned earlier, low rate flutter components generally contribute large TBE and are primarily responsible for the frequency smearing effect; high frequency flutter components, unless excessively large, would normally cause no frequency smearing, although they do generate some small sidebands.

3. For multi-tone flutter there are various terms of sum and difference frequencies in addition to the various sidebands associated with each flutter component. Nevertheless, the effective frequency spreading is not appreciably different from that of the single tone cases.

4. A conventional flutter specification such as cumulative peak value over a given bandwidth offers very little information about the effect of various flutter components on a recorded signal. A flutter analysis is necessary to understand the distortion of various signal frequencies more thoroughly.

When the TBE (or flutter) is a random function, the sideband spectrum is no longer composed of discrete lines; instead, it becomes continuous. This can be demonstrated for a single sinewave of frequency f_s; the resultant power density spectrum due to random TBE is of the form as shown in Figure 11, where part of the signal power is converted into random noise in the frequency domain.

The ratio of the net signal power to the total random noise power may be used as a criterion for measuring TBE (or flutter). For TBE with a Gaussian amplitude distribution this ratio is

$$\left(\frac{S}{N}\right)_p \sim \frac{1}{\sigma_T^2 \; \omega_s^2} \tag{14}$$

where σ_T is the rms TBE and $\omega_s = 2\pi f_s$. For random flutter with a rectangular power density spectrum, from Equation (6), $\sigma_T^2 = \frac{\sigma_F^2}{f_1 f_2}$

$$\left(\frac{S}{N}\right)_p \sim \frac{1}{4\pi^2} \quad \frac{f_1 f_2}{\sigma_F^2 \, f_s^2} \tag{15}$$

Substituting some typical figures in Equation (15), say $f_1 = 100$ cps, $f_2 = 10$ kc, $\sigma_F^2 = 10^{-7}$ (corresponding to 0.2 percent peak-to-peak flutter), then

$$\left(\frac{S}{N}\right)_p \sim \frac{0.25 \times 10^{12}}{f_s^2}$$

When f_s = 500 kc, $(S/N)_p = 1$, which means that 50 percent of the signal power is converted into incoherent sidebands. This illustrates how critically a wideband recorder is affected by random flutter.

It should be mentioned here that the noise term is defined in the frequency domain; in the time domain, the signal primarily exhibits jittering of zero-crossover points and perhaps some amplitude fluctuation. This frequency distortion caused by flutter (or TBE) may completely jeopardize the high frequency performance of a wideband recorder.

Effect of TBE on FM Recording Consider an FM signal being recorded on tape,

$$e_i(t) = \sin\left(\omega_c t + \frac{\Delta f_c}{f_s} \sin \omega_s t\right)$$

where $\omega_c = 2\pi f_c$ = carrier frequency, f_s = signal frequency, Δf_c = frequency deviation, and m = modulating index = $\Delta f_c/f_s$. Due to TBE introduced in the record-reproduce process, the output becomes

$$e_o(t) = \sin\left\{\omega_c \left[t + h(t)\right] + \frac{\Delta f_c}{f_s} \sin \omega_s \left[t + h(t)\right]\right\} \quad (16)$$

$$\text{instantaneous frequency} = \omega_c + \omega_c \frac{dh(t)}{dt} + 2\pi \Delta f_c \left(1 + \frac{dh}{dt}\right) \cos \omega_s \left[t + h(t)\right]$$

$$\text{demodulated output} = \frac{\Delta f_c}{f_c} \cos \omega_s \left[t + h(t)\right] + \frac{dh(t)}{dt}\left[1 + \frac{\Delta f_c}{f_c} \cos \omega_s (t + h)\right] \quad (17)$$

The first term in Equation (17) represents the desired output, which has suffered the same type of time base distortion as in direct recording, and the second term is generally referred to as the flutter noise in FM recording because dh/dt = F(t), which is the flutter. The exact expression of the demodulated signal may vary depending upon the degree of approximation being made[2]. However, it is felt that Equation (17) is quite adequate for our investigation.

The signal-to-noise ratio of an FM system can be calculated from the last equation. For wideband FM, $\Delta f_c / f_c$ may be as high as 0.4, and the noise term has a maximum value of 1.4 times the flutter. Assuming a typical flutter of 0.1 percent (peak value) the signal-to-noise ratio is about 49 db. For narrowband FM, where $\Delta f_c / f_c = 0.075$ approximately, signal-to-noise ratio is about 37 db and deteriorates rather fast.

