

# **EFFECTS OF TAPE FLUTTER ON NOTCH NOISE LOADING TEST PERFORMANCE OF PREDETECTION RECORDING OF A FREQUENCY MODULATED CARRIER**

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**Summary** IRIG Document #L18-71 "Test Methods for Telemetry Systems and Subsystems" lists the notch noise loading test for establishing a figure-of-merit for frequency division systems. This paper reports measured effects of tape flutter on notch noise test data on pre-detection tape recorded FM carriers. The effects are explained on the basis of spectra of the output of the FM demodulator. The principal effect is to reduce the measured noise power ratio, NPR, in those notches at the low end of the baseband which overlap the flutter spectrum. The effect of tape flutter on FM/FM systems is reviewed.

**Summary of Test Data** Table I presents NPR data with a 12-108 kHz baseband frequency modulated on a 450 kHz carrier and pre-detection tape recorded/reproduced. Two tape machines were used to illustrate the flutter effect. Machine A is specially designed to reduce flutter and was just put into service and machine B has been in use for five years. The Marconi notch noise test equipment was used to generate the test signal. For the machine B test, the DCS model GSO-1 vco was used to generate the frequency modulated carrier at 450 kHz. The EMR 4142 tuneable discriminator set for  $\pm 40\%$  bandwidth was used. The "back-to-back" NPR data give the performance of the combination without the tape recorder/reproducer. For machine A test, the internal FM discriminator was used in conjunction with the DCS vco so back-to-back data were not obtained. It may be presumed that back-to-back performance of this combination is comparable to, or perhaps better than, the DCS/EMR combination. Both machines were set up in accordance with IRIG standards.

Referring to Table I, note that for the 14 kHz notch, the NPRO, which is the noise power ratio with the carrier modulation removed <sup>(1)</sup>, is 6 db higher for machine A than for machine B. The NPRO is a measure of the additive baseband noise since with no modulation there can be no intermodulation. Thus there is more additive noise at the low

end of the baseband with machine B then with machine A. Figures 1 and 2 are spectra of the output of the carrier discriminators of the two machines. The lower trace is without carrier modulation and the upper trace is with modulation by the notch noise test signal. The upper trace is displaced 10 db upward (except as noted) to keep the traces from overlapping. The Hewlett-Packard Model 141T/8556A/8552B spectrum analyzer was used for these photographs. The trace without the modulation is the flutter spectrum. Thus the flutter spectrum is added onto the modulation spectrum in the discriminator output. As will be seen in the following section, there is also a spreading effect on the modulation spectrum but the sensitivity is not great enough to show in the spectra of Figures 1 and 2.

Since the flutter spectrum dies off with increasing frequency, the additive flutter noise reduces the NPRO mainly in the 14 kHz notch. It should be mentioned that the flutter spectrum is affected by tape tension. In machine B, the tension is dependent on the amount of tape on the reels so that the spectrum varies. Figure 3 is a spectrum corresponding to Fig. 1a but with about 10% of the tape remaining on the supply reel. It is evident from Figure 1 that the flutter spectrum remains essentially unchanged for different tape speeds. All of the data presented in this paper were taken on a single record/reproduce pass - i.e., the machine was not rewound. The effect of rewinding and then reproducing on a second pass is to increase the output flutter spectrum at frequencies above the tracking capabilities of the transport servo by about 3 db.

Thus, the NPRO data in Table I for the 14 kHz notch are explained by the spectra in Figures 1, 2 and 3.

**Analysis** let  $x(t)$  be the signal in volts frequency-modulating the carrier. Then the reproduced waveform,  $s(t)$ , can be written as

$$s(t) = A(t) \cos \left\{ \omega_0 [t + \eta(t)] + M \int_a^{t+\eta(t)} x(\beta) d\beta \right\} + n(t) \quad (1)$$

where  $n(t)$  is the additive noise,  $A(t)$  is the amplitude of the output wave which varies in time because of the variation in head-tape spacing due to tape roughness dropout, etc.,  $\eta(t)$  is the instantaneous time base error due to flutter<sup>(2)</sup>,  $\omega_0$  is the carrier frequency in radians per second,  $a$  is a constant and  $M$  rad/volt is the carrier deviation parameter. An FM discriminator can be modeled as a device whose output is proportional to the derivative of the phase of the carrier. Let  $q(t)$  be the discriminator in response to  $s(t)$ . Then neglecting  $n(t)$  in this analysis,

