HIGH-FREQUENCY, HIGH-SPEED PHASE-ANGLE MEASUREMENTS AND STANDARDS

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ABSTRACT

Counter-timers capable of measuring the delay between two signals at frequencies up to 20 MHz have been evaluated as phase angle meters with applications in heterodyne interferometry. A scheme for calibrating these instruments both statically and dynamically (with the phase angle changing as fast as $10°/\mu s$) is described.

INTRODUCTION

Digital phase meters, capable of measuring the angle between two signals of equal frequency, have been commercially available for a number of years. However, these instruments are generally limited to signal frequencies below 1 MHz, with the highest accuracies ($<0.1°$) in the audio-frequency range. Phase meters are used to characterize a broad class of electronic equipment ranging from audio to navigation systems. Within the past few years, a new high-precision phase measurement requirement has surfaced in the field of dimensional metrology - specifically heterodyne interferometry. In this application, a knowledge of the phase angle between two electrical signals (derived from the interferometer) can be used to measure mechanical displacements to fractions of an optical wavelength. Electrical signal frequencies are normally above 1 MHz, and to complicate matters further, the rate-of-change of the phase angle between these signals is a function of the rate-of-change of displacement. Thus, in certain applications the phase meter must be able to make a new measurement every microsecond. Several commercial counter-timers (capable of resolving sub-nanosecond time differences) can be configured as phase meters for this application. This paper describes the theory of operation of these phase meters, as well as measurement techniques developed to test and evaluate them in the 100 kHz to 20 MHz frequency range.

COUNTER-TIMERS AS PHASE METERS

Many commercial counter-timers are able to measure the time interval between events that occur on different channels. A few of these instruments, also referred to as "time interval analyzers", are able to measure time intervals with sub-nanosecond precision using analog interpolation techniques.

The basic interpolation technique is illustrated in Fig. 1. The phase angle between signals V_r and V_t, may be defined in terms of:

$$\Phi_r = (T_+/T_r) \times 360^\circ \quad (1)$$

where T_+ is the time difference between the positive going zero crossings of the reference, V_r , and test, V_t , signals, and
T_r is the period of the reference signal.

The internal frequency reference of the time interval analyzer, F, (of period T_c) is counted from t_1 to t_2 to provide a coarse measure (NT_c) of the time interval T_+. The time from t_1 to the first positive going edge of F is T_1, while the time from t_2 to the next positive going edge of F is T_2. Both T_1 and T_2 are computed using an analog interpolation technique similar to that shown at the bottom of Fig. 1. In this method, a capacitor is charged during the interpolation interval. If the charge rate is constant, then the total charge, Q, accumulated during the interval T_1 is $Q = IT_1$, where I is the charging current. The voltage developed across the capacitor due to this charge is Q/C and thus the time interval can be expressed as:

$$T_1 = VC/I \quad (2)$$

where C and I are known and V is measured using a fast analog-to-digital converter (ADC) or, as shown in Fig. 1, by discharging C back to its starting voltage with a current -I/k. This provides a negative going ramp of time interval kT_1 , which can be measured by the digital time-interval function in the instrument. To complete the measurements needed to compute the phase angle between V_r and V_t , a third interpolation is performed at t_3 to estimate T_r .