Methods for flutter noise compensation in FM recording are well known. The instantaneous flutter is recovered by demodulating a pilot signal which has been recorded and reproduced in synchronism with the data. This flutter signal may be subtracted from the data to render a better signal-to-noise ratio. Or, in case a pulse averaging type of demodulator is used, the flutter signal is used to control the pulse width before averaging.

It should be emphasized that this type of flutter compensation in FM recording tends to correct only the additive noise which is the second term in Equation (17); it does not solve the TBE problem, which is still involved in the first term of the equation. Depending upon the signal bandwidth and system requirement, this time base distortion may or may not be serious.

Interchannel Time Base Error (ITBE) By definition, ITBE is the time error between a reference data channel and another channel of a multi-channel recorder. The measuring technique is very similar to that of TBE except for the difference in choosing the reference signal.

A typical spectral distribution of the variable ITBE (dynamic skew) is shown in Figure 12; static skew merely represents a constant delay which can be compensated quite readily. Dynamic skew is primarily random in nature, except at the low frequency end where some once-around components exist. The spectral envelop appears to follow a 6-db-per-octave slope, and the high frequency end terminates at a few hundred cps.

The major cause of dynamic skew appears to be the shearing force across the width of the tape which causes the two channels to move in opposite directions in terms of timing error. The amount of ITBE is almost directly proportional to the separation between the two channels (assumed to be on the same head stack). To verify this statement, some experimental measurements were made according to the block diagram shown in Figure 13. The center channel B was used as reference and the ITBE of channel A and C, one on each side, was observed as shown in Figure 14. Notice that A/B and C/B are practically opposite in phase, and the sum of these time errors is almost zero. This situation holds true for 1/2-inch tape and it is still a good approximation for 1-inch tape. Therefore, one may conclude that the ITBE is largely correlated among all channels, although the amplitudes may vary randomly.

ITBE is important in certain applications such as correlation analyses, diversity combining, and redundant recording. For a given amount of ITBE and a maximum tolerable phase error between two channels, the highest usable frequency (upper limit of the signal bandwidth) can be calculated quite easily; or, for a known signal bandwidth, the process may be reversed to determine the maximum allowable ITBE.

Statistical Evaluation of Flutter and Time Errors The residual flutter and TBE of an instrumentation recorder with a reasonably good servo system are largely random in nature because the coherent periodic components are practically eliminated. Therefore, it becomes rather inadequate to specify the magnitude of time function with a randomly fluctuating amplitude, such as flutter or TBE, by single number. A peak-to-peak value would definitely involve a certain amount of arbitrary decision on the part of an observer. Alternately, specifying the rms value alone would not determine the peak (crest) factor without some knowledge of the probability distribution.

Gaussian distribution is generally used to approximate that of a random variable containing many uncorrelated sinusoidal components. To substantiate this assumption, a probability density analyzer was used to analyze the flutter and TBE; results are shown in Figures 15 and 16. In general, these probability density distributions closely follow the Gaussian model in the region of concern; hence, the latter may be used with fairly good accuracy for specifying random flutter and TBE. For instance, the 3-σ level may be used in place of a peak-to-peak value, and the probability of this being correct is well over 99.5 percent; while the 2-σ level would yield a probability of about 95 percent.

The value of a can be calculated f rom the spectral distribution; however, it can be measured directly by using an rms meter with a high crest factor. The ± 3-σ level simply means six times the rms reading. This has been confirmed experimentally by observing the waveform of a random function and estimating the probability, which came very close to that of the Gaussian model, at the 3-σ level. Hence, this procedure should be good enough for all practical purposes, and it is not only simple but more meaningful than the conventional peak-to-peak value.

Generally speaking, once the random nature of flutter and TBE is verified and accepted, it becomes quite obvious that all the standard tools of statistics and probability can be applied to a tape recorder in dealing with problems associated with tape dynamics and signal distortion.

