THE EFFECTS, MEASUREMENT, AND ANALYSIS OF FLUTTER IN INSTRUMENTATION RECORDERS

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Summary As instrumentation recorders are improved to provide wider bandwidths and shorter recorded wavelengths, the effects of flutter and attendant time base distortion severely limit the potential for accurate recording and retrival of data. The effects of flutter on typical classes of data is given and the measures necessary to determine flutter with high accuracy shown. Since the degrading effects of flutter depend upon the application and the characteristics of the flutter, means of analyzing flutter both in the time domain and in the frequency domain are necessary. A self contained instrument for accurate measurment and analysis of flutter sensitive enough for the most sophisticated transports is described, as are necessary conditions for its use.

Introduction The detrimental effects of flutter depends upon the characteristics of the flutter, the mode of recording, and the nature of the data being recorded, as well as the accuracy being attempted. To determine the suitability of a transport for a specific application it is necessary to accurately evaluate its flutter performance.

When attempting to record data which cannot be duplicated, at least without great expense, such as is typical of space experiments, it is essential that tests of the recording system be made immediately before the event. To make such testing practical, an instrument of known accuracy and adequate sensitivity must be used. Such a flutter meter should lend itself to rapid testing and should not require an engineer or highly trained specialist to interpret its reports.

Maintenance of acceptable performance of tape transports is facilitated if the flutter meter can quickly show the frequency spectrum of the flutter. Instead of depending upon a specialist's art, a rational approach to the causes of malfunctions is possible.

Description of Flutter Fourier components of the flutter may be represented by

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

where the a_n's are expressed as a fraction of nominal velocity.[1] Time Base Error (TBE) is

$$h(t) = \sum_{1}^{n} \int_{0}^{t} F(t)dt \quad = \sum_{1}^{n} \frac{a_n}{\omega_n} \sin(\omega_n t + \theta_n) \tag{2}$$

Equation (2) shows that the contribution to TBE is inversely proportional to flutter rate. Figure 1 shows typical flutter spectra for a modern open-loop transport and for an elaborate positional servo transport. The rising response with frequency is the resultof using a constant 10% bandwidth analyzer for the measurment. Uniform flutter power density as a function of frequency would lead to a 3dB/octave rise in output amplitude with frequency.

The flutter plots show components caused by the capstan and bearings, as well as line related perturbations from the motors. At frequencies above 150 - 300 Hz, the flutter in uniform and noise-like until the prominent “scrape” component is reached. This frequency is determined by the length of unsupported tape in contact with the head; the amplitude by the surface properties of the tape and the efficacy of scrape idlers in absorbing the energy of the resonant section of tape.

Direct Recording The effects of flutter on direct recording are to introduce a TBE in the events recorded and to smear out the frequencies of the recorded signal.[2] The smearing comes from converting part of the recorded signal power into side bands about the original frequencies in the recorded signal.

FM Recording When a signal

$$e_i(t) = \sin\left(\omega_c t + \frac{\Delta f_c}{f_s} \sin \omega_s t\right) \tag{3}$$

is recorded on tape and reproduced with added flutter, the demodulated output

$$e_o = \frac{\Delta f_c}{f_c} \cos \omega_s \left[t + h(t)\right] + \frac{dh(t)}{dt} \left[1 + \frac{\Delta f_c}{f_c} \cos \omega_s (t + h) \right] \tag{4}$$

[1] S. C. Chao, “Flutter and Time Errors in Instrumentation Magnetic Recorders,” IEEE Transactions on Aerospace and Electronic Systems, vol AES-2, No. 2, pp 214-223; March, 1966.

[2] ibid.

