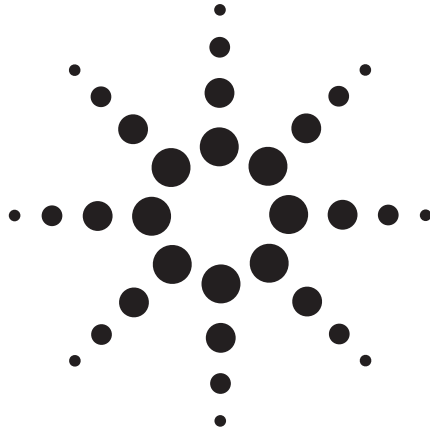**Digital Multimeter Measurement Errors Series**

AC Voltage Measurement Errors in Digital Multimeters

Application Note AN 1389-3

Introduction

When you make measurements with a digital multimeter (DMM), common errors will crop up. The following discussion will help you eliminate potential measurement errors and achieve the greatest accuracy with a DMM. This paper covers ac voltage measurement errors. For an overview of system cabling errors and dc voltage measurement errors, see Application Note 1389-1. For a discussion of resistance; dc current; ac current; and frequency and period measurement errors, see Application Note 1389-2. (NOTE: The Agilent 34401A, a 6-1/2-digit, high-performance DMM with both benchtop and system features, will be used as an example throughout this article).

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AC Voltage Measurement Errors

Many of the errors associated with dc voltage measurements also apply to ac voltage measurements. This paper covers errors that are unique to ac voltage measurements. For information about dc voltage measurement errors, see Application Note 1389-1.

Common Mode Errors — Errors are generated when the multimeter's input LO terminal is driven with an ac voltage relative to earth. The most common situation where unnecessary common mode voltages are created is when the output of an ac calibrator is connected to the multimeter "backwards." Ideally, a multimeter reads the same regardless of how the source is connected. However, both source and multimeter effects can degrade this ideal situation.

Because of the capacitance between the input LO terminal and earth (approximately 200 pF for the Agilent 34401A), the source will experience different loading, depending on how the input is applied. The magnitude of the error is dependent on the source's response to this loading. The multimeter's measurement circuitry, while extensively shielded, responds differently in the backward input case due to slight differences in stray capacitance to earth. The multimeter's errors are greatest for high-voltage, high-frequency inputs. Typically, the multimeter will exhibit about 0.06% additional error for a 100 V, 100 kHz reverse input. You can use the grounding techniques described for dc common mode problems to minimize ac common mode voltages (see Application Note 1389-1).

True RMS AC Measurements. True RMS- (root mean square) responding multimeters like the Agilent 34401A measure the "heating" potential of an applied voltage. Unlike an "average-responding" measurement, a true RMS measurement is used to determine the power dissipated in a resistor. The power is proportional to the square of the measured true RMS voltage, independent of waveshape. An average-responding ac multimeter is calibrated to read the same as a true RMS meter for *sinewave inputs only*. For other waveform shapes, an average responding meter will exhibit substantial errors (see Figure 1).

The multimeter's ac voltage and ac current functions measure the ac-coupled true RMS value. This is in contrast to the ac+dc true RMS value shown above. Only the "heating value" of the ac components of the input waveform are measured (dc is rejected). For sinewaves, triangle waves and square waves, the ac and ac+dc values are equal since these waveforms do not contain a dc offset. Non-symmetrical waveforms such as pulse trains contain dc voltages, which are rejected by ac-coupled true RMS measurements.

Crest Factor Errors — A common misconception is that "since an ac multimeter is true RMS, its sinewave accuracy specifications apply to all waveforms." Actually, the shape of the input signal can dramatically affect measurement accuracy. A common way to describe signal waveshapes is *crest factor*. Crest factor is the ratio of the peak value to the RMS value of a waveform.

For example, a pulse train's crest factor is approximately equal to the square root of the inverse of the duty cycle as shown in Figure 9. In general, the greater the crest factor, the greater the energy contained in higher frequency harmonics. All multimeters exhibit measurement errors that are crest-factor-dependent.
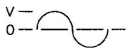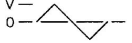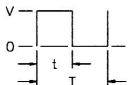
Waveform Shape	Crest Factor (C.F.)	AC RMS	AC+DC RMS	Average Responding Error
	1.414	$\dfrac{V}{1.414}$	$\dfrac{V}{1.414}$	Calibrated for 0 error
	1.732	$\dfrac{V}{1.732}$	$\dfrac{V}{1.732}$	−3.9%
	$\sqrt{\dfrac{T}{t}}$	$\dfrac{V}{C.F.} \times \sqrt{1 - \left(\dfrac{1}{C.F.}\right)^2}$	$\dfrac{V}{C.F.}$	−46% for C.F. = 4

Figure 1.

