Assuring Accuracy in Modulation Measurements

by Leslie E. Brubaker

ONE OF THE MOST DIFFICULT PROBLEMS in making very accurate measurements of AM depth or FM deviation is calibrating the measuring instrument. A precisely modulated signal must be generated to serve as a calibration standard. Option 010 for the 8901A Modulation Analyzer solves this problem for the user by providing built-in precise AM and FM modulation standards. The calibrators built into an 8901A that has Option 010 can also be used to calibrate other 8901As that do not have this option.

The AM standard is generated by summing two identical 10.1-MHz signals. When one of the signals is switched on and off at a 10-kHz rate, the result is 33.33 percent AM depth. By internally measuring* any slight difference in the levels of the 10.1-MHz signals the analyzer is able to determine the actual depth to ±0.1 percent accuracy. To further improve the modulation envelope, the rise and fall transitions are smoothed to eliminate ringing that might otherwise occur in the 8901A's audio filters when this signal is measured.

The FM standard is generated by square-wave modulating a VCO with a nominal 33-kHz peak deviation. By using the internal counter to measure* the upper and lower frequency of this signal, the actual peak deviation is determined to ±0.1 percent accuracy. To prevent ringing, the square wave is modified to a round-edged trapezoid.

Once the actual AM depth and FM deviation have been calculated and stored, the modulation analyzer can be calibrated. With the calibration signal applied to the analyzer's RF input port, the internal demodulators measure the signal being applied, and a pair of percentage

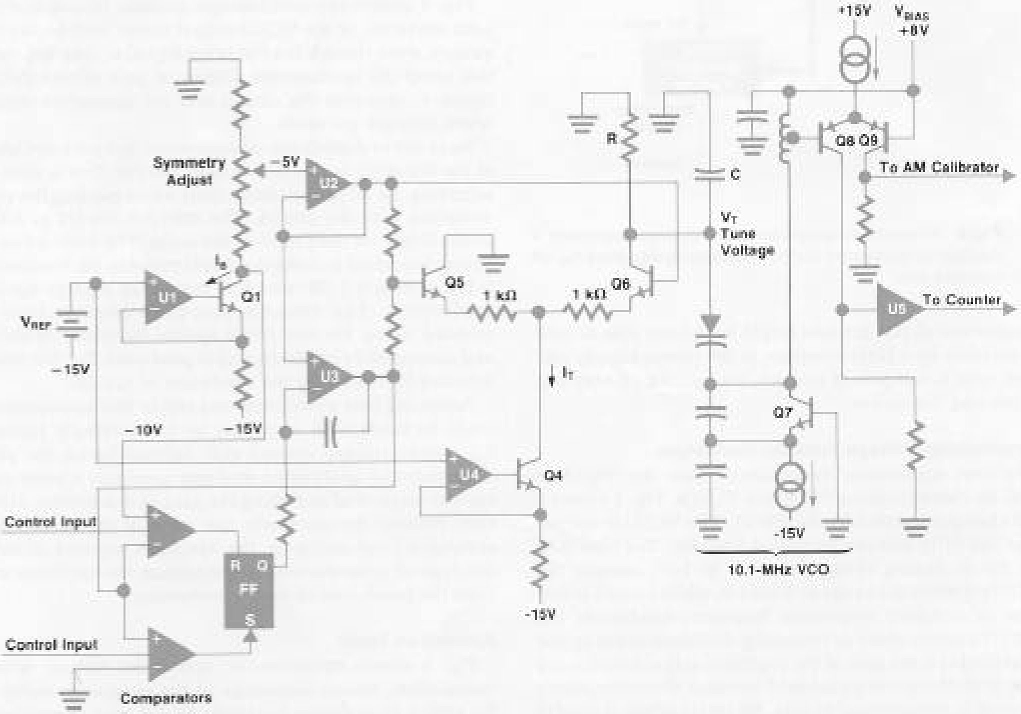

Fig. 1. *FM calibrator circuit diagram. 10.1-MHz oscillator Q7 is switched between two frequencies by the output of differential amplifier Q5-Q6.*

---

* The 8901A interacts with the AM and FM calibrators to calculate the actual amount of generated modulation, but the AM and FM detectors, which will later be calibrated using the signals generated by the AM and FM calibrators, are not used in the calculation. Because of this indirect method, any counter could determine the FM deviation and any digital voltmeter could measure the two RF levels for the AM depth. The 8901A is simply a convenient instrument to use to find the magnitudes of the calibration signals.

accuracies are determined using the calculated values of AM and FM as references. For example, if the measured value of AM or FM deviates from the calculated value by −0.1%, the display shows 99.90%. The two percentage accuracies, one for FM and one for AM, may be stored and used as scale factors to correct subsequent readings. If commanded to do so by means of a special function command, the analyzer will correct its readings automatically.