The first term of (4) represents the desired output, contaminated by the same time-base distortion that would occur in direct recording. The second term is the noise in the demodulated output caused by flutter $\left(\frac{dh(t)}{dt} = \text{Flutter}\right)$. The signal-to-noise ratio for an FM system can be determined from (4) if the flutter is accurately known. In wide band FM systems where $\frac{\Delta f_c}{f_c} = 40\%$, and with an instrument with .3% peak-to-peak flutter with an approximately random distribution, measured to 2σ limits, the rms signal to noise ratio is $\frac{4}{\sqrt{2}} \cdot \frac{.4}{\sim 1 \times 3 \times 10^{-3}} = 377 = 51.5\text{dB}$. (rms signal = $\frac{.4}{\sqrt{2}}$ peak; rms flutter = $\frac{1}{4}$ 2σ peak-to-peak). A narrow band FM system where $\frac{\Delta f_c}{f_c} = 7.5\%$, and with the same flutter as above, the new signal to noise ratio will be $\frac{4}{\sqrt{2}} \cdot \frac{.075}{\sim 1 \times 3 \times 10^{-3}} = 70.7 = 37\text{dB}$. In the above examples, if the flutter is predominantly a single sinusoid, the signal-to-noise will be 3dB lower, i.e. the noise higher in the ratio of the rms value of a p-p sinewave to the rms value of 2σ p-p Gaussian wave: $\frac{4}{2\sqrt{2}}$. Note that if an average responding meter is used to measure noise with a Gaussian distribution it will indicate a value ≈ 1dB low, but because of calibration will correctly report the value of a sine wave.

The usual methods of flutter correction derived from a demodulated pilot signal recorded and reproduced in synchronism with the data can be used to improve the S/N ratio of the FM data but will not affect the TBE. Wide tapes also exhibit inter-channel TBE due to dynamic tape skew which limits the degree of flutter compensation possible unless a pilot signal is used for each track

Measuring Flutter with high accuracy Tc measure flutter a test signal is recorded on tape, rewound, and the FM of the test signal caused by the transport speed variation is measured by the Flutter Meter. Figure 2 is a block diagram of a Flutter Meter. The test signal is provided by a crystal controlled oscillator which puts out a low distortion sine wave with exceptionally low phase jitter and noise. When measuring very low values of flutter, precision demands the highest possible signal-to-noise ratio from the recorded tape. At first thought, it might seem best to saturate the tape with a square wave test signal to obtain the highest level possible from the tape. However, such a procedure does not lead to the best signal-to-noise ratio from the tape, because beats between higher harmonics of the test frequency and bias signal will lead to spurious components within the flutter band due to intermodulation within the non-linear tape oxide. Figure 3 shows a typical noise spectrum of an instrumentation recorder. Note the high noise components at the low and high ends of the response spectrum. An input bandpass filter as allowed by IRIG Document 106-66 contributes to the ease of measurments with most recorders, since noise components and disturbances outside the frequency band necessary for the measurment are rejected.

To illustrate the effect of signal-to-noise on measuring low values of flutter, consider a typical case where:

Test Frequency = 108 kHz
Flutter Bandwidth = 10 kHz
and S/N = 40dB in a ± 10 kHz band centered at 108 kHz.

For an FM demodulator,[3]

$$E_o = \frac{1}{\sqrt{2}} \left(\frac{N_i}{S_i}\right) \frac{K}{\sqrt{3}} \text{ fm} \qquad (5)$$

where N = noise input, S = peak signal input, K = demodulator slope, and fm = Flutter bandwidth. For convenience, use the 0.3% range of the MICOM 8300 Flutter Meter. The demodulator output = 100 mV for 0.3% frequency deviation, hence $K = \frac{10^{-1}}{3 \times 10^{-3} \times 1.08 \times 10^{5}} = 3.08 \times 10^{-4}$ V/Hz, then $E_o = \frac{1 \times 10^{-2}}{\sqrt{2}\ \sqrt{3}} \times 3.08 \times 10^{-4} \times 10^{4} = 12.6$ mV rms. The peak-to-peak output will be 4 x the rms output when measured to 2σ limits (95% of the time). The 2σ flutter reading will therefore be $\frac{50.4}{100} \times 0.3\% = 0.15\%$. This noise output will be added to any flutter present. The example illustrates the need to record the test signal on high quality, carefully erased, tape at the highest level which does not degrade the signal-to-noise ratio. It also shows the importance of choosing the optimum test frequency for the transport involved. Unless the noise output, including modulation noise, of the transport increases more than 6dB/octave, the highest test frequency available should be used. The above example assumed an ideal demodulator and ideal input filter. Real bandpass filters will have some envelope delay across the pass-band and will therefore convert amplitude variations in the recorded output into FM, as will demodulators with insufficient or unsymmetrical limiting.

