MEANINGFUL FM TRANSMITTER

MODULATION LINEARITY MEASUREMENTS*

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ABSTRACT

In Frequency Division Multiplex (FDM) systems, nonlinearities in the modulation and demodulation processes of the transmission system produce intermodulation (IM) products which are effectively added to the desired modulation. The effect of these added products is the degradation of data accuracy in the form of noise on the subcarrier data. Currently there are no standard test procedures or specifications that permit the prediction of the level of these IM products during system design. The characterization of transmitter modulation linearity by the measurement of IM, or cross-products, produced by simultaneous modulation by two tones, is considered ideal. This is because the test conditions can closely simulate the highest modulation level subcarriers used and the necessary demodulation equipment can he readily calibrated using common frequency modulated sources. The modulation tones used are both in the upper portion of the transmission system's baseband and at a modulation level near the level of intended use. Measurement of only the difference frequency IM component, ($f_2 - f_1$), is considered adequate for the determination of 2nd order nonlinearities. The 3rd order IM components are measured only at ($2f_1 - f_2$) and ($2f_2 - f_1$) and are normally found to be of equal amplitudes with FM transmitters. All higher order products, as well as direct harmonics, are ignored. From the three IM level measurements, and the two desired tones, the 2nd and 3rd order modulation intercept points (IP_2 and IP_3) are determined in essentially the same manner as the intercept point, or IP, that is common in specifying the linearity of broadband RF amplifiers. When the amplitude of the various signal and IM components are plotted on log-log scales, the desired signals have a slope of one while the 2nd and 3rd order products have slopes of two and three respectively. On log-log plots the intercept point is the modulation level at which extensions of the low level values of the IM components meet the extension of the desired modulation level. Once the IP values are determined, they may be readily used for system IM calculations. Measured IM levels in a sixteen channel FDM system compared very favorably with predicted levels using the

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IP values obtained from two-tone tests. The nonlinearities of the demodulator employed in the test system may be evaluated by the use of the “beat” frequency of two independently modulated FM signal sources as the required input to the demodulator. The IM products in the demodulator output in this case are due only to the demodulator’s transfer characteristics. IM product levels of the test system greater than 60 dB below the simultaneous modulation level of ±300 kHz each by 400 and 450 kHz tones are obtained at Sandia Laboratories. The use of two-tone IM tests for the evaluation and specification of FM transmitter modulation linearity is strongly recommended.

INTRODUCTION

Currently the only indicator for the modulation linearity of a transmitter is harmonic distortion. Modulation linearity is a characteristic that requires a demodulator for evaluation, and the isolation of the demodulator’s nonlinearity from that of the unit under test is normally very difficult. For simplicity in both the required measurements and specifications, all harmonic components are normally summed as “Total Harmonic Distortion” or “THD” and liberally specified for both measurement and contractual purposes. Test equipment for the measurement of transmitter THD frequently employs receivers whose THD has been measured with a high quality signal generator. The THD measured with the signal generator is considered to be that of the test system and may be subtracted from the THD values measured with the transmitter under test. To permit the harmonics to remain in the baseband of the system, the modulation frequency should be a small fraction of the highest level subcarrier employed or the harmonics may fall outside the measurement system’s baseband. Modulation linearity measurements obtained under these conditions are considered of no value for the prediction of system performance.

The use of the telemetry system’s entire multiplex as the modulation source in transmitter linearity testing sounds ideal, but would present a tremendous task in measuring and recording all of the IM products in most systems. For example, if only the 2nd and 3rd order nonlinearities exist, a six channel multiplex would produce over 200 IM products. Even if only the IM products below the upper subcarrier were of concern, the results could not justify the effort.

The two-tone test method not only permits the test frequencies and levels to be essentially equal to those of the largest subcarriers in the multiplex, but also facilitates the evaluation of the demodulator linearity independent of the modulation linearity of a reference generator.