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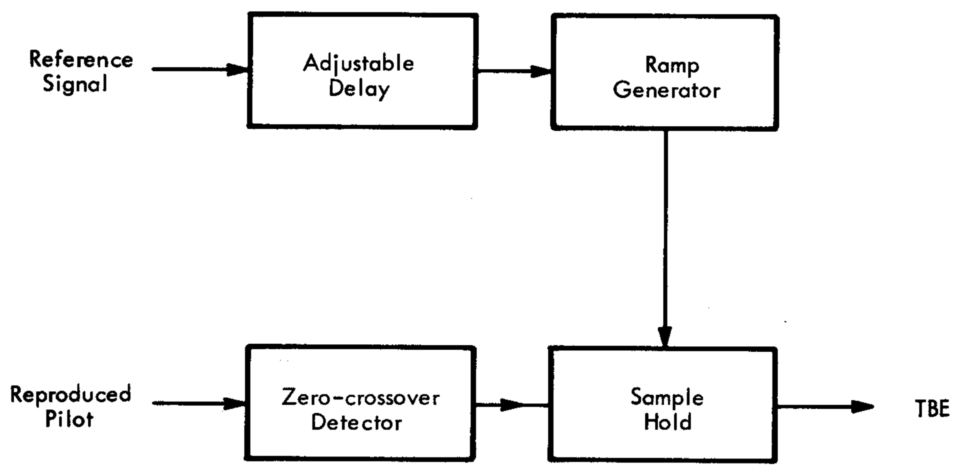