The following equation shows how to estimate the measurement error due to signal crest factor:

Total Error = Error$_{sine}$ + Error$_{crest factor}$ + Error$_{bandwidth}$

Where:

Error$_{sine}$ = DMM's Sinewave Accuracy
Error$_{crest}$ = DMM's Crest Factor
Error$_{bandwidth}$ = Estimated Bandwidth Error (see below):

$$Error_{bandwidth} = \frac{-C.F.^2 \times F}{4\pi \times BW}$$

Where:

C.F. = Signal Crest Factor
F = Fundamental Input Signal Frequency
BW = DMM's −3 dB Bandwidth (1 MHz for the Agilent 34401A)

Example: Calculating Crest Factor Error

Calculate the approximate measurement error for a pulse train input with a crest factor of 3 and a fundamental frequency of 20 kHz. For this example, assume the multimeter's 90-day accuracy specifications: ±(0.05% + 0.03%) and the error for a 2-3 crest factor is specified as 0.15% of reading.

Total Error = (0.05+0.03)% + 0.15% + ((3^2*20kHz)/(4π*1000kHz))%

Total Error = 0.08% + 0.15% + 1.4% = 1.6%i

AC Loading Errors — In the ac voltage function, the input of the Agilent 34401A appears as a 1MW resistance in parallel with 100 pF of capacitance. The cabling used to connect signals to the multimeter will also add additional capacitance and loading. Figure 2 shows the multimeter's approximate input resistance at various frequencies.

Input Frequency	Input Resistance
100 Hz	1 MW
1 kHz	850 kW
10 kHz	160 kW
100 kHz	16 kW

Figure 2.

For Low Frequencies:

$$Error\ (\%) = \frac{-100 \times R_s}{R_s + 1M\Omega}$$

Additional error for high frequencies:

Where:

$$Error\ (\%) = 100 \times \left[\frac{1}{\sqrt{1 + (2\pi \times F \times R_s \times C_{in})^2}} - 1 \right]$$

R_s = Source Resistance

F = Input Frequency

C_{in} = Input Capacitance (100 pF) plus Cable Capacitance

Note: *Be sure to use low-capacitance cable when measuring high-frequency signals.*

Low-Level AC Measurement Errors — When measuring ac voltages less than 100 mV, be aware that these measurements are especially susceptible to errors introduced by extraneous noise sources. An exposed test lead will act as an antenna and a properly functioning multimeter will measure the signals received. The entire measurement path, including the power line, acts as a loop antenna. Circulating currents in the loop will create error voltages across any impedances in series with the multimeter's input. For this reason, apply low-level ac voltages to the multimeter through shielded cables, and connect the shield to the input LO terminal.

Make sure the multimeter and the ac source are connected to the same electrical outlet whenever possible, and also minimize the area of any ground loops that cannot be avoided. A high-impedance source is more susceptible to noise pickup than a low-impedance source. To reduce the high-frequency impedance of a source, place a

capacitor in parallel with the multimeter's input terminals. There may be some experimentation involved to determine the correct capacitor value for the particular application.

Most extraneous noise is not correlated with the input signal. The equation below shows how to determine the error:

$$Voltage\ Measured = \sqrt{V_{in}^2 + Noise^2}$$

Correlated noise, while rare, is especially detrimental because it will always add directly to the input signal. Measuring a low-level signal with the same frequency as the local power line is a common situation where this error is likely to occur.

Temperature Coefficient and Overload Errors — The Agilent 34401A uses an ac measurement technique that measures and removes internal offset voltages when you select a different function or range. If you leave the multimeter in the same range for an extended period of time, and the ambient temperature changes significantly (or if the multimeter is not fully warmed up), the internal offsets may change. For the Agilent 34401A, this temperature coefficient is typically 0.002% of range per °C. The coefficent is automatically removed when you change functions or ranges.

When manual ranging to a new range in an *overload condition*, the internal offset measurement may be degraded for the selected range. Typically, an additional 0.01% of range error may be introduced. This additional error is automatically removed when you remove the overload condition and then change functions or ranges.

Conclusion

When making high frequency or low voltage AC measurements it is important to minimize error mechanisms. When practical, use a low-impedance source, use proper cabling and minimize loops between cables. To determine AC measurement errors, it is important to include errors due to signal shape, noise and frequency.

For more information about the Agilent 34401A DMM, go to **www.agilent.com/find/34401a**

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