$$q(t) = K \left\{ \omega_0 \eta'(t) + M [1 + \eta'(t)] x [t + \eta(t)] \right\} \text{ volts} \quad (2)$$

where it has been assumed that the discriminator has been tuned to  $\omega_o$ . The quantity  $\eta'(t)$ , the time derivative of  $\eta(t)$ , is the relative flutter <sup>(2)</sup>. The constant K is the discriminator sensitivity.

For subcarrier systems,  $x(t)$  is the sum of the subcarriers modulating the carrier. For PCM it is the bit stream, etc. In this section, the effect of tape flutter on the notch noise test will be discussed. For this case,  $x(t)$  is the noise signal simulating a frequency division baseband. We are interested in the spectrum of  $q(t)$ . The first term of equation (2) gives the flutter spectrum as in Figures 1, 2 and 3. Since  $\eta(t)$  is small compared to unity, the second term can be approximated by  $M \times [t + \eta(t)]$ . The effect of  $\eta(t)$  is to spread the spectrum of  $x(t)$ . If this spreading were comparable to the notch width, the NPR could be affected. Figure 4 gives the spectra of upper part the 12-108 kHz baseband from machine B at 120 ips with the 105 kHz notch inserted. The lower edge of the notch appears on the left. The bottom horizontal trace is the noise floor spectrum with the transport not running (very little different from the output noise with transport running with bias using a degaussed tape with no signal input). The top trace in the 105 kHz notch is with the machine running in the direct record mode. The bottom trace in the 105kHz notch is the spectrum at the output of the notch noise set (no tape). The difference in these two traces is mostly intermodulation noise in the record/reproduce process. With tape, the NPR is about 40 db and the NPRO is about 55 db. At the level of intermodulation indicated, no spreading due to tape flutter is observed. This can be understood qualitatively by observing Figure 5 which is a spectrum of a 100 kHz carrier at 120 ips. The sideband spectrum is that of  $\eta(t)$ . Note that these sidebands are down about 50 db or more. As shown in Appendix I, the spectrum spreading is greater at the high end of the baseband than at the lower end. Thus, it may be inferred that spreading is not significant relative to intermodulation in any notch and, therefore, the spreading has no observable effect on NPR achievable with currently available tape machines.

**Effect of Tape Flutter on a Subcarrier Multiplex** The extension to an FM subcarrier multiplex is direct. In this case

$$s(t) = A(t) \cos \left\{ \omega_o [t + \eta(t)] + \int_{\Sigma_1 M_1}^{t+\eta(t)} \sin \left[ \Omega_1 \gamma + m_1 \int_{y_1}^{\gamma} (\beta) d\beta \right] d\gamma \right\} + n(t) \quad (3)$$

where  $n(t)$  is additive noise independent of desired signal. The carrier discriminator output is, neglecting  $n(t)$  for this analysis,

$$q(t) = K \omega_o \eta'(t) + K [1 + \eta'(t)] \Sigma_1 M_1 \sin \left\{ \Omega_1 [t + \eta(t)] + m_1 \int_{y_1}^{t+\eta(t)} (\beta) d\beta \right\} \text{ volts} \quad (4)$$

where  $M_i$  is the peak carrier modulation due to the  $i^{\text{th}}$  subcarrier,  $\Omega_i$  is the frequency of the  $i^{\text{th}}$  subcarrier,  $m_i$  is the deviation parameter of the  $i^{\text{th}}$  subcarrier, and  $y_i(t)$  is the data signal in the  $i^{\text{th}}$  subcarrier. The first term in equation (4) is the additive term discussed previously. As before, spectrum spreading occurs because of the presence of  $\eta'(t)$  and  $\eta(t)$  in the second term. However, as shown, the effect is small so that the resulting cross modulation can be neglected. This is also true if the subcarrier amplitudes are increased with increasing frequency (tapered) because most of the spreading takes place in less than ten kHz. Since the weak subcarriers in the taper are separated from the strong by much more than ten kHz, the spreading has little effect on them.