Even the best of tape has occasional drop-outs and some modulation noise, therefore exceptionally effective limiters must be used to measure low values of flutter. The usual 40 to 60dB of limiting found in conventional FM demodulators is not adequate to measure 0.1% peak-to-peak flutter over a 10 to 20kHz bandwidth with high accuracy. IRIG document 106-66 considers this problem by calling for a discriminator which has an output noise caused by 30% amplitude modulation of the reference carrier by any single frequency from DC up to the flutter upper band limit of less than 10% p-p of the peak-to-peak specification flutter signal. If the discriminator used does not meet this performance, it is permissible to subtract the noise output due to 30% amplitude modulation found above from the flutter measurments. Up to 25% of the flutter specification may be subtracted on this basis.

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[3] Phillip F. Painter, “Modulation, Noise, and Spectral Analysis”, McGraw-Hill Book Company, New York, N.Y., pp 431-436; 1965.

For a realistic evaluation of flutter, a correction of this magnitude is excessive, and will permit acceptance of transports with out-of-tolerance flutter. The modulation noise on good quality tape does not even approximate 30% amplitude modulation at, say 10kHz. The amplitude modulation on tape is noise-like in its distribution and has its largest amplitude at relatively low frequencies. Spurious demodulator outputs from this kind of amplitude variation can be made very low with adequate phase control of the band-pass filters and adequate symmetrical limiting in the demodulator. There is a real difficulty in even testing a demodulator designed to measure 0.3% peak-to-peak flutter to 1OkHz. There are very few modulators available that will provide 30% amplitude modulation of a 100kHz carrier at a 10kHz rate with less than .03% spurious FM of the modulated signal. A more realistic specification of demodulator AM rejection would involve an appropriate amplitude modulation of the test signal by a noise-like waveform with a 1/f frequency spectrum up to the upper bandlimit of the flutter measurment.

Since the flutter spectrum on wide-band systems may extend beyond 10kHz, accurate and comparable measurments require that the frequency response of the demodulator, low pass filters be carefully controlled. Figure 1 shows typical flutter spectra for transports of better performance. Plot A is from an open loop transport, plot B typical of a large positional servo controlled machine. In these cases, there is a large component of “scrape” flutter at around 6kHz and 12kHz respectively. The frequency and amplitude of this component is largely dependent on the length of unsupported tape across the heads.

IRIG 106-66 prescribes flutter bandwidths for each tape speed and center frequency. Generally, the flutter bandwidth, described is 1/2 the information bandwidth, up to 10kHz. On the most sophisticated transports, a very significant portion of the flutter may be above 10kHz, although there is no evidence that substantial amounts are present beyond 20kHz: above 20kHz mechanical disturbances are low in amplitude and the FM approaches the noise level due to the tape. IRIG 106-66 allows the low pass flutter bandwidth filter to have either a flat frequency response 3dB down at the band-edge or a Gaussian frequency re’sponse 6dB down at the upper band edge. Figure 4 shows the flat response used in a commercial flutter meter and a comparable mini-mum-phase filter with an approximately Gaussian response. Although the Gaussian filter will have greatly superior transient response, it does not lend itself to accurate measurment of cumulative wideband flutter from typical transports. Reference to Figure 1 shows that the “scrape” components of flutter will be greatly attenuated by a Gaussian filter.

Analysis of Flutter Flutter, which approaches a noise-like character as transports are improved, but which has substantial sinusoidal components in openloop or malfunctioning machines, may be usefully analyzed either in the frequency domain or statistically in amplitude distribution. IRIG Document 106-66 requires that cumulative flutter be reported on a peak-to-peak basis with random peaks occuring less than 5% of the time excluded (2σ limits). The document recommends photographing an oscillographic display over a 10 second period. Because of the minimum spot size of an oscilloscope trace, it is not possible to determine the peaks occuring 95% of the time for ordinary flutter rates using this method. Figure 13 of 106-66 describes a digital go-no go method of determining whether a transport is within a specified limit of peak-to-peak flutter 95% of the time over a 10 second period. Certain types of flutter which would be intolerable in actual use are not necessarily revealed with the digital setup. For example, a deformed reel that causes very large bursts of flutter lasting 0.1 second every 3 seconds would be ignored.