IM CHARACTERISTICS

The proposed two-tone test procedure requires the measurement of five voltage levels with a spectrum or wave analyzer. Two of the measurements represent the deviation level produced by the input tones. One measurement, whose amplitude varies as the square of the transmitter modulation voltage or deviation, is at the difference frequency of the modulation signals and is caused by the second order term in the modulation transfer function. The other two IM products are caused by the third order term of the transfer function which varies as the cube of the modulation voltage or deviation. One of these third order products is located below the lowest input tone by the frequency difference in the two modulation tones and the other is above the upper modulation tone by the difference frequency. A complete expression of the products produced by the application of two sine waves to a device whose transfer characteristics include only second and third order terms is given in Appendix A. For convenience and simplicity, equal level modulation tones are used in testing.

INTERCEPT POINT - IP

If the various output components of a device whose transfer function is $e_{out}=k_1e_{in}+k_2e_{in}^2+k_3e_{in}^3$ are plotted on a log-log scale (e_{out} vs e_{in}), the desired signal components due to k_1e_{in}, have a slope of one; the components due to the second term $k_2e_{in}^2$, have a slope of two, while the components due to the third term $k_3e_{in}^3$, have a slope of three. The definition of the intercept point, or IP, is the output level at which the line representing a higher order IM product intersects the line representing the linear, or desired term k_1e_{in}. Figures 1 and 2 provide a graphical representation of the relationship between these terms. Included on the figures are the mathematical relations between the intercept points, the signal, and the IM levels.

A plot of the measured values of the desired signal and IM products will not follow straight lines to their intersection because of saturation or limiting effects that occur. With practical “linear” devices, however, the low level or small signal portion of the plots possess the slopes as described. By projecting lines of the proper slope through the appropriate measured IM levels, the intercept points can be readily found. Once the intercept points are determined, they can be used for specifications and to predict IM product levels for any practical set of modulation conditions without further qualification.

TEST SYSTEM

Figure 3 is a block diagram of the two-tone test system. Compared to conventional distortion measuring systems, it employs an additional modulation source and requires the use of a spectrum or wave analyzer as opposed to a total distortion meter. There are two quality checks that should be made on the test system. One is to determine that appreciable IM is not occurring in the modulation sources due to the output of one source feeding into the output of the other. This is easily done by viewing the combined modulation signals with the spectrum analyzer. The other quality check is the determination of the linearity of the demodulator which is done with the arrangement shown in Figure 4. In this setup, the two modulation sources individually modulate two separate FM generators. The outputs of the FM generators are applied to the inputs of a double balanced mixer. The output of the mixer is fed to the input of the demodulator. This arrangement requires that the frequencies of the FM generators produce a sum or difference frequency which is the frequency required by the demodulator. One or both of the FM generators may be an FM transmitter of the proper frequency and level to feed the double balanced mixer. In this test arrangement, the demodulator sees the modulation of both generators that has been summed in the double balanced mixer, as opposed to the summed modulation signals that are applied to a transmitter under test. The modulation addition by this method does not produce IM products of the modulating signals; therefore, any IM products observed will be due to the demodulator. In the test arrangement employed at Sandia, a 10 MHz center frequency wide band demodulator is used.

The use of band pass filtering on the input of the demodulator is avoided because of the possible effects of phase nonlinearities on the signal. Measured 3rd order IM products of the demodulator employed are typically greater than 60 dB below a ±300 kHz per tone deviation level. Second order IM products are even lower, as they should be if the demodulator transfer characteristic has image symmetry.

TEST RESULTS

The system with which the two-tone test procedure was to be initially used employed a total of sixteen subcarriers ranging in frequency from the 16±2 kHz channel to the 384±16 kHz channel with a total of 20 dB pre-emphasis. The calculated peak deviation (sum of the peak deviations produced by each of the subcarriers) exceeded ±1 MHz. By the use of IP data determined from the transmitter tests, calculated system IM component levels produced by the two largest subcarriers, compared within ±2 dB of the measured IM levels when the full subcarrier multiplex was modulating the transmitter. The test tones were chosen to be 400 kHz and 450 kHz with peak deviations of ±200 kHz each. In more recent tests, the test conditions have been increased to ±500 kHz deviation per tone and modulation tones of 800 and 900 kHz. In over approximately four years of IM testing IP_2 has been found to vary over a range from approximately 5 to 500 MHz while IP_3 varied from approximately 1 to 15 MHz. The nominal values were in the region of 40 and 4 MHz for IP_2 and IP_3 respectively.

