APPLICATION NOTE 191-6

PRECISION TIME INTERVAL GENERATION AND MEASUREMENT APPLICATIONS LIBRARY

PRECISE CABLE LENGTH AND MATCHING MEASUREMENTS USING THE 5370A UNIVERSAL TIME INTERVAL COUNTER AND 5363B TIME INTERVAL PROBES

INTRODUCTION

Characterization of cable parameters such as electrical length (delay) is very important in the design of cable systems, balanced networks, matching stubs and other applications where cable assemblies are trimmed to specific electrical lengths. This application note describes a technique to measure either the length, dielectric constant or propagation delay matching of transmission lines using an HP 5370A Universal Time Interval Counter and an HP 5363B Time Interval Probe.

The measurement technique used for both transmission line matching and length measurements employs the injection of a pulse into the system. A time interval measurement is then made between incident and reflected pulse on the same line for length and dielectric constant measurements. Both length and dielectric constant can then be computed from equation 1 using the time interval measured. For matching transmission line lengths, a time interval measurement is made between incident and reflected pulse on a reference transmission line and the resultant time interval is then compared with a similar propagation delay measurement made on another line. The length of the transmission line under test is then trimmed so its propagation delay matches that of the reference transmission line.

Cable parameter measurements as discussed in this application note are time interval measurements which can best be made using instruments specifically designed for that purpose, such as the 5370A Universal Time Interval Counter and 5363B Time Interval Probes which when used together form a very powerful time interval measurement system. The 5370A represents the highest resolution single-shot time interval counter available in the world today. The counter utilizes an innovative technique of phase locked vernier interpolation, which allows single shot-time interval measurements with ±20 picosecond resolution. This technique also allows positive, zero and negative time intervals to be measured. The 5363B allows accurate and repeatable time interval measurements by an extended dynamic range, precise and convenient trigger level settability and minimum circuit loading by low capacitance active probes which make the measurement at the point under test.

THEORETICAL CONSIDERATIONS

The velocity of propagation of an electrical signal through a medium is dependent upon two specific properties of the medium: the permeability μ and the permittivity e, and is given by

$$V_p = \frac{1}{\sqrt{\mu\epsilon}}$$

The velocity of propagation in free space (or air), V_o, is given by

$$V_o = \frac{1}{\sqrt{\mu_o\ \epsilon_o}} = 3.00 \times 10^8 \text{ meters/sec} = c$$

where $\mu_o = 4\pi \times 10^{-7}$ henries/m and $e_o = 1/36\pi \times 10^{-9}$ farads/m. The velocity of propagation in any medium may be expressed as

$$V_p = \frac{V_o}{\sqrt{\mu_r\ \epsilon_r}}$$

where μ_r = relative permeability = μ/μ_o and ϵ_r = relative permittivity (dielectric constant) = ϵ/ϵ_o. For most cases of interest, $\mu = \mu_o$ and the velocity of propagation becomes

$$V_p = \frac{V_o}{\sqrt{\epsilon_r}} = \frac{3.00 \times 10^8 \text{ meters/sec}}{\sqrt{\epsilon_r}}$$

This expression is valid also when loss in the medium is present.

In this application note, the capability of both the 5363B and 5370A are used to precisely measure the time interval between an incident and reflected pulse on a transmission line. The time interval (t) measured by the counter is twice the one-way cable delay. The length of the cable is computed, when the dielectric constant of the material (ϵ_r) is known, from the equation,

$$(1) \qquad l = \frac{c \cdot t}{2\sqrt{\epsilon_r}}$$

where l = length of transmission line

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TABLE 1

Dielectric Material	**ϵ_r (1 MHz)**
air	1.0
*Teflon beads	1.02
Teflon helix	1.23
foam polyethylene	1.5
solid Teflon	2.04 - 2.1
solid polyethylene	2.25 - 2.34
solid polypropylene	2.25

*Teflon is Dupont's trade name for polytetrafluoroethylene.

Table 1 is a tabulation of dielectric constants for the dielectric materials most often used in coaxial cables. Even though the values were determined at 1 MHz, ϵ_r, is relatively independent of frequency for non-polar dielectrics (such as polyethylene and teflon).

If the dielectric constant of the transmission line is unknown, it can be experimentally determined by cutting a sample of the test transmission line to a known length and solving for the dielectric constant in equation 1

$$\epsilon_r = \left(\frac{c \cdot t_1}{2l_1}\right)^2 \tag{2}$$

where t_1 = measured time interval between incident and reflected pulses on the sample.

l_1 = measured length of the sample

In lieu of calculating the dielectric constant of the sample, a simpler ratio method can be used to determine the length of the transmission line, i.e.

$$l_2 = \frac{l_1 \cdot t_2}{t_1} \tag{3}$$

where

l_2 = length of test cable
l_1 = length of sample cable
t_2 = measured time interval between incident and reflected pulses on test cable.
t_1 = measured time interval between incident and reflected pulses on sample cable.