By using a statistical peak-to-peak reading voltmeter, anunambiguous meter indication of the flutter is made. The meter time constants are such that the meter will track changing amplitudes or statistics of the flutter while providing a precise indication of the peak-to-peak amplitude of the flutter 95% of the time in its 2σ position. Further analysis of the amplitude distribution may be made by reading peak-to-peak to a 2σ reading and a 3σ reading. If the flutter has a Gaussian distribution or is made of many small sinusoidal components as would be expected from an ideal transport, the flutter readings would be in the ratio of 1:2:3 for 1σ, 2σ, and 3σ respectively.

Readings that do not differ greatly between 1σ and 2σ but that are much larger at 3σ are indicative of recurring short spikes of flutter and are a warning of possible mechanical trouble.

Frequency analysis of flutter is provided for in the MICOM 8300-W Flutter Meter. A wave analyzer with a 10% 3dB, passband permits separating flutter components over the frequency range of 1/2Hz to 20kHz. The spectra illustrated in Figure are typical of properly functioning recorders. One can identify the components caused by the capstan, line related disturbances due to the motors, as well as “scrape” frequencies near the upper end of the flutter band.

The wave analyzer is an invaluable time-saver in determining the cause of excessive flutter in transports with trouble. Most mechanically induced speed variations are caused by once-around effects of rotating members. For each tape speed of a given transport there is usually a 1:1 correspondence between the rotating speed of the member and the frequency of the flutter it causes. Once the frequency of the flutter is known, most common causes are readily identified. When trouble-shooting an unfamiliar transport, time can be saved in localizing malfunctioning parts by triggering a hand-held stroboscope with the output of the Wave Analyzer timed to a specific flutter component. The offending component can oftenbe identified visually because of its synchronism with the flashing lamp.

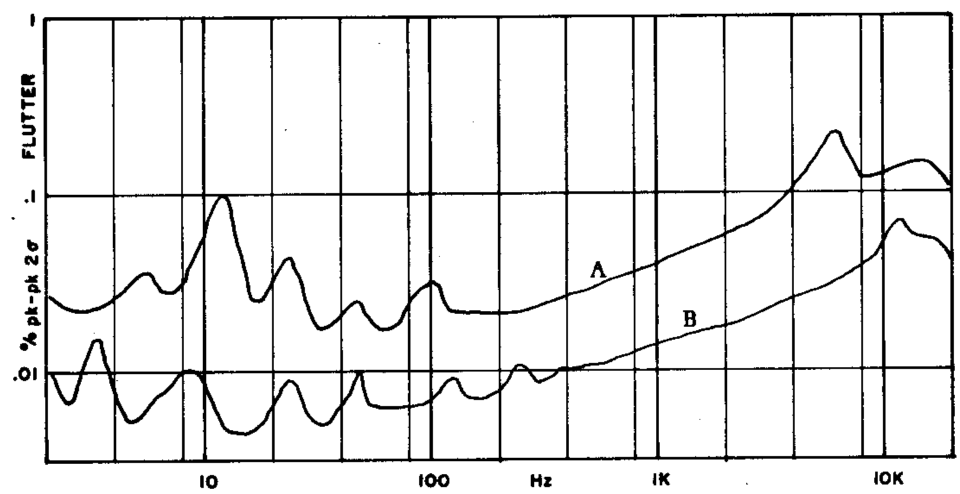

Fig. 1 - Typical flutter spectra. A - open loop transport, B - transport with positional servo.