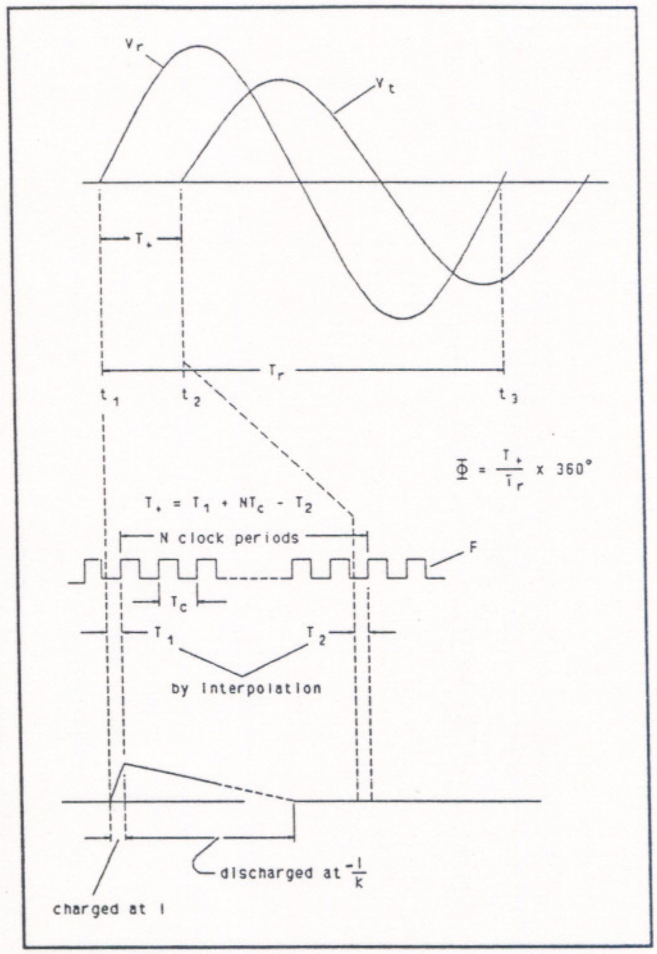

Fig. 1. Time interval measurements using conventional digital methods enhanced by analog interpolation techniques.

Using the techniques described above, the accuracy of the phase angle measurement depends on the time resolution, linearity, and stability of the time interval analyzer. In the case of a 1-MHz signal frequency ($T_r = 1\ \mu s$), a precision of 1-ns is required to resolve 1/1000 of a period (0.36°). Fig. 2 shows the phase resolution that can be achieved at signal frequencies from 2 kHz to 20 MHz with time resolutions from 10 ps to 100 ns. There are a number of commercial time interval analyzers with the ability to resolve 1 ns or less. Their maximum update rates range from 1 kHz to 5 MHz with "single shot" time resolutions from 10 ps to 1 ns (resolution can generally be increased with averaging). These instruments all use analog timing interpolators to achieve resolutions much smaller than the period of their internal frequency references. The interpolators are often proprietary circuits that vary from one instrument to the next, but they typically work, as described above, by charging a circuit during the interpolation period, and then measuring the accumulated charge either with an ADC or by timing the discharge rate.

Strictly speaking, the phase angle between two signals is defined only when those signals are the same frequency; however, it is useful in interferometer applications to relax the definition somewhat and allow the frequencies to be different. If, for example, V_t has a frequency that is 1.5 times higher than V_r, as shown in Fig. 3, we define the phase angle in terms of the period of the higher frequency signal, V_t:

$$\Phi_t = (T_+ / T_t) \times 360^\circ \qquad (3)$$

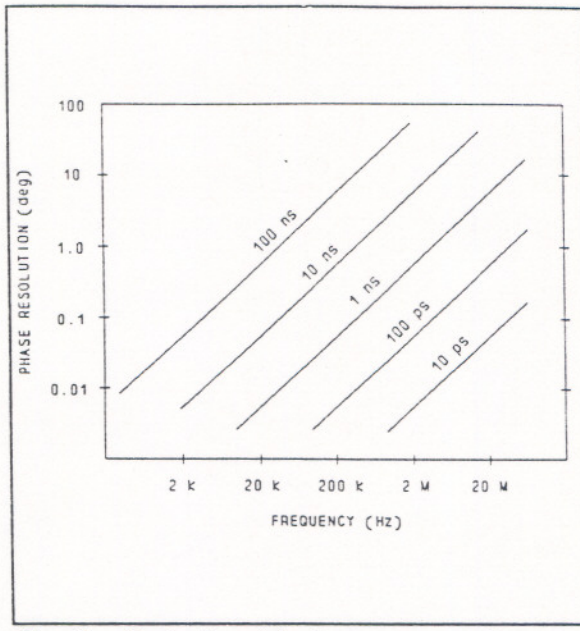

Fig. 2. Relationship between analyzer time resolution and phase resolution.

and measure the time interval between the two signals, T_+, beginning at the positive going zero crossing of the lower frequency signal, V_r.