Fig. 1- Block Diagram for TBE Measurement

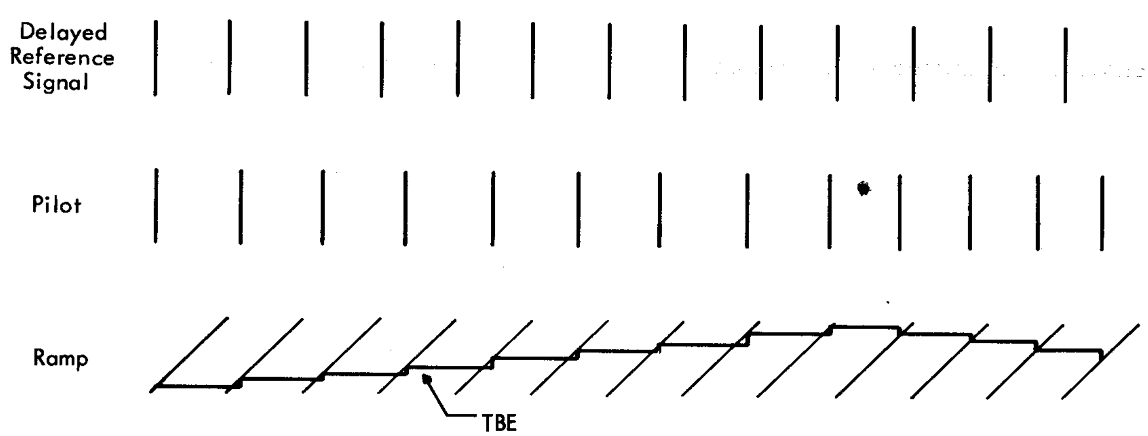


Fig. 2- Signal Sequence Diagram for TBE Measurement

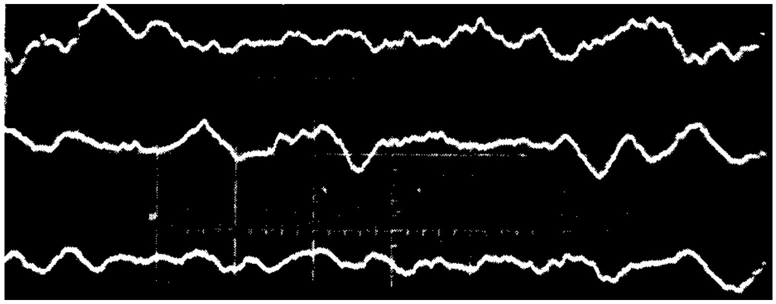


Fig. 3- Typical TBE Signal

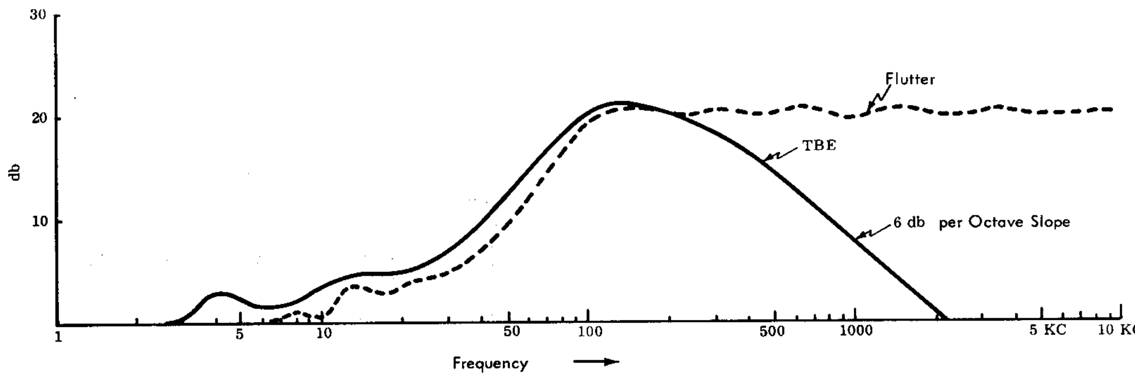


Fig. 4- Comparison of Flutter and TBE Spectrum