Now consider the output of the  $i^{\text{th}}$  subcarrier discriminator.

$$a_i(t) = K_i \left\{ \Omega_i \eta'(t) + m_i [1 + \eta'(t)] y_i [t + \eta(t)] \right\} + a(t) \text{ volts} \quad (5)$$

where  $a(t)$  is the noise in the output due to the additive term  $K\omega_o\eta'(t)$  (t). If  $\Omega_i$  is sufficiently large so that the additive term has died out,  $a(t)$  can be neglected. If this is not the case, then this term must be included as noise in the input to the subcarrier discriminator. The factor  $K[1 + \eta'(t)]$  has been removed by the subcarrier limiter. The term  $K_i\Omega_i \eta'(t)$  produces additive noise independent of modulation. This quantity, suitably scaled and delayed in time to compensate for filter delays, can be used to subtract out the term  $K_i\Omega_i \eta'(t)$ . This type of compensation is sometimes used in direct-record systems. The multiplicative factor  $\eta'(t)$  in the second term is small relative to unity and generally is not corrected. This leaves the data  $y_i[t + \eta(t)]$  subject to time base error. One way to correct for this is to record a time code on the same track and to time tag the samples of  $y_i [t + \eta(t)]$ .

**Conclusion** Tape flutter frequency modulates the pre-detection signal. After carrier demodulation, this produces two effects. One is an additive signal which is proportional to the tape flutter. The other is a spectrum spreading of the modulating signal. The spectrum of the first effect dies off rapidly but still can limit the NPRO in the 14 kHz notch. Because of the width of the notches and smallness of the relative flutter, the second effect is insignificant compared to intermodulation from other causes. With FM/FM there is an additive effect associated with the carrier demodulation and one associated with each subcarrier demodulation. The effect from the carrier demodulation adds noise to the lower frequency subcarriers. This should be taken into account when setting the subcarrier taper. The effect from the subcarrier demodulation adds noise to the data. This effect is sometimes compensated by use of the pilot tone method. Flutter also adds time base error to the data. This effect can be compensated by time-tagging the data.

## Appendix 1

**Estimate of Spectrum Spreading Due to Time Base Error** The purpose of this appendix is to estimate the spectrum spreading of the notch noise test signal  $x(t)$  caused by the tape time base error  $\eta(t)$  which phase modulates the test signal. Because of the smallness of  $\eta(t)$ , only first order modulation sidebands are considered. Thus, only the first term of the Bessel series expansion of the phase modulated signal components needs to be considered. This permits the assumption of superposition.

For purposes of the estimation, consider Figure 6. To compute the spectral power at frequency  $f$ , it is necessary to add the side band power due to the frequency components of  $S_x(f)$  separated from  $f$  by the variable  $\alpha$ . The phase modulation index,  $\beta$ , for each component may be written as  $2\sqrt{2} \pi (f - \alpha) \sqrt{G_\eta(\alpha) \Delta f}$ . The amplitude,  $A$ , of each component of  $S_x(f)$  is  $\sqrt{2} S_x(f - \alpha) \Delta f$ . The power in the increment  $\Delta f$  at  $f$  caused by the test signal component in the increment  $\Delta f$  at  $f - \alpha$  is obtained by approximating  $J_1(\beta)$  by  $\beta/2$  to give

$$\left(\frac{\beta}{2}\right)^2 \frac{A^2}{2} = 2\pi^2 (f - \alpha)^2 G_\eta(\alpha) S_x(f - \alpha) (\Delta f)^2 \quad (6)$$

Thus the ratio,  $R(f)$ , of the spectral power at  $f$ , due to spreading, to  $S_x(f)$  (notch out) is obtained by integrating over  $\alpha$ , to give

$$R(f) \cong \frac{2\pi^2}{S_x(f)} \int_{f-f_m}^{f+f_m} (f - \alpha)^2 S_x(f - \alpha) G_\eta(\alpha) d\alpha \quad (7)$$