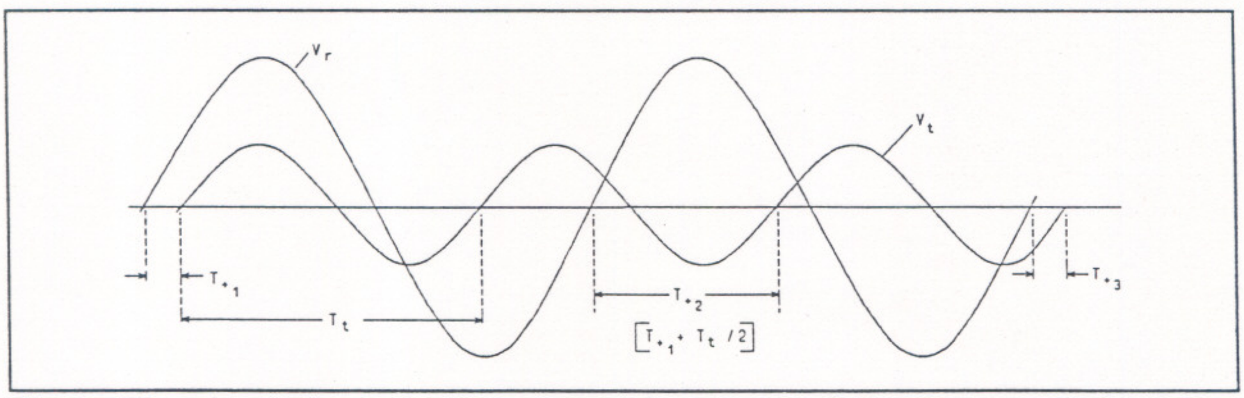

Fig. 3. Time intervals required to measure the phase angle between two signals of different frequency.

For this example, the phase angles will appear to change at a rate of $180^\circ/T_r$ (period of V_r in seconds). Similarly if V_r is a higher frequency than V_t, then measurements will be made at the positive zero crossing of V_t and the phase will be defined using equation 1.

PHASE ANGLE STANDARDS AND TEST METHODS

A type of standard commonly used for calibrating audio frequency phase meters is based on digital synthesis techniques in which sine wave approximations are created by applying stored data to a digital-to-analog converter (DAC). These standard generators [1,2] produce two sine waves, between 1 Hz and 100 kHz, which are adjustable in phase with resolution and accuracy from 0.001° to 0.05°. At higher frequencies it becomes more difficult to synthesize pure waveforms digitally and, above about 100 kHz, it is possible to achieve better phase linearity using a different approach. Two function generators with a common reference oscillator can be configured to produce relatively pure sine waves that are adjustable in phase angle. In one type of generator, the phase relationship between the output signal and the reference oscillator is adjustable in 0.1° steps. Thus if two of these generators are connected to a common reference oscillator, it is possible to program the phase shift between the two output signals by adjusting the phase relationship of one or both signals referenced to the oscillator. Earlier tests of the timing linearity of signals produced by this technique were made using a sampling instrument known as a Sampling Voltage Tracker [3]. Results of those tests indicated that, for this particular function generator, the "time delay" nonlinearity between the reference oscillator and the output signal was less than 10 ps at 20 MHz. This corresponds to a phase nonlinearity of 0.07°.

Based on this performance, a dual channel "Reference Source" (consisting of two function generators) was assembled to test a number of commercial phase meters and time interval analyzers from 250 kHz to 20 MHz. A block diagram of the test setup is shown in Fig. 4. The phase nonlinearity of the signals produced by the reference source was tested below 100 kHz using a digital phase meter that had been calibrated by the phase standard described in reference 1. Results of these tests indicate that the integral phase nonlinearity of the Reference Source was less than ±0.1°. Between 100 kHz and 20 MHz, a technique similar to that employed in [3] was used. Since it is possible to shift the phase of both signals with respect to the common clock, it was possible to generate signals with the same phase angle, by shifting the phase of both signals by an equal amount. For example, if a phase angle of 30° is set between V_r and V_t, and if this angle is measured by a phase meter, then both signals can be shifted by 10°, 20°, ... 360° to measure the differential phase nonlinearity of the two generators in 10° steps (the error of the phase meter drops out because it always sees the same 30°). The results of this test (which will be reported in a future paper) tend to confirm the measurements reported in [3] indicating phase nonlinearities of less than 0.1° from 100 kHz to 20 MHz.