DISCUSSION

Most frequently the group of subcarriers forming the multiplex in FDM systems employs pre-emphasis such that the higher subcarrier channels modulate the transmitter more than the lower channels. This is desired because the noise density on the output of FM systems above threshold increases with frequency in the baseband. By the use of pre-emphasis the signal-to-noise ratio of the various subcarrier channels can be made equal if desired. For equal bandwidth subcarrier channels that cover a decade frequency range the theoretical pre-emphasis is 20 dB. In cases where the multiplex exceeds a decade frequency range, the pre-emphasis taper is frequently removed from the lower subcarriers because of the excessive noise on their data caused by the difference frequency products of the higher frequency channels.

The quality of frequency division multiplexed data is bounded on one side by thermal noise due to the limited received power and on the other side by the amount of cross-talk, or self-generated interference, that is present in the system. The improvement of system modulation linearity will not only provide less noise on subcarrier data under strong signal conditions but also, with some increase in the modulation level, improve the data quality under weak signal conditions.

CONCLUSIONS

The use of the two-tone tests for the evaluation of FM transmitter modulation linearity has proven to be easier and more valuable than anticipated. The testing method will: 1. Permit test conditions to be representative of intended use in FDM systems; 2. Provide test data and specifications that can be easily extrapolated to other modulation levels; 3. Provide necessary data for the prediction of intermodulation noise in FDM systems; and 4. Virtually eliminate sources of errors in the measuring system.

REFERENCES

1. McVay, Franz C., “Don’t Guess the Spurious Level” Electronic Design, February 1, 1967.

2. Hardy, James, High Frequency Circuit Design, Reston Publishing Co., Reston, VA, 1979 pp. 9-14.

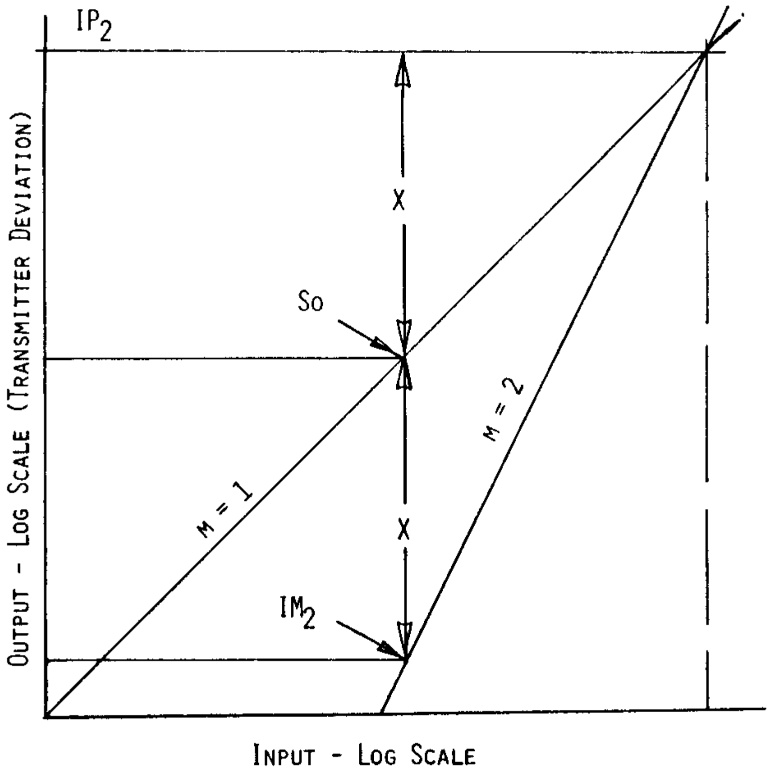
3. HP Application Note 150-11, Spectrum Analysis...Distortion Measurement, October 1976.