In obtaining this expression it is assumed that the amount of power removed from  $S_x(f)$  by the spreading is small. Thus it is seen that  $R(f)$  is largest at the high end of the baseband because of the factor  $(f - \alpha)^2$ . Since  $S(f)$  is assumed to be constant and if  $f \gg \alpha$

$$R(f) \cong 2\pi^2 f^2 \int_{f-f_m}^{f+f_m} G_\eta(\alpha) d\alpha \quad (8)$$

To estimate  $R(f)$  in the center of a high frequency notch, it should be noted that the notch widths are ten or more kHz wide. Thus for estimating the NPR due to spreading, the lower limit of the integral in equation (8) should be the order of 104. Figure 7 is a time base error spectrum of machine B which can be approximated as shown by  $G_\eta(f) = 2.5/10^{10} |f|^3$ . Substitution of these conditions into equation (8) gives  $R(f)$  about -66 db which is too far down to be observed in Figure 4.

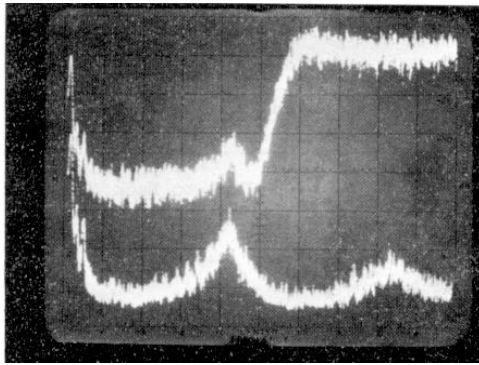
**References:**

- (1) W. R. Hedeman and M. H. Nichols ITC '70 Proceedings, Page 390.
- (2) M. H. Nichols ITC '67 Proceedings, Page 361.

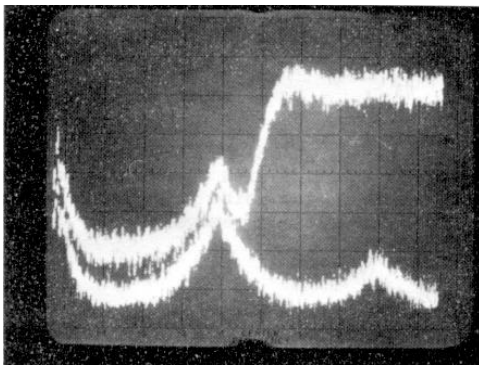
**Table 1****Notch Noise Loading Test Data**

Notch Freq.	NPR/NPRO db		Back-to Back for Machine B	Tape Speed ips	rms Modulation kHz
	Machine B	Machine A			
14	43/46	49/53	49/65	60	72
34	44/46	44/49	50/65	60	72
70	40/44	40/44	44/64	60	72
105	34/41	37/41	40/63	60	72

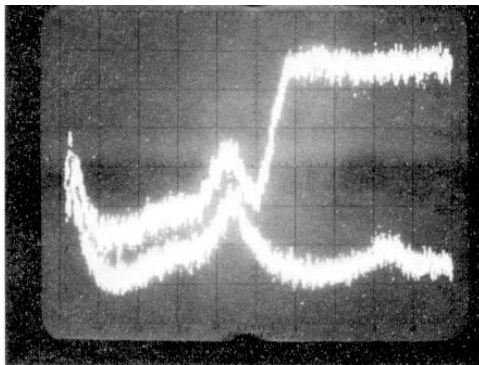
The first number in the NPR/NPRO column is the noise power ratio in db measured with the carrier modulated and the second number is the noise power ratio in db measured with the carrier modulation removed.



(a) 120 ips, 12-204 kHz test signal, rms carrier modulation 93 kHz (top trace displace 20 db upward).

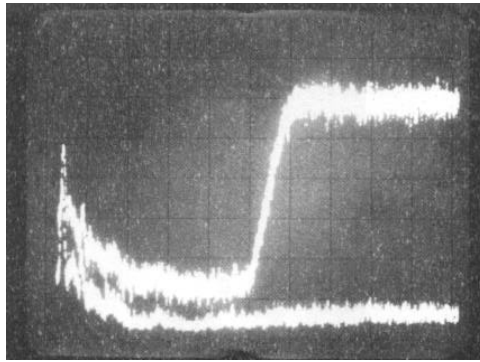


(b) 60 ips, 12-108 kHz test signal. rms carrier modulation 46 kHz.