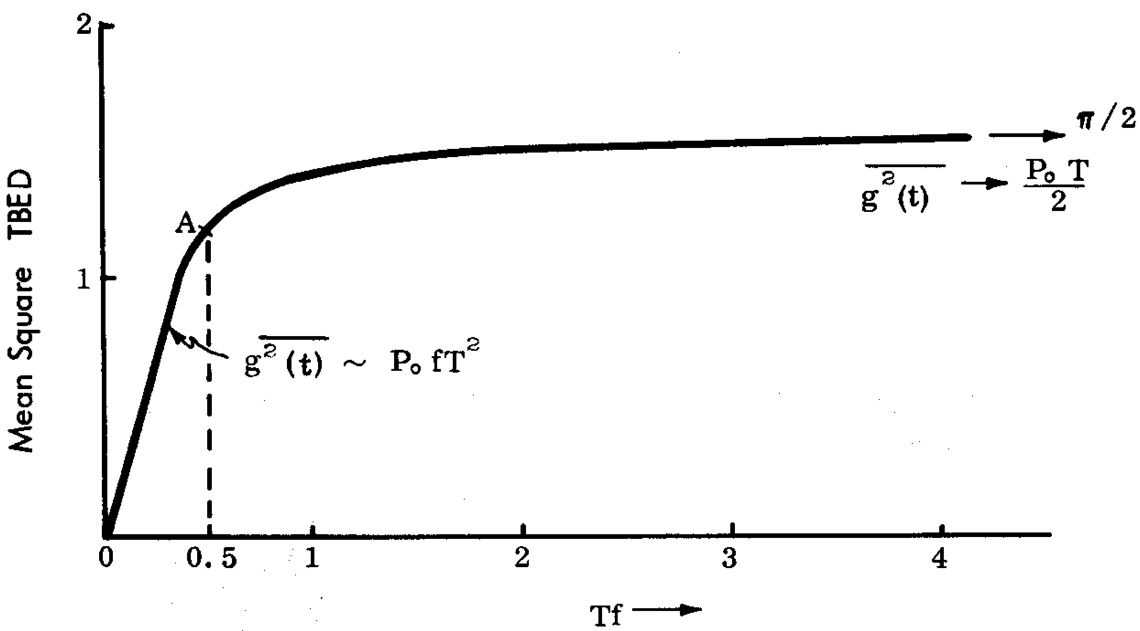


Fig. 5- Mean Square TBE versus Flutter Rate

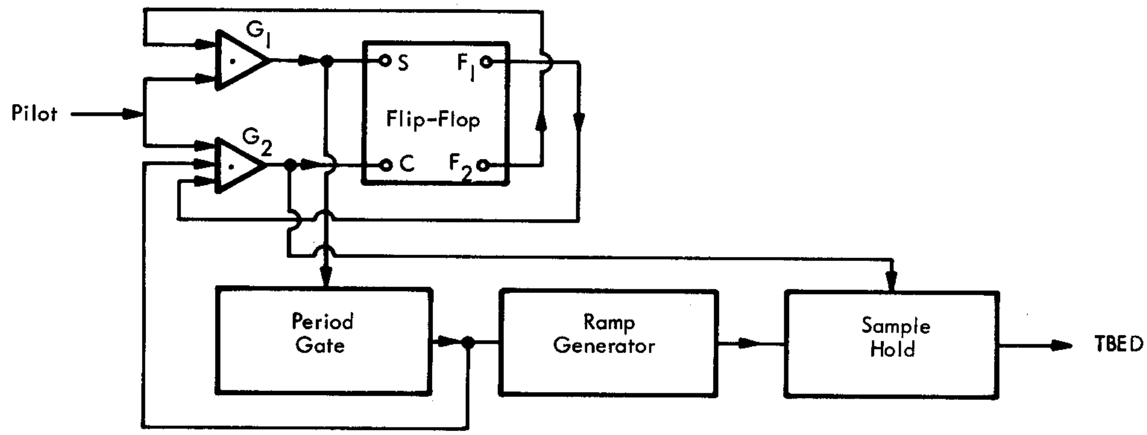


Fig. 6- Block Diagram for TBED Measurement

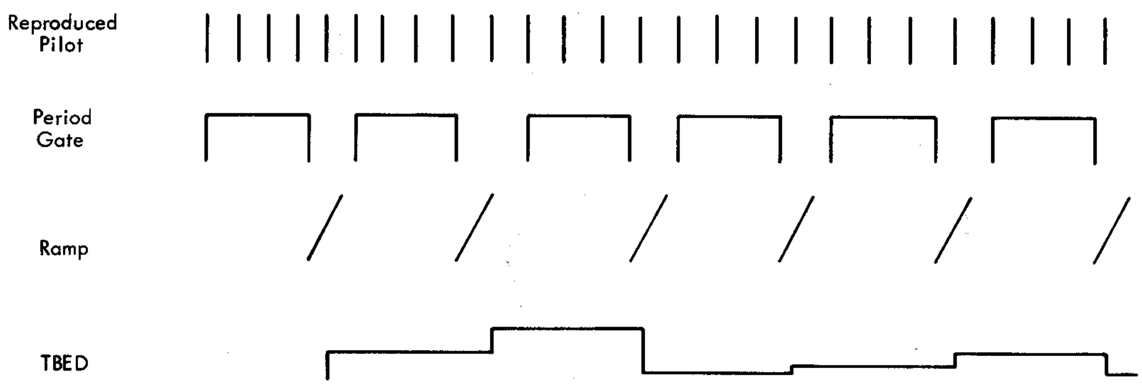
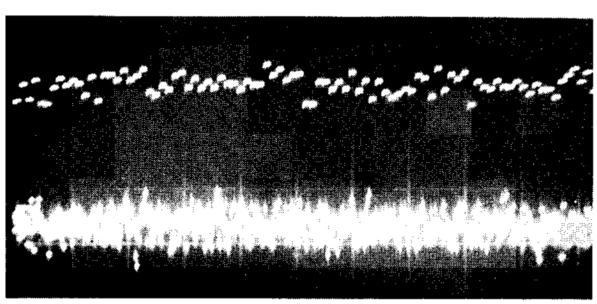