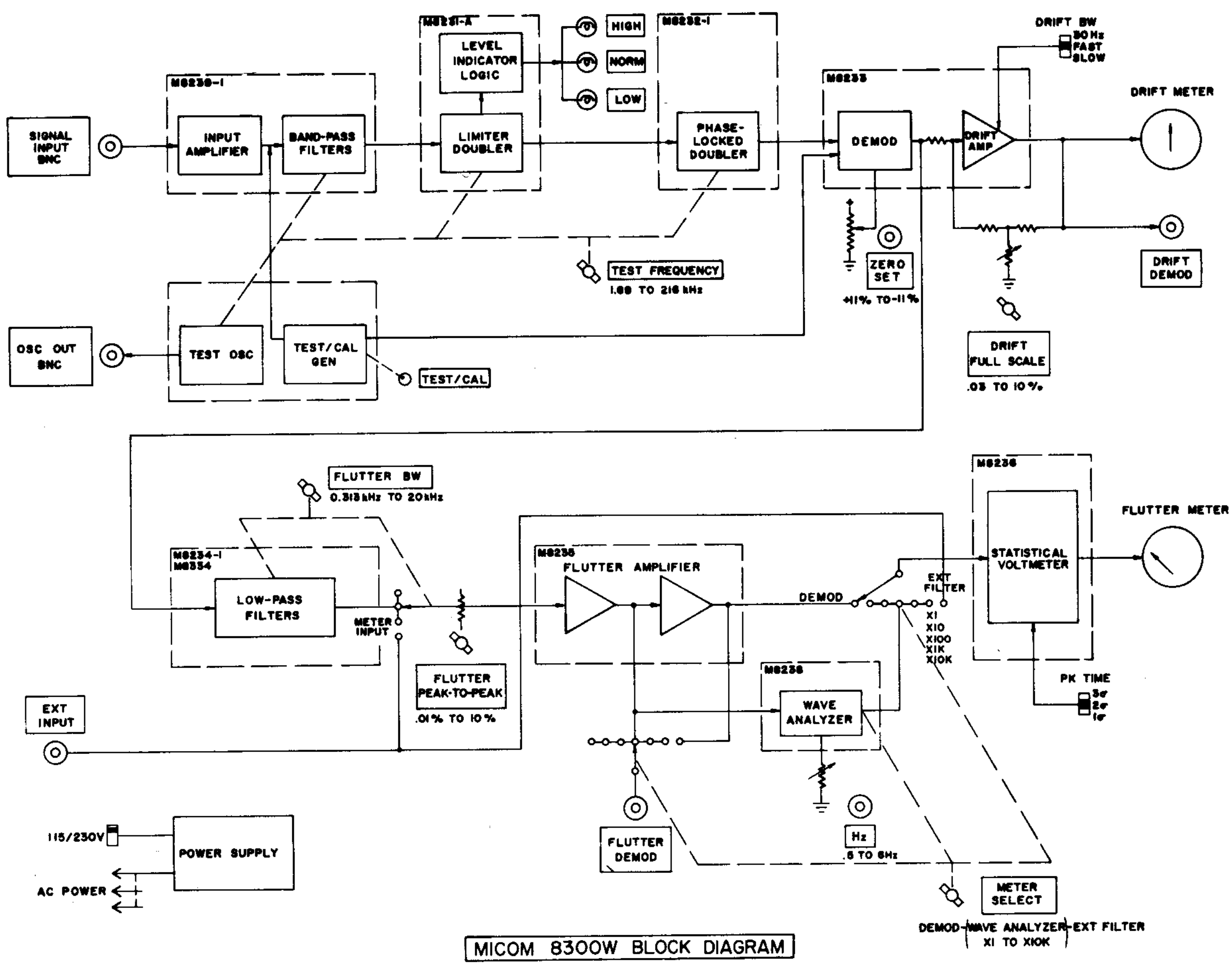

Fig. 2 - Flutter meter block diagram.

