Electronic Limitations in Phase Meters for Heterodyne Interferometry

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Reasonable attention has been given to the fidelity of the process by which heterodyne interferometers convert optical path difference between beams that have traversed a test leg and a reference leg, respectively, to a phase difference between electrical signals from the test and reference photodetectors. This paper reports on a study of the next step; to obtain a quantitative result from these signals by measuring the electrical phase difference between the two photodetector signals.

In the least demanding applications, where the test reflector is moved and then stopped (with respect to the reference reflector), a fixed phase relationship exists between the two electrical signals at the time of measurement. Commercial phase angle meters operate at signal frequencies out to about 500 kHz, with angular uncertainties of ±0.2° and measurement speeds on the order of one reading per second. The recent advent of commercial time interval analyzers has made it possible to make phase angle measurements at the higher frequencies and update rates required by heterodyne interferometry.

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, a precision of 1-ns is required to resolve 1/1000 of a period (0.36°). Fig. 1 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).

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 measure the apparent phase angle between two signals of different frequency. If the test reflector is moved to produce a signal that is changing in phase relative to the reference signal, the test signal may be expressed as:

$$V_t = A \cos (wt + \phi(t)),$$

where w = frequency of the reference and $\phi(t)$ is the rate of change of phase.

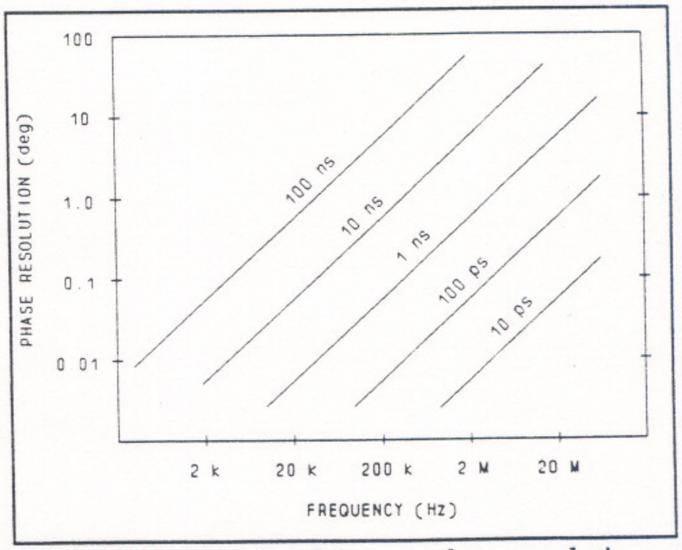

Fig. 1. Relationship of time to phase resolution at frequencies from 2 kHz to 20 MHz.

It can be shown that $\phi(t)$ is equivalent to a frequency term that, depending on the direction of phase shift, either increases or decreases the frequency of the test signal [1]. For example, if the reference signal is 1 MHz and the test signal is phase shifted at a rate of 180°/μs, then the frequency of the test signal will be 1.5 MHz.

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. Tests of the timing linearity of signals produced by this technique indicated that, for this particular function generator, the "time delay" nonlinearity between the reference oscillator and the output signal is less than 10 ps [2]. This corresponds to a phase uncertainty of less than 0.01° at 2 MHz. Based on this performance, a dual channel 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.

Static tests (both signals at the same frequency) were performed on a number of different analyzers configured as phase meters. The results of tests performed at 2 MHz on two of these instruments are shown in Fig. 2. Based on tests at other frequencies, an experimental figure for the phase uncertainty (due to nonlinearity and random scatter) of a typical time interval analyzer used to measure phase is given by: ±(0.05 + 0.1F)°, where F is the test frequency in MHz.