TWO TONE TEST EQUATION FOR 2ND 9 3RD ORDER NONLINEARITIES

$$
\begin{aligned}
e_{out} = {} & k_2\left(e_1^2 + e_2^2\right)/2 \\
& + \left(k_1e_1 + 3k_3e_1e_2^2/2 + 3k_3e_1^3/4\right) \sin \omega_1 t \\
& + \left(k_1e_2 + 3k_3e_1^2e_2/2 + 3k_3e_2^3/4\right) \sin \omega_2 t \\
& - \left(k_2e_1^2/2\right) \cos 2\omega_1 t \\
& - \left(k_2e_2^2/2\right) \cos 2\omega_2 t \\
& - \left(k_3e_1^3/4\right) \sin 3\omega_1 t \\
& - \left(k_3e_2^3/4\right) \sin 3\omega_2 t \\
& - \left(k_2e_1e_2\right) \cos \left(\omega_2 - \omega_1\right)t \\
& - \left(k_2e_1e_2\right) \cos \left(\omega_1 + \omega_2\right)t \\
& + \left(3k_3e_1^2e_2/4\right) \sin \left(2\omega_1 - \omega_2\right)t \\
& - \left(3k_3e_1^2e_2/4\right) \sin \left(2\omega_1 + \omega_2\right)t \\
& + \left(3k_3e_1e_2^2/4\right) \sin \left(2\omega_2 - \omega_1\right)t \\
& - \left(3k_3e_1e_2^2/4\right) \sin \left(2\omega_2 + \omega_1\right)t
\end{aligned}
$$

EQUATION OF THE OUTPUT SIGNAL PRODUCED BY THE PASSING OF AN INPUT $E_{IN} = E_1 \sin \omega_1 T + E_2 \sin \omega_2 T$ THROUGH A DEVICE HAVING A TRANSFER EQUATION OF $E_{OUT} = K_1 E_{IN} + K_2 E_{IN}^2 + K_3 E_{IN}^3$.

APPENDIX A



For Equal Signals

$$\frac{IP_2}{So} = \frac{So}{IM_2} \qquad IP_2 = \frac{So^2}{IM_2}$$

$$IM_2 = \frac{So^2}{IP_2} = K_2 So^2$$

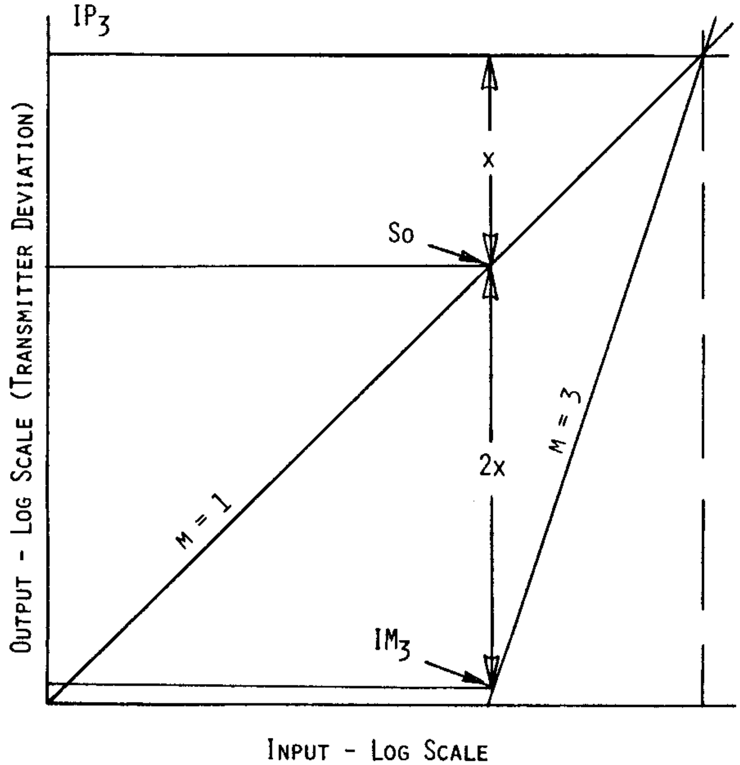
$$K_2 = \frac{IM_2}{So^2} = \frac{1}{IP_2}$$