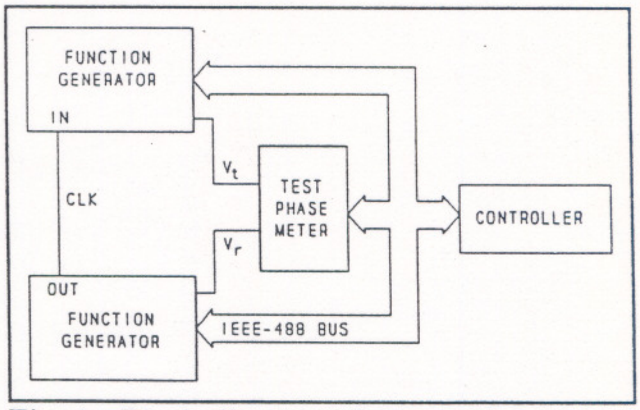

Fig. 4. Block diagram of the test setup and Reference Source (consisting of two function generators with a common clock).

TEST RESULTS

Static tests (both signals at the same frequency) were performed on three different commercial time interval analyzers (configured as phase meters), a commercial phase meter, and a phase meter used in a commercial interferometer system. The results, shown in Figs. 5-7 represent a compilation of measurements made with 1-V signals between 250 kHz and 20 MHz at phase angles between 0° and 360°. The plotted data illustrate the error at each phase angle assuming linear phase of the Reference Source. The zero offset of the

Reference Source was nulled before the tests by applying the same signal to both channels of the phase meter under test and noting the difference between this reading and the reading at the 0° setting of the Reference Source.

Dynamic tests were performed on two of the time interval analyzers that are capable of update rates in excess of 2 MHz. In these tests the Reference Source provided two phase locked signals at different frequencies. This technique relies on the short-term frequency stability of the two signals to produce a linear phase angle rate-of-change that is a function of the difference frequency. The dynamic tests were performed at various signal frequencies from 100 kHz to 2 MHz. The results of tests, performed with V_r = 2 MHz and V_t = 2.2 MHz is shown in Fig. 8. In order to perform a new phase angle measurement at each zero crossing of V_r, the time interval analyzer must have an update rate of 2 MHz (be able to make a new phase measurement every 500 ns). The results shown in Fig. 8 represent the average of 5 measurements made at each of 12 phase angles from 0° to 330° (in increments of 30°). The data were fitted to a straight line (assuming a linear phase rate-of-change) and the residuals of the fit are plotted as phase errors in the figure.

CONCLUSIONS

A new class of counter timers has been evaluated as phase meters which use a combination of digital and analog timing techniques to measure the time interval between the zero crossings of two signals. These instruments operate in the frequency range of <1 Hz to beyond 20 MHz, whereas conventional digital phase meters are designed for optimum performance in the 10 Hz to 50 kHz range with at least one commercial meter specified over a 5 Hz to 500 kHz range. With one exception, the phase angle nonlinearity of the instruments tested was approximately ±(0.05 + 0.1F)° where F is the frequency in MHz. This is an

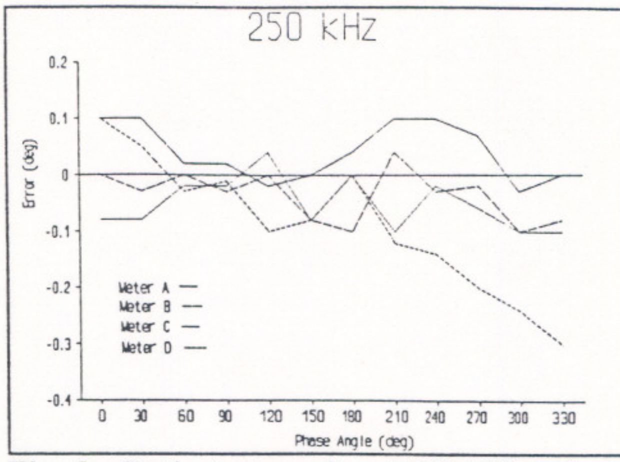

Fig. 5. Static test results at 250 kHz, where signals of the same frequency were applied to both channels.