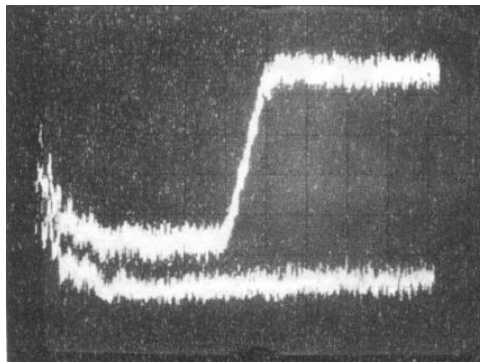


(c) 30 ips, 12-60 kHz test signal, rms carrier modulation 23 kHz.

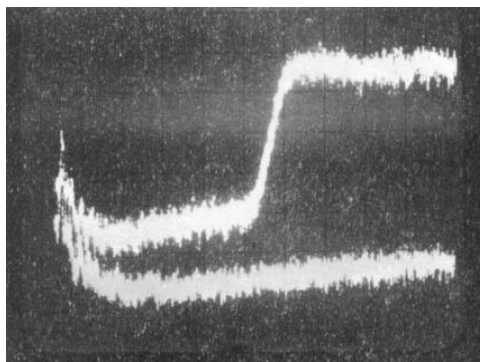
Figure 1. Baseband spectra of Pre-detection Tape Recorded/Reproduced FM carrier from Machine B. The horizontal scale is 2 kHz per division and the vertical scale is 10 db per division. The top trace is with modulation noted and the bottom trace is with unmodulated carrier. The IF bandwidth of the spectrum analyzer was 100 Hz and the video bandwidth 10 Hz.



(a) 120 ips, 12-204 kHz test signal, rms carrier modulation 93 kHz.



(b) 60 ips, 12-108 kHz test signal, rms carrier modulation 46 kHz.



(c) 30 ips, 12-60 kHz test signal, rms signal modulation 23 kHz.

Figure 2. Baseband spectra of Pre-detection Tape Recorded/Reproduced FM carrier from Machine A. The horizontal scale is 2 kHz per division and the vertical scale is 10 db per division. The top trace is with modulation noted and the bottom trace is with unmodulated carrier. The IF bandwidth of the spectrum analyzer was 100 Hz and the video bandwidth 10 Hz.

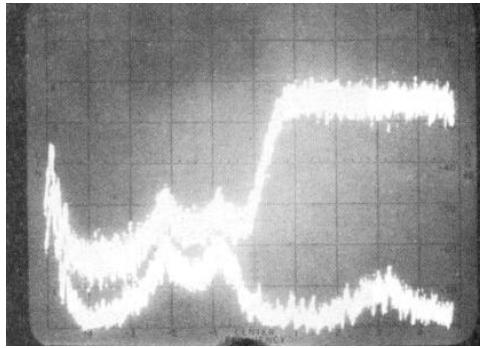


Figure 3. Spectrum corresponding to Figure 1a but with 10% of the tape remaining on the reel. Top trace displaced 10 db upward.

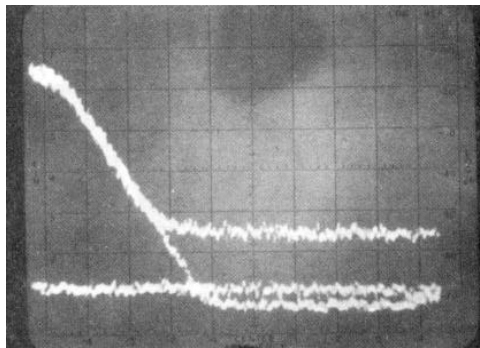


Figure 4. Spectrum of 105 kHz notch direct recorded/reproduced on Machine B illustrating the masking of spectrum spread of  $x(t)$  by overmodulation noise. Text explains the traces shown. The horizontal scale is 2 kHz per division. The vertical scale is 10 db per division.