The amplitude of the reflected pulse is another important aspect of transmission line length measurements. As the length of the transmission line increases, the high frequency loss in the line increases and consequently the amplitude of the reflected pulse decreases. The amplitude of the reflected pulse, therefore, not only depends upon the incident pulse amplitude but also on its frequency which is related to pulse width. This can be expressed as

$$\frac{dB}{l} = \frac{\propto}{\sqrt{pw}} \tag{4}$$

where

dB = attenuation
pw = incident pulse width
$\propto$ = a quality constant of the transmission line which depends on the inherent loss in the line
l = length of sample line

$\propto$ can be calculated from our sample of test transmission line, i.e.

$$\propto = \frac{dB\sqrt{pw}}{l} \tag{5}$$

to aid in calculating the length of the cable, or the necessary incident pulse width for detecting a discontinuity in the test cable or its length.

MEASUREMENT ERRORS

When determining the length of a transmission line from equation 1, the error in length (Δl) is a function of the time interval measurement error (Δt_1) and dielectric constant error ($\Delta\epsilon_r$). Mathematically the error in length measurement, dl, is given by,

$$dl = \frac{\partial}{\partial t}\left[\frac{c \cdot t_1}{2\sqrt{\epsilon_r}}\right] dt_1 + \frac{\partial}{\partial \epsilon_r}\left[\frac{c \cdot t_1}{2\sqrt{\epsilon_r}}\right] d\epsilon_r$$

$$dl = \left[\frac{c}{2\sqrt{\epsilon_r}}\right] dt_1 - \left[\frac{l}{2\epsilon_r}\right] d\epsilon_r \tag{6}$$

where:

$d\epsilon_r$ = uncertainty in dielectric constant
dt_1 = time interval measurement accuracy from equation 7.

$$dt_1 = \pm \left[\frac{\overset{(1)}{\text{trigger error}}}{\sqrt{N}}\right] \pm \left[\frac{\overset{(2)}{\text{jitter}}}{\sqrt{N}}\right] \pm \left[\begin{matrix}(3)\\ \text{trigger level}\\ \text{timing error}\end{matrix}\right] \pm \left[\begin{matrix}(4)\\ \text{differential channel}\\ \text{delay error}\\ \text{(systematic)}\end{matrix}\right] \pm \left[\begin{matrix}(5)\\ \text{timebase error}\end{matrix}\right] t_1 \pm \left[\begin{matrix}(6)\\ \text{differential}\\ \text{linearity}\end{matrix}\right] \tag{7}$$

(1) trigger error (rms) $= \dfrac{1.414\sqrt{x^2 + en^2}}{\text{Input Slew Rate (V/Sec)}}$

where: X = effective rms noise of 5363B's input channel (typically 125 μ volts)

en = rms noise voltage of input signal measured over a bandwidth equal to the 5363B's input amplifier bandwidth.

(2) jitter = for 5363B, typically 100 picoseconds

(3) trigger level

$$\text{timing error} = \frac{\text{trigger level error}}{\text{signal slew rate at trigger point}}$$

(4) differential channel delay, for 5363B, typically ± 1 nsec. Can be eliminated by performing time zero calibration of instrument.

(5) 5370 Timebase: crystal frequency 10 MHz

STABILITY:

Aging rate: $<3 \times 10^{-7}$ per month
Short term: $<2 \times 10^{-9}$ rms for 1 s average
Temperature: $<2 \times 10^{-6}$ 25°C to 35°C
$<5 \times 10^{-6}$ 0°C to 55°C
Line Voltage: $<1 \times 10^{-8}$, ± 10% from nominal

Option 001: High Stability Time Base
(HP Model 10544A)

Crystal Frequency: 10 MHz

STABILITY:

Aging Rate: $<5 \times 10^{-10}$ per day
Short Term: $<1 \times 10^{-11}$ for 1 s average
Temperature: $<7 \times 10^{-9}$ 0°C to 55°C
Line Voltage: $<1 \times 10^{-10}$, ±10% from nominal