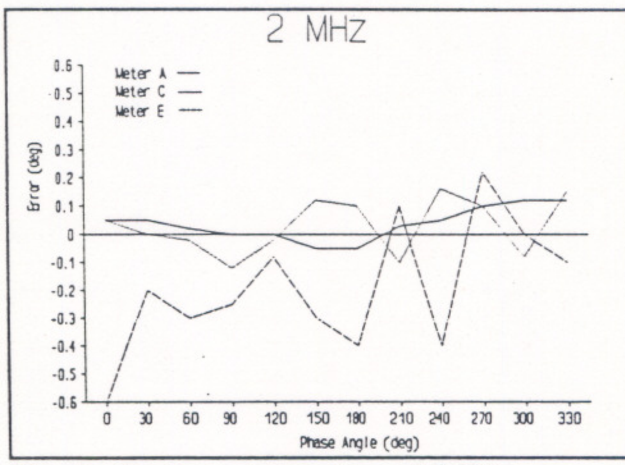

Fig. 6. Static test results at 2 MHz.

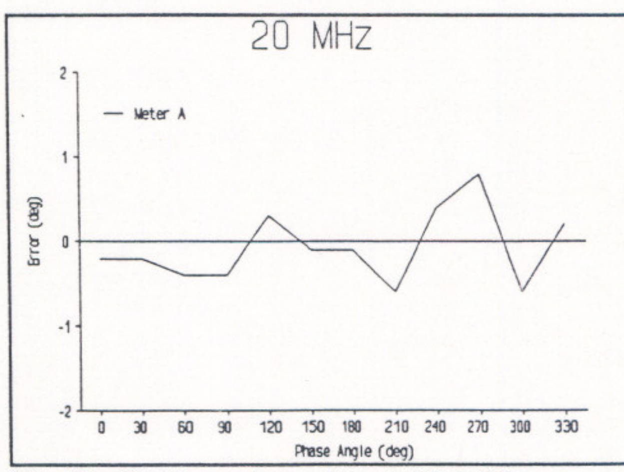

Fig. 7. Static test results at 20 MHz.

experimental figure based on measurements made with signals of the same amplitude and wave shape applied to each channel. The time interval analyzers generally have much higher update rates; 1 kHz to 5 MHz compared to 1 Hz or less for the digital phase meters. However, the digital phase meters are intended for higher accuracy applications, employ techniques to minimize the influence of waveshape, and operate over a much wider amplitude range.

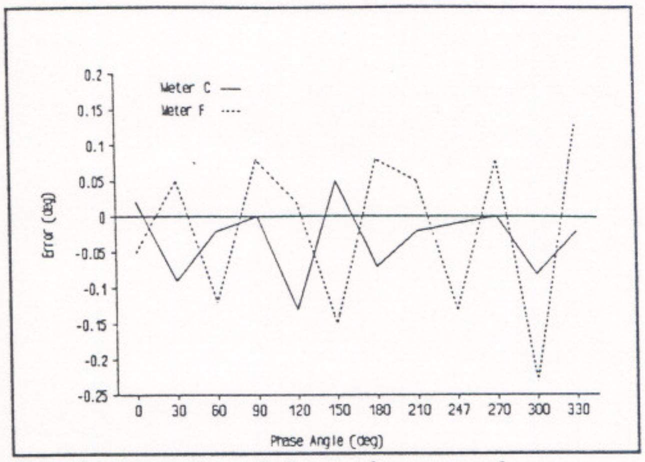

Fig. 8. Results of dynamic tests where a 2 MHz signal was applied to one channel and a 2.2-MHz signal applied to the other.

The dynamic performance of several of the newer time interval analyzers is of particular interest to users of heterodyne interferometers. In this application electrical signals, proportional to mechanical displacement can be processed to measure the position of a moving object in microsecond time regimes. The measurements reported in this paper show that under the best conditions, electronic limitations imposed by the phase measurement will begin to limit the interferometer accuracy at about 0.3° which corresponds to less than 1/1000th of a wavelength.

ACKNOWLEDGMENT

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