Because the modulation standards are internal to the analyzer, there is little need for metrology laboratories to purchase separate calibration standards. Also, because of the technique used, it is easy to verify that the calibrators are operating properly. The two levels in AM and the two frequencies in FM are very accurately determined in a nonmodulating mode. By analyzing the circuit performance, it is possible to show that the amount of modulation generated is the same as that indicated by knowing the nonmodulated states. The error analysis will follow the circuit description.

FM Calibrator

The FM calibrator circuit diagram appears in Fig. 1. The main portions of the circuit are the 10.1-MHz VCO (Q7) and the differential amplifier made up of Q5 and Q6 with its emitter current source U4 and Q4. The oscillator is a varactor-tuned Colpitts type with a tapped inductor for signal extraction. The 10.1-MHz signal is removed by the differential amplifier made up of Q8 and Q9. The collector of Q9 drives the input to the AM calibrator, which looks like a through path to the front-panel output when in the FM calibration mode. The collector of Q8 drives a line receiver with TTL output. This stage acts as a level converter for driving the 8901A's internal counter and provides reverse isolation that keeps counter noise from modulating the VCO. The collector bias of Q7 also supplies base bias for the differential amplifier and reverse bias for the varactor diode. This bias partially temperature compensates drift of the varactor capacitance. Low drift is required to improve accuracy when calculating the deviation of the FM calibration signal, since any drift will directly add to or subtract from the difference measurement.

The oscillator tuning voltage is generated by switching a constant current on and off with Q5 and Q6. Suppose that Q6 is fully on and Q5 is fully off. All the current from Q4 flows through Q6 and none through Q5. This makes $V_T = I_T R$. Since this causes greater reverse bias on the varactor, the frequency is increased to f_U, which is counted and stored. If Q5 then is turned on and Q6 is off, all of I_T flows through Q5 and none through Q6. Then $V_T = 0V$, and a lower frequency f_L is generated and counted. The peak FM deviation is $\frac{1}{2}(f_U - f_L)$. If Q5 and Q6 are allowed to switch at a 10-kHz rate, we then have an RF signal modulated at a 10-kHz rate with a precisely known peak deviation. This is the signal that is used to calibrate the 8901A FM demodulator.

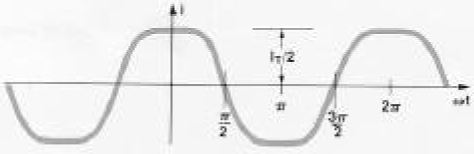

Fig. 2 *Current waveform in the FM calibrator differential amplifier. The FM calibration frequency is proportional to this current. The rounded corners prevent ringing in the 8901A's audio filters.*

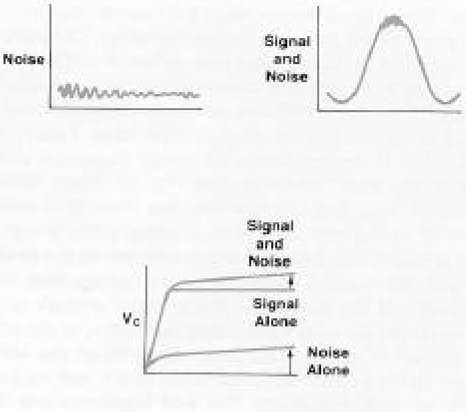

Fig. 3. *Effective noise during peak detection.*

The remaining portion of the calibrator consists of control and reference circuits. A very stable voltage source is used as a reference for the tuning current and a bias current (I_B). U3 integrates the output voltage of a CMOS flip-flop and causes Q5 to be switched on and off. The output of the integrator is sensed by two comparators that control the state of the flip-flop. When in the modulating mode, this circuit causes a triangle waveform at the U3 output. The comparison points are 0V and −10V. I_B flows through three resistors to generate the −10V. There is a voltage tap at half of the −10V that sets the bias of Q5 and Q6 and the reference for the integrator. Thus Q5 and Q6 are always biased halfway between the comparison points even if I_B drifts. This is necessary because otherwise the area above and below the midway point would change, making the indicated plus peak deviation different from the minus peak deviation. The peak-to-peak deviation would still be correct, but it would be more difficult to set the demodulator gain accurately.