Fig. 7- Simplified Signal Sequence Diagram for TBED Measurement



Sample Period 100 μsec
Vertical 100 nsec/cm

Horizontal 1 msec/cm

Horizontal 10 msec/cm

Tape Speed 60 ips

Fig. 8- Typical TBED

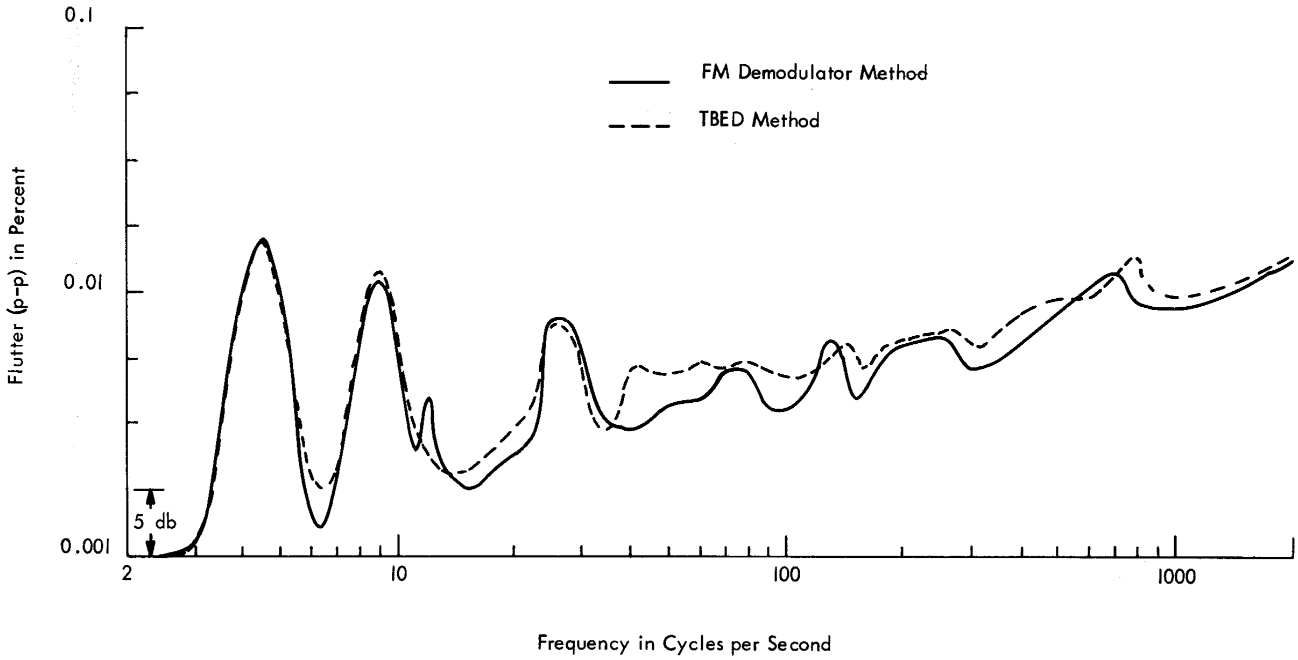


Fig. 9- Flutter and TBED Spectral Analysis

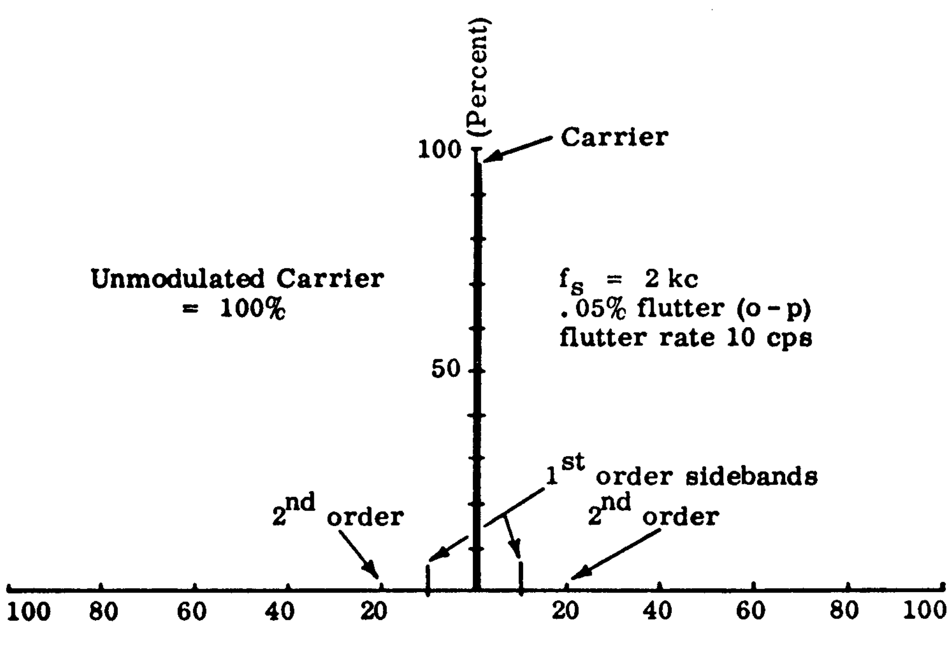
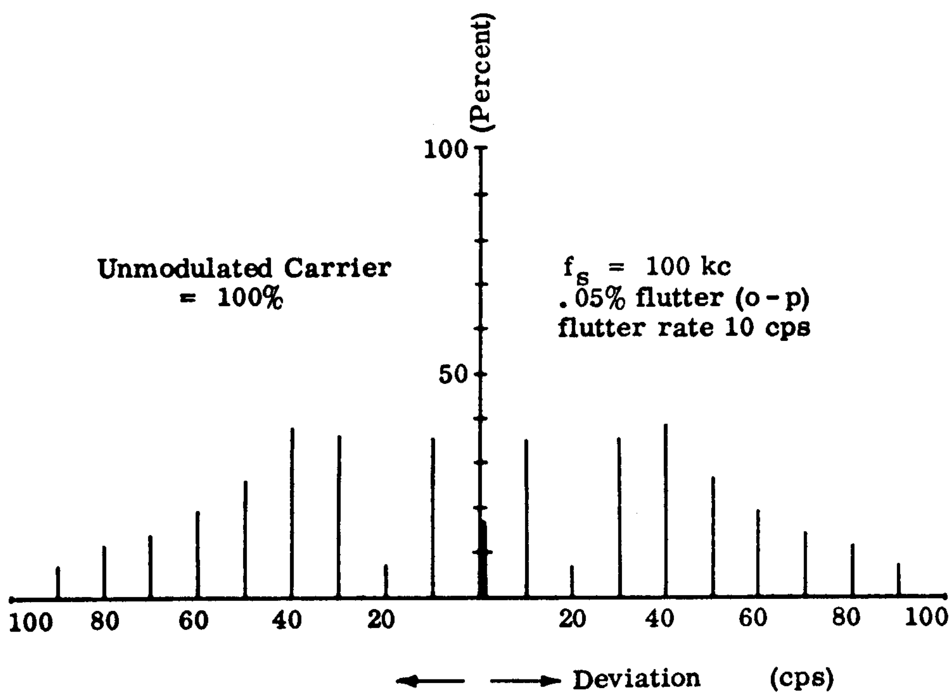