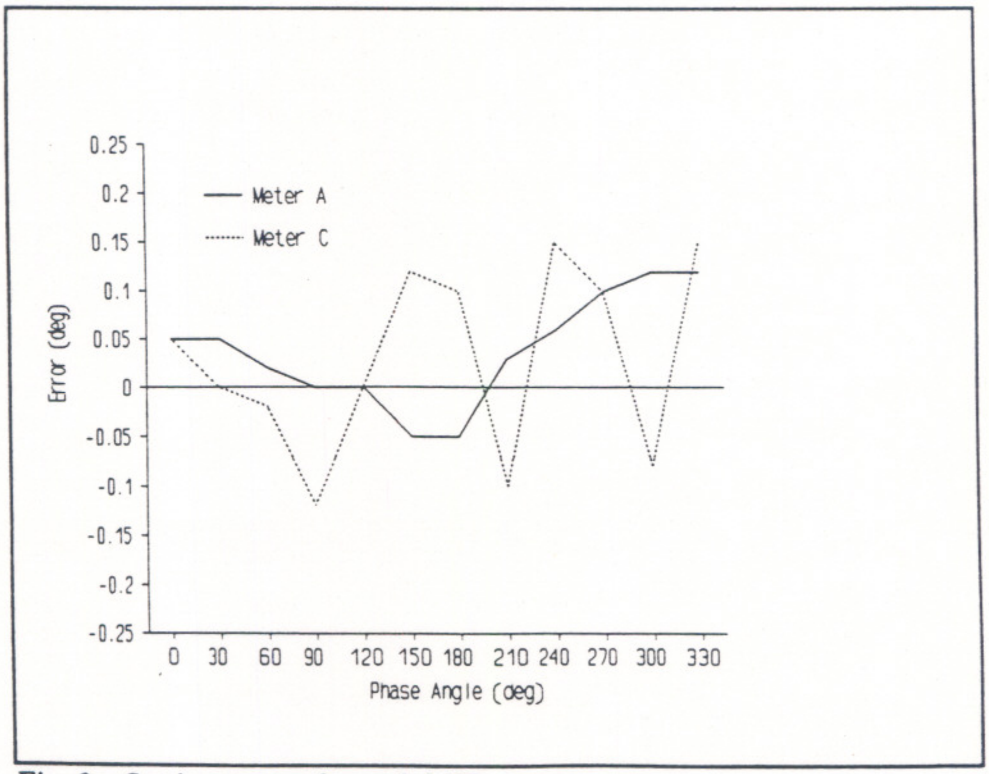

Fig. 2. Static test results at 2 MHz.

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 signal was 2 MHz and the test signal (which simulates the Doppler shifted signal from the moving test reflector) was about 2.2 MHz giving a linear phase angle rate-of-change of 30°/μs. The dynamic nonlinearities shown in Fig. 3 are based on time interval measurements made on-the-fly at 500 ns intervals.

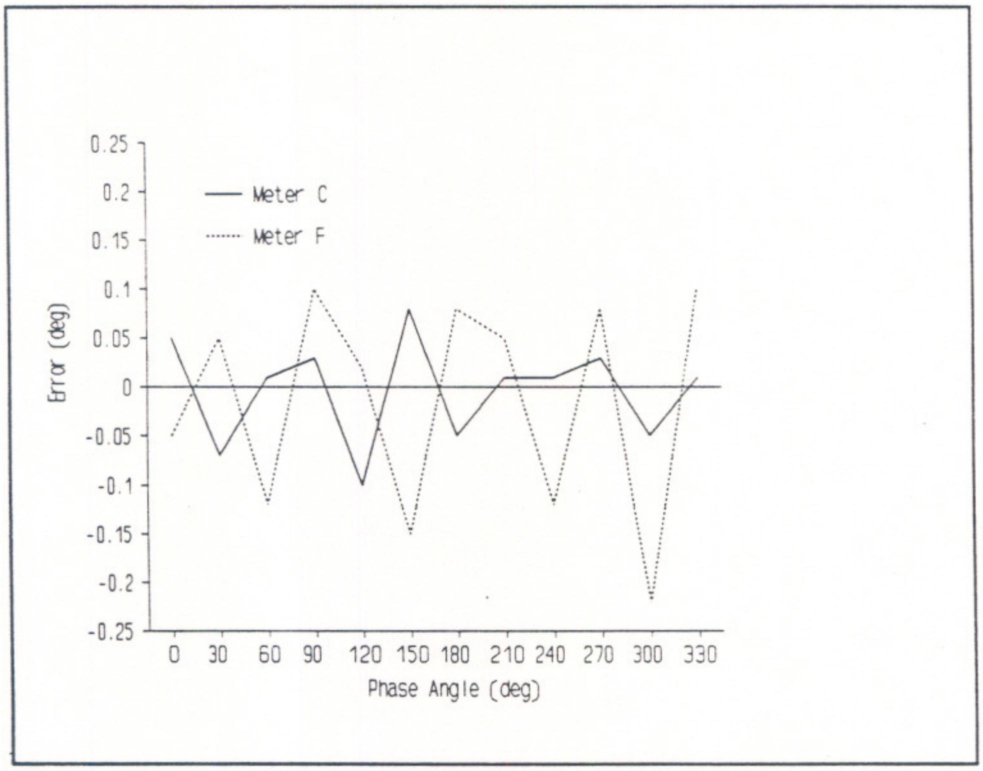

Fig. 3. Dynamic test results at 2 MHz and 2.2 MHz.

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, electronic limitations imposed by the phase measurement correspond to timing errors of about 350 ps (±0.25° at 2 MHz) which will limit the precision of a simple Michelson interferometer, to about 1/3000th of a wavelength at a reference signal frequency of 2 MHz.

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2. Oldham, N.M. and Hetrick, P.S., "High-Frequency, High-Speed Phase Angle Measurements and Standards," Conf. Proc. of the 1991 NCSL Workshop and Symposium, Albuquerque, NM, August 19-23, 1991, pp 252-256.