To prevent ringing in the audio filters (ringing would result in an improper indication from the 8901A's peak detector), it was necessary to modify the transfer characteristic of the Q5-Q6 differential amplifier. The large (1 kΩ) emitter resistors give the stage a gain of 1.3 and cause the transistors to turn on and off with rounded, rather than sharp corners (see Fig. 2). The rounding also causes a reduction in high-frequency components that would otherwise have to be handled by the system.

FM Error Analysis

Among the errors in the FM calibrator, several sources are negligible: the drift of the VCO with time, the change of the VCO tuning constant with temperature, and the change of α in the current source and differential amplifier transistors.

The counter introduces uncertainty in the measured frequency difference: a resolution of 2 Hz and accuracy of ±1 count gives 0.01% error for 30-kHz deviation. The varactor diodes require RF bypassing at the collector of Q6, giving rise to an RC time constant that must be short compared to the modulation period. Eight time constants are allowed for settling to the final value, giving 0.03% error. Finally, the residual FM of the unmodulated carrier causes an uncertainty in the peak indication (see Fig. 3). When random noise alone is applied to a peak detector, the output voltage will build up to a particular level. If signal alone is applied to the detector, the detector output will rise to the peak of the input. When signal and noise are applied together, some amplitudes of the noise will not be large enough to put additional charge onto the holding capacitor, so the effective amount of noise is reduced. Analysis of the 8901A circuits yields a noise reduction factor of 0.7, and we know that factor with a certainty that will introduce less than 0.025% error. Adding 0.7 times the peak residual FM to the calculated value of the FM from the calibrator gives the correct amount of deviation that the 8901A should indicate when measuring the calibration signal with its FM demodulator. Some of these errors are random while others are always in one direction. By appropriately combining errors, we can arrive at an uncertainty of 0.06% in determining the actual modulation. This is well within the 0.1% specified accuracy.

AM Calibrator

Fig. 4 is the block diagram of the AM calibrator. The unmodulated 10.1-MHz signal from the FM calibrator goes through a limiting stage and then is split into two identical paths containing a buffer, an RF modulator and a common-base stage. The two signals are joined again by summing the collector currents of the common-base stages. From there the signal goes to the front-panel output as the AM calibration signal and to an RF level detector. The output of the detector is monitored by the microprocessor both directly and after 10× amplification for increased resolution on the AM calculation.

The technique of generating AM is similar to that of generating FM. Two known states are precisely determined in a nonmodulating mode, and we then switch between those two states at an audio rate. Assume that I_B is off and that I_A is on. Also, assume that V1 is large enough to turn on D1 and turn off D2. All of I_A will flow through D1 causing $V_A = 0$. When V1 causes D1 to be off and D2 to be on, I_A will cause a voltage (V_A) at the emitter of Q1. In this fashion a square wave of voltage at the RF rate will appear at the emitter of Q1 with amplitude V_A. Notice that this amplitude depends only on the impedance at node A and the value of the dc current source I_A, not on V1 or the diodes (as long as the diodes are being switched on and off by V1). The output of Q1 is amplified and detected. An identical operation occurs for the B modulator when I_B is on and I_A is