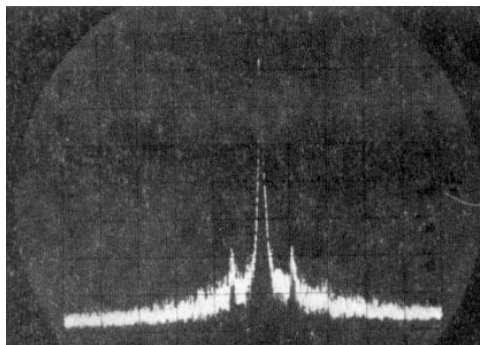


Figure 5. Spectrum of 100 kHz carrier recorded reproduced on Machine B at 120 ips. The horizontal scale is 10 kHz per division. The vertical scale is 10 db per division.

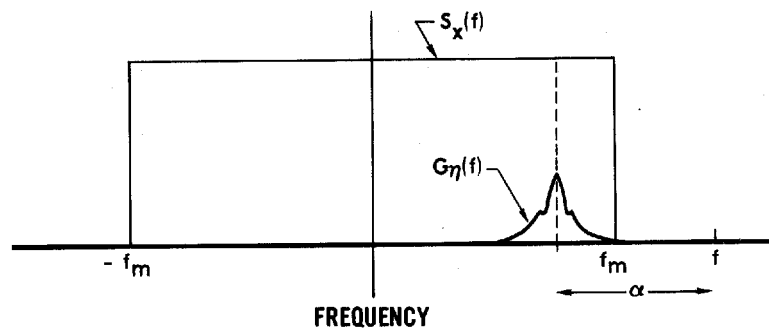


Figure 6. Schematic of test spectrum  $S(f)$  and time base error spectrum  $G(f)$ .

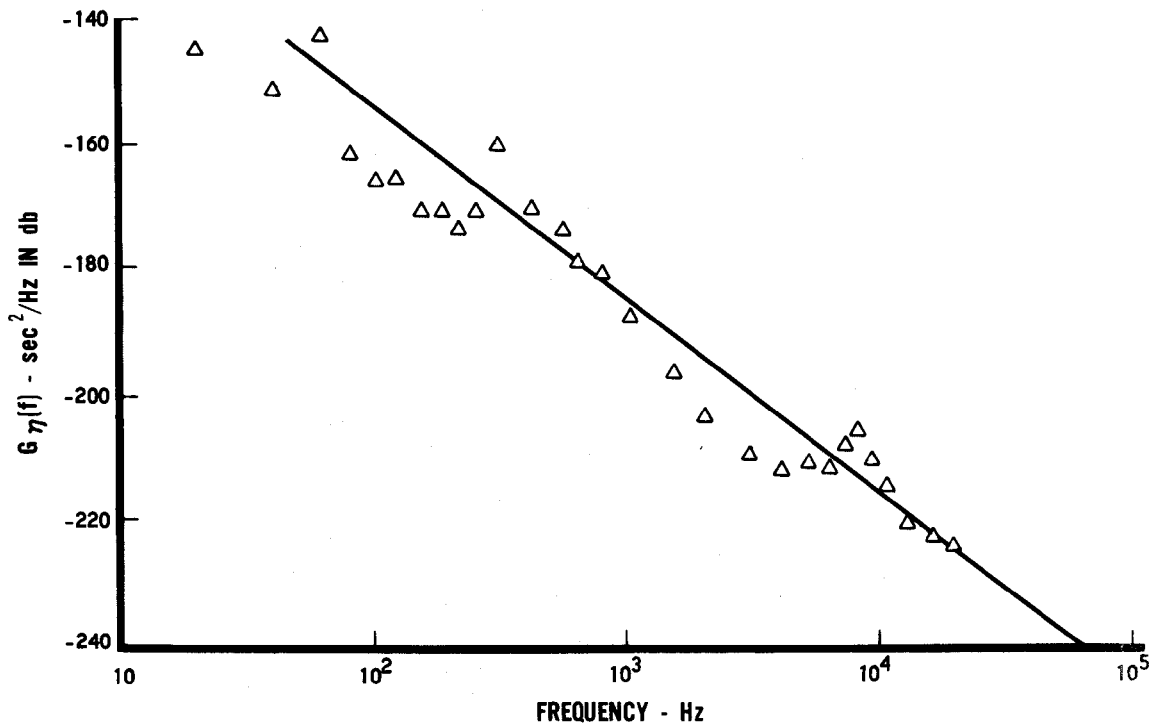


Figure 7. Time Base Error Spectrum for Tape Machine B at 120 ips.