(6) differential linearity, typically $< \pm 20$ picoseconds

By using the ratio method, equation 3, measurement error is dependent on the uncertainty in sample cable length (Δl_1) and both sample cable and test cable time interval measurement errors (Δt_1 Δt_2). Mathematically the error in measurement, dl_2, is given by,

$$dl_2 = \frac{\partial}{\partial l_1}\left[\frac{l_1 t_2}{t_1}\right] dl_1 + \frac{\partial}{\partial t_2}\left[\frac{l_1 t_2}{t_1}\right] dt_2 + \frac{\partial}{\partial t_1}\left[\frac{l_1 t_2}{t_1}\right] dt_1$$

$$(8) \qquad dl_2 = \frac{l_1 t_2}{t_1}\left[\frac{dl_1}{l_1} + \frac{dt_2}{t_2} - \frac{dt_1}{t_1}\right]$$

dl_1 = uncertainty in actual length of sample line.

dt_1, dt_2 = time interval measurement accuracies from equation 7

MEASUREMENT SYSTEM OPERATION

The basic measurement system set-up is shown in figure 1 and photo 1. An HP 8007A pulse generator is used to inject pulses into the test cable. The pulse generator's trigger output externally triggers the oscilloscope. One probe of the HP 5363B Time Interval Probes is used to make the time interval measurement, its start and stop outputs are connected to the start and stop inputs of the HP 5370A Universal Time Interval Counter. To visually monitor the measurement, an oscilloscope is connected to the point at which pulses are injected into the test cable.

For further practical consideration, the delay between trigger output of the pulse generator and its pulse output must be about 10 μsec so that the leading edge of the incident pulse can be observed on the oscilloscope. In order to ensure a quality display on the oscilloscope, a high impedance probe (10:1) with a short connection from probe tip ground to system ground must be used. Trigger level settings on the 5363B are critical parameters in the measurement setup. Ideally both trigger levels are set on the linear portion of both incident and reflected pulses. However, the reflected pulse is normally subjected to degradation and is of lower amplitude and shape than the incident pulse.

In order to make a meaningful time interval measurement, the stop trigger point must be as close to the base of the pulse as possible without having the base noise affect the trigger level.

Systematic error due to differential channel delay can be eliminated by performing a Time Zero Calibration of the 5363B Time Interval Probes or by doing a zero time interval measurement and pressing the SET REF key on the 5370A which causes the error to be subtracted from all future measurements.

Figure 2 is a typical timing diagram of the measurement system.