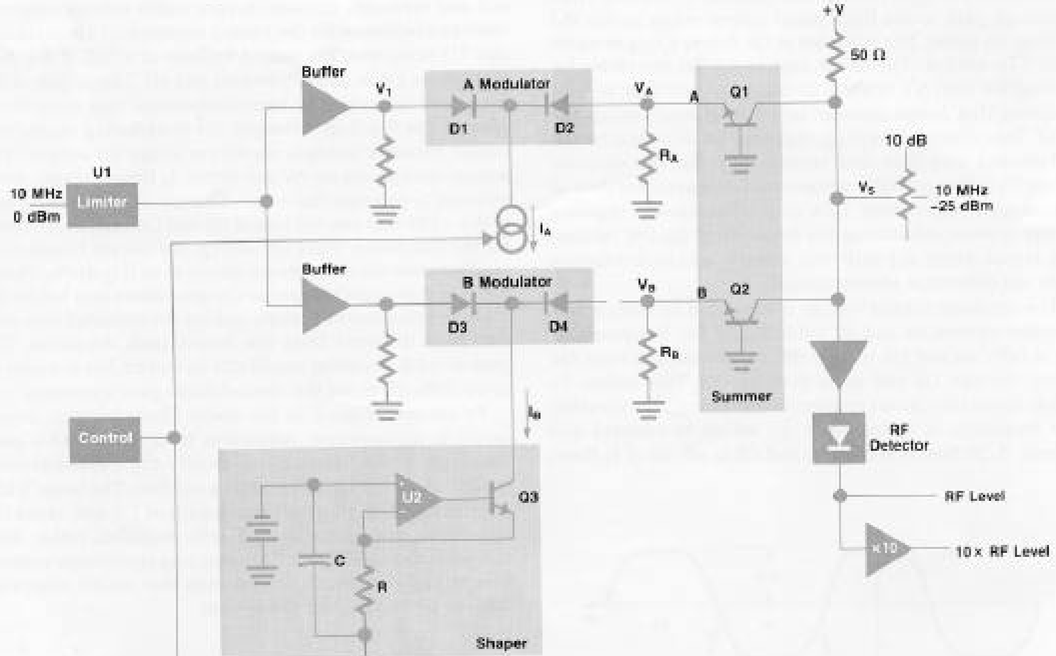

Fig. 4. *AM calibrator circuit diagram. The 10.1-MHz signal from the FM calibrator is split into two identical paths. The signal in one path is switched on and off, and the two paths are then summed.*

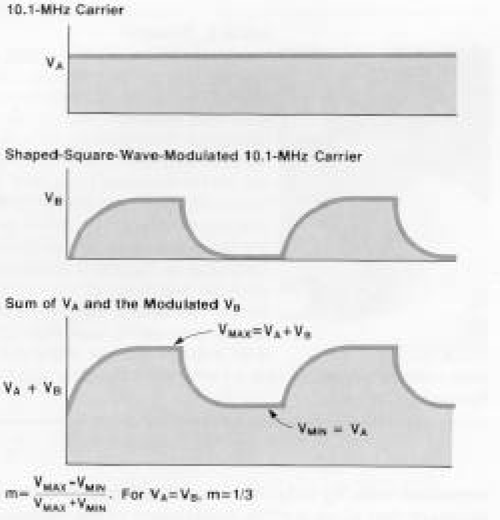

Fig. 5. *Generation of the AM calibration signal by summing.*

off, thus generating V_B. If both I_A and I_B are on, then the sum of the two voltages appears at V_S. AM is generated by turning on I_A continuously but switching I_B on and off at an audio rate (see Fig. 5). For one-half period, the output is V_A and for the other half period it is $V_A + V_B$. For $V_A = V_B = V$, the modulation index is $m = 1/3$. The expression for m is:

$$m = \frac{V_{max} - V_{min}}{V_{max} + V_{min}}$$

$$m = \frac{(V_A + V_B) - V_A}{(V_A + V_B) + V_A} = \frac{1}{3 + 2\,(V_A - V_B)/V_B}$$

We have added the 10× amplifier for V_A and V_B to get increased resolution on the $V_A - V_B$ measurement. This expression shows that, as V_A and V_B become equal, any uncertainty in measuring V_A and V_B becomes insignificant. This removes stringent requirements for the RF detector to be highly linear or to make highly accurate absolute measurements.

The shaping of the I_B current drive to the B modulator is accomplished by driving a current through a parallel RC network using U2 (see Fig. 4). Assume that I_B has been off and that there is no charge on C. There is also no current in R. Now let I_B make a step increase to its maximum value. All of I_B flows through C and starts to build up charge. Since the voltage between the + and − terminals of the operational amplifier must be zero, a current is forced through R, developing a voltage that will equal the voltage on C. This current is the emitter current of Q3, and it reduces the current through C. This process continues until all of I_B flows in Q3. The current in Q3 follows a simple exponential rise. When I_B is turned off, C supplies the current to R giving an exponential decay. Since the size of the square waves of RF developed at node B are directly proportional to I_B, the RF waveform also has an exponential rise and decay.