Fig. 10a- Frequency Spectrum of a 2-kc Signal



(b) Frequency Spectrum of a 100-kc Signal

Fig. 10b- Frequency Spectrum of a 100-kc Signal

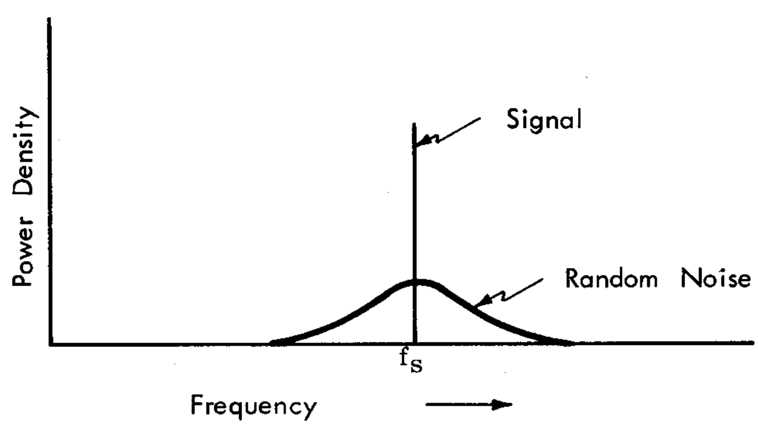


Fig. 11- Power Density Spectrum of a Single Sinewave Due to Random TBE

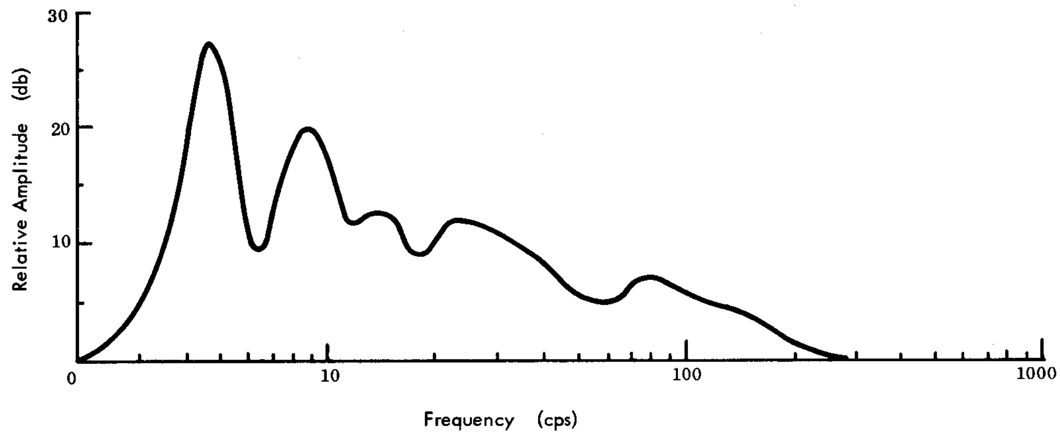


Fig. 12- Typical Spectral Distribution of Variable ITBE

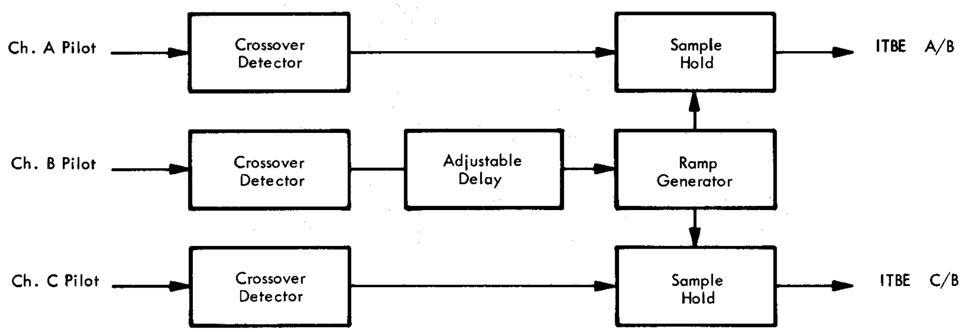


Fig. 13- Block Diagram for ITBE Measurement

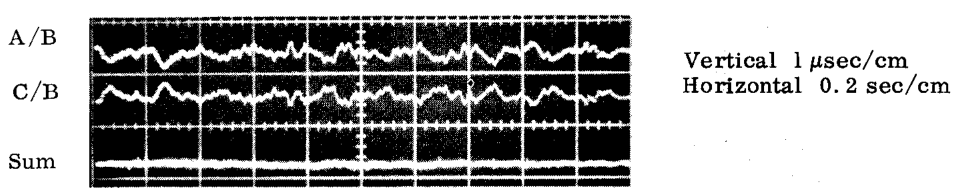


Fig. 14- Typical ITBE

Horizontal Scale ± 5 Sigma

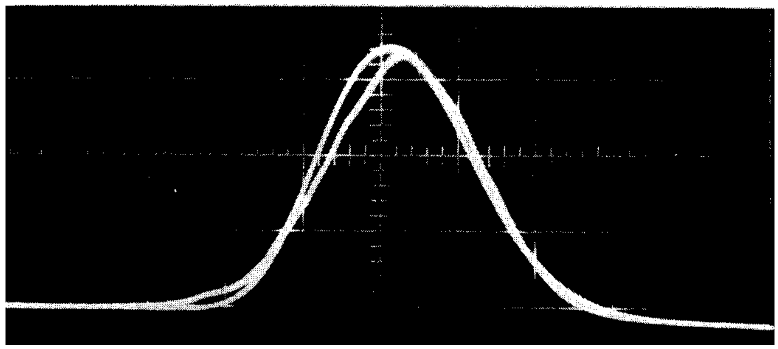


Fig. 15- Probability Density of Flutter versus Gaussian Distribution

Horizontal Scale ± 5 Sigma

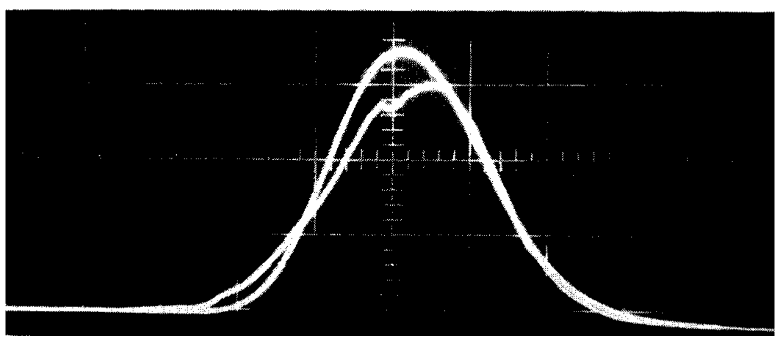


Fig. 16- Probability Density of TBE versus Gaussian Distribution