For Unequal Signals

$$IM_2 = K_2 S_1 S_2$$

$$\text{FOR}\left(\omega_1 \pm \omega_2\right)$$

FIGURE 1 2ND ORDER INTERCEPT POINT - IP_2



For Equal Signals

$$\frac{IP_3}{So} = \sqrt{\frac{So}{IM_3}} \qquad IP_3 = \sqrt{\frac{So^3}{IM_3}}$$

$$IM_3 = \frac{So^3}{IP_3^{\,2}} = K_3 So^3$$

$$K_3 = \frac{IM_3}{So^3} = \frac{1}{IP_3^{\,2}}$$

For Unequal Signals

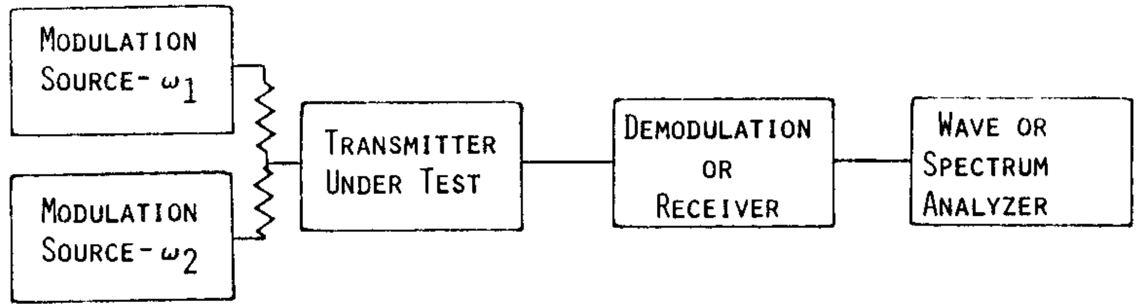
$$IM_3 = \frac{3K_3}{4} S_1^{\,2} S_2$$

$$\text{FOR}\left(2\omega_1 \pm \omega_2\right)$$

$$IM_3 = \frac{3K_3}{4} S_1 S_2^{\,2}$$

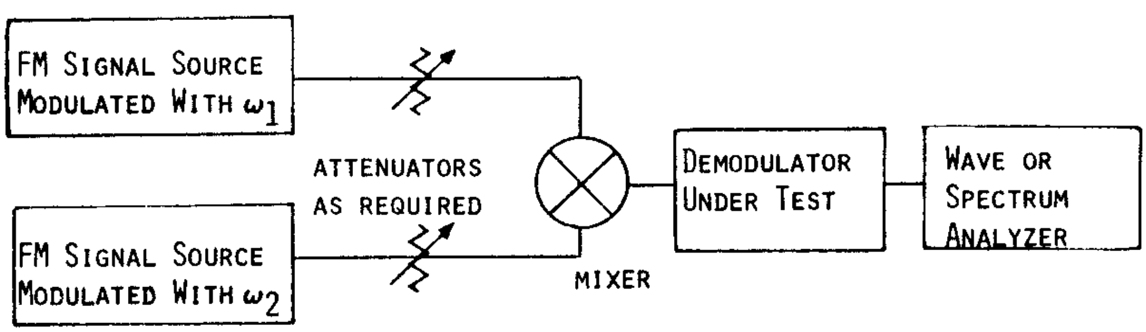
$$\text{FOR}\left(2\omega_2 \pm \omega_1\right)$$

FIGURE 2 3RD ORDER INTERCEPT POINT - IP_3



RECOMMENDED TEST CONDITIONS	WAVE ANALYZER READINGS
ω_1 = 80% OF BASEBAND	LEVELS OF
ω_2 = 90% OF BASEBAND	ω_1 AND ω_2
DEVIATION LEVELS SHOULD BE EQUAL TO OR NEAR THE DEVIATION LEVEL ANTICIPATED FOR THE LARGEST SUBCARRIERS.	$\omega_2-\omega_1$
	$2\omega_1-\omega_2$
	$2\omega_2-\omega_1$

FIGURE 3 TWO-TONE INTERMODULATION TEST SETUP



SUM OR DIFFERENCE OF THE CENTER FREQUENCIES OF THE FM SIGNAL SOURCES MUST EQUAL THE REQUIRED DEMODULATOR INPUT FREQUENCY.

FIGURE 4 DEMODULATOR LINEARITY TEST