AM Error Analysis

Once again it is necessary to verify that the amount of modulation generated in the switching mode is the same as that calculated from measurements in the static mode. The first errors that need to be considered are in determining the RF level. The factors involved are the nonlinearity and offset voltage of the RF detector and the internal digital voltmeter, the resolution of the digital voltmeter, and the gain uncertainty of the 10× amplifier. A list of magnitudes and their influence on the uncertainty in knowing m is given below:

A. Nonlinearity of RF detector = 0.07% for 3% change of RF level
B. Offset voltage of RF detector = 15 mV = V_0
C. Gain uncertainty of 10× amplifier = 0.5%
D. Nonlinearity of DVM <0.1%
E. Offset voltage of DVM <1 mV (0.05% for 2V input)
F. Resolution of DVM = 1 Bit (0.05% for 2V input).

Let

X_1 = % error in knowing $V_0 = 100\%$
X_2 = % error in knowing $V_A - V_B$
$= 0.07 + 0.5 + 0.1 + 2(0.05) = 0.77\%$
X_3 = % error in knowing $V_B = \frac{0.015V}{V_B} \times 100 + 2(0.05)$
$= 0.85\%$

Then the uncertainty in knowing m because of the detector errors is:

$$\frac{\Delta m}{m} = \frac{2}{3}\,\frac{V_A - V_B}{V_B}\,\left(\left|\frac{V_0}{V_B}X_1\right| + |X_2| + |X_3|\right).$$

For example, let V_A be within 3% of V_B. Then:

$$\frac{V_A - V_B}{V_B} \le 0.03$$

and

$$\frac{\Delta m}{m} = \frac{2}{3}\,(0.03)\,(0.75 + 0.77 + 0.85) = 0.047\%$$

We test the value of $(V_A - V_B)/V_B$ for less than 3% difference during each calibration cycle and halt if the test fails. This insures that there will never be more than 0.047% error because of the detectors.

Since the AM calibration technique depends on adding two signals to get a peak value that is the sum of the two signals, the peaks of the waveform must be coincident. Therefore the differential phase shift between the two modulator paths must be small. A typical phase difference of ½° results in approximately 0.001% error.

Since the modulators are not ideal and have stray capacitive coupling around the diodes, they do not totally shut off the signal to the summing amplifier when I = 0. The level of this feedthrough is about 60 dB down from the desired RF level, but since it is at an angle of 90° it has negligible effect on the magnitude of the resultant signal.

Another source of error comes from generating an exponential leading and trailing edge on the modulating current source. There must be enough time for the exponential to reach the same final value as was measured statically. Approximately nine time constants occur from the start to the end of each half period, resulting in 0.012% error.

The change of α in the current source transistors also affects the AM calculation, but in this case it is not negligible because of higher power dissipation. When measuring V_B, Q3 dissipates 35 mW, but when modulating, Q3 has only a 50% current duty cycle, so the dissipation is only 17.5 mW. For the transistor used this results in a 6°C temperature change and a change in α of 0.03%.

Finally, the residual AM measurement must be modified to include the effects of peak-detecting a signal plus noise. The effective peak noise is 0.7 of the measured peak noise, as in the FM case. There is an additional factor to be considered in the AM case because of AGC action in the 8901A's AM demodulator. The AGC loop adjusts the gain of an amplifier to maintain the same average IF level into the demodulator. When V_B alone is applied the gain is 1.5 times higher than when the modulated signal is applied. Notice that the modulated signal goes between V_B and $V_A + V_B$, resulting in a higher average RF level. The reduction of gain while modulating also reduces the noise applied to the demodulator by a factor of 0.8, so the actual amount of noise affecting the calibration is 0.56 times the peak noise measured with V_B only. We know the factor of 0.56 to an accuracy that gives 0.025% uncertainty to the calibration. During calibration, the 8901A should then indicate the value that is calculated in the AM calibrator plus 0.56 times the peak noise.

Combining the above errors results in 0.07% uncertainty in the AM calibration. This is within the 0.1% specification.

Leslie E. Brubaker

Les Brubaker completed his BSEE studies in 1972 at the University of New Mexico, having previously worked as a technician for several years in Albuquerque. Two years later he received his MSEE degree from Stanford University. An HP employee since 1972, Les has contributed to the 8505A Network Analyzer and the 8482A, 8483A and 8484A power sensors. He designed the calibrators for the 8901A Modulation Analyzer, and designed the 11715A AM/FM Test Source. He's now a production engineering supervisor. Les is an avid tennis player and enjoys radio-controlled flying. He land his wife have a daughter and live in Sunnyvale, California.