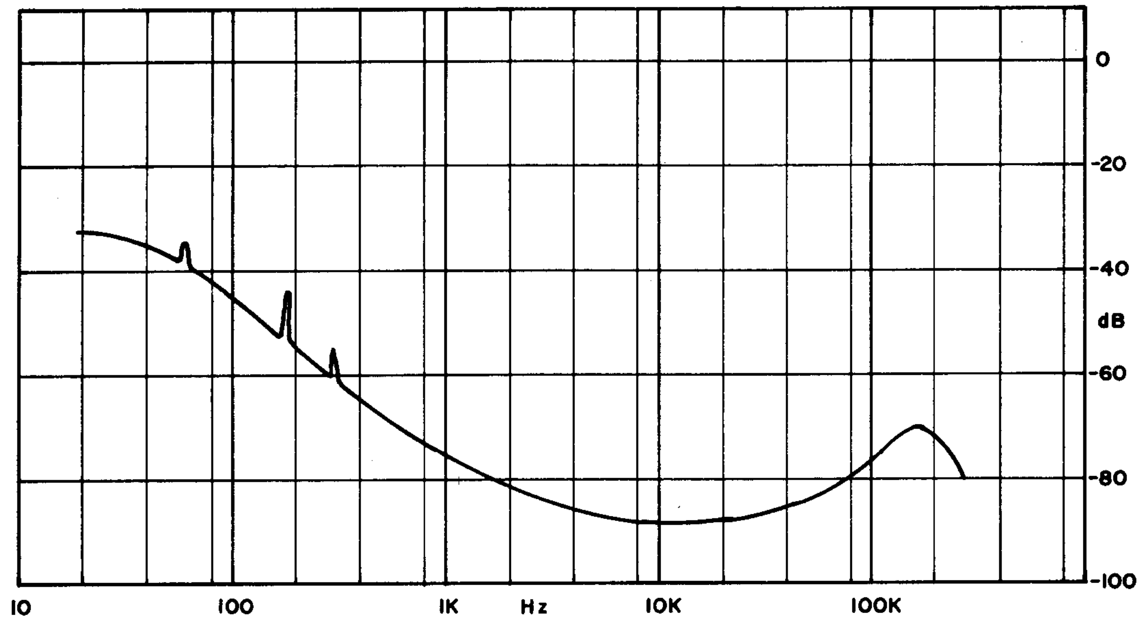

Fig. 3 - Typical reproduced noise spectrum. Noise measured in 10 Hz band, referred to normal reproduce level.

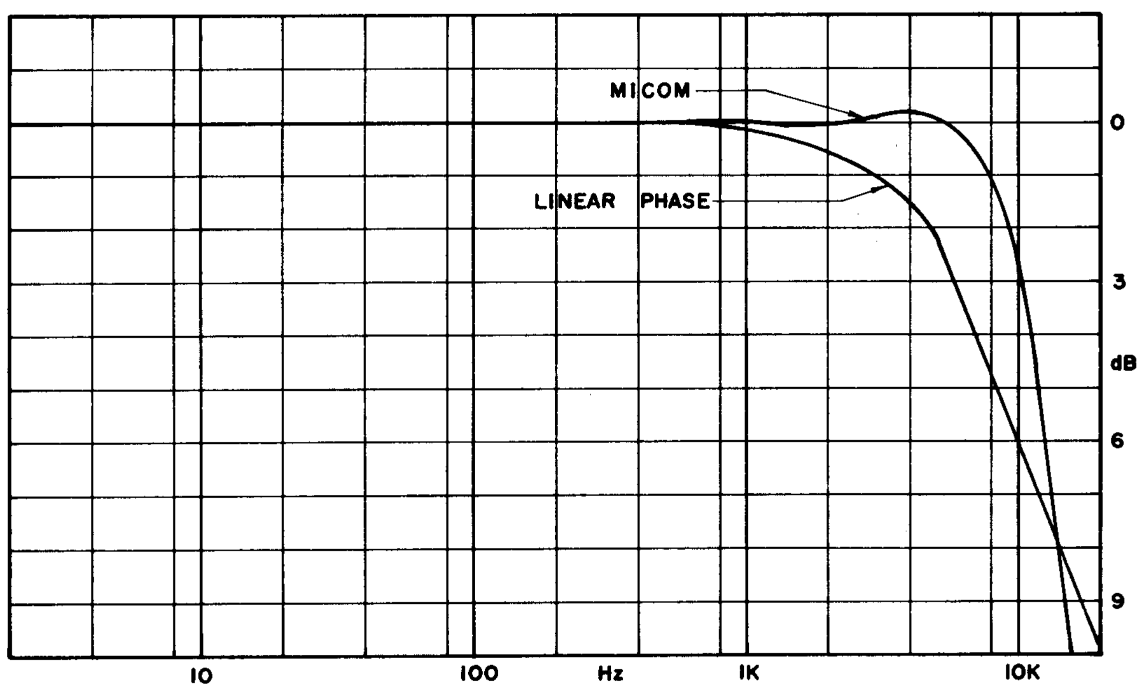

Fig. 4 - Low pass response of flutter bandwidth filters.