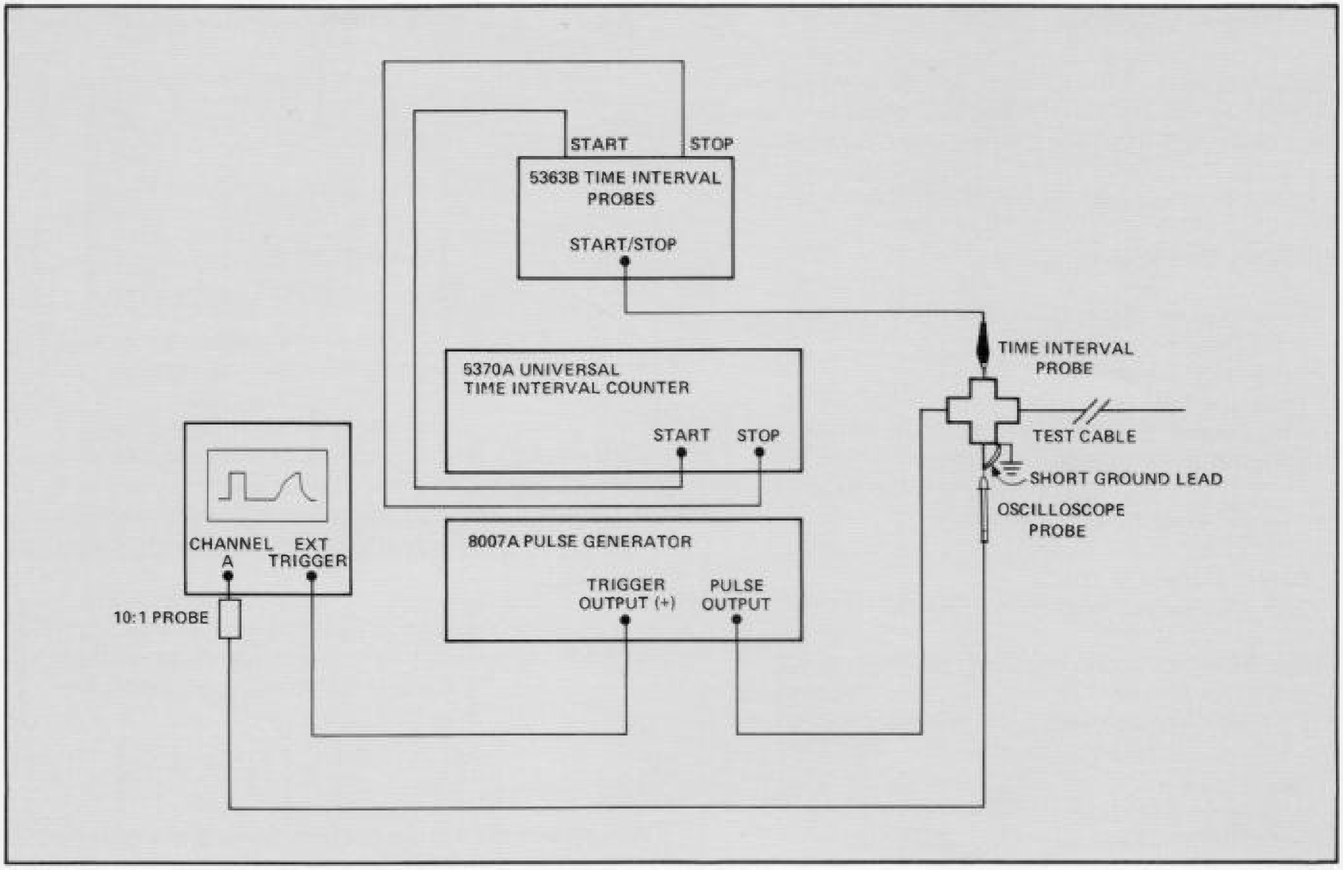
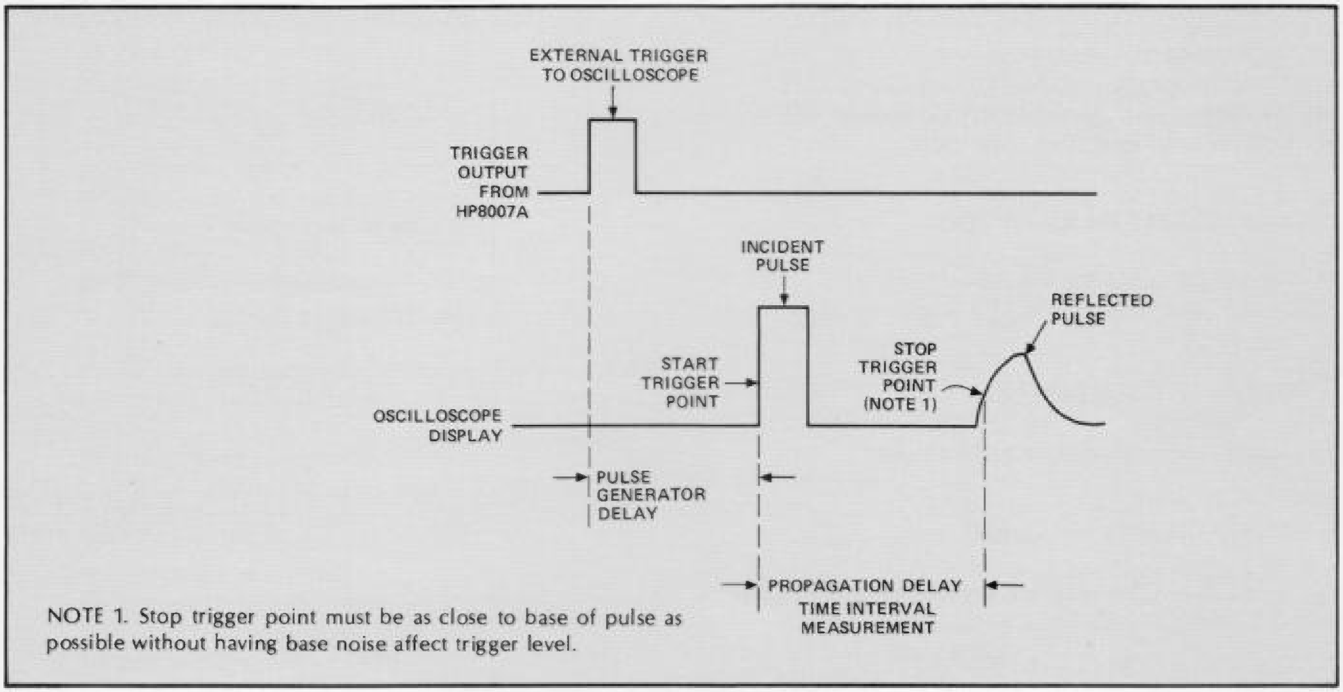


Figure 1. Measurement System Connection



NOTE 1. Stop trigger point must be as close to base of pulse as possible without having base noise affect trigger level.

Figure 2. Measurement System Timing Diagram

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