FLUKE®

Fluke PM 6681 Timer / Counter / Analyzer
Accurate phase calibration

Application Note

The PM 6681 Timer/Counter Analyzer is a multifunction instrument that is ideal for calibrating a wide variety of time and frequency related parameters - including frequency, period and time intervals, and phase. The very high single-shot resolution of 50 ps (1 ps averaged) combined with a wide variety of time base options including a super high-stability atomic rubidium timebase oscillator. Together, these provide fast calibration of time and frequency parameters with very high accuracy, both in the field and in the calibration lab.

The built-in statistics functions simplify calibration by instantly calculating the mean value, standard deviation and max-min peaks over any selected sample size up to 4 billion samples. The TimeView™ PC analysis software enables visual feedback and documentation of the measurement process. Measurement vs. time graphs, smoothing (digital filtering) and distribution histograms are all possible.

Phase calibration

The PM 6681 can calibrate phases very accurately, particularly when the procedures on the next page are followed. Several factors may influence the uncertainty when calibrating the phase angle between signals on channel A and channel B, and the following conditions should be considered for maximum accuracy.

a) Perform internal hysteresis calibration before making the (single-key) phase calibration

b) Combine single-shot measurements with statistical calculation of the mean value to improve resolution.

c) Use DC- instead of AC-coupling for frequencies below 500 Hz to eliminate phase errors caused by tolerances in AC coupling components.

d) The optimum input voltage range for highest accuracy is between 0.3 and 3 Vrms (3 and 30 Vrms with 10× input attenuation). Higher input voltages than 30 Vrms need external attenuation; lower input voltages than 0.3 Vrms lead to increased uncertainty.

e) Use two external matched low-pass filters for signals that may contain noise.

f) Externally swap the start and stop signals and take the average value of these measurements to reduce the uncertainty caused by trigger level offsets and inequality of external filters.

Calibration procedure for Phase calibrating a generator

Before calibrating, be sure that both generator and PM 6681 are in a controlled climatic environment, and that both instruments are warmed up according to the manufacturers' specifications.

A. Set up the PM 6681 Timer/Counter/Analyzer

1. Select function PHASE A-B
2. Set input channels A and B to:
   - DC coupling (for freq. < 500 Hz)
   - 1 MΩ input termination
   - Positive Slope
   - Trigger level 0 V
   - AUTO trigger Off
3. Select MEASUREMENT – SINGLE: on

4. Set MEASUREMENT – TIME – 100 µs to speed up the readings
5. Select STAT – ON – MEAN – 100 samples to reduce jitter and improve resolution

B. Make an internal hysteresis calibration

1. Disconnect any signal cables from the A and B input channels on the PM 6681
2. Press button AUX MENU, select CAL HYST and press ENTER.
3. Reconnect signal cables.

C. Connect the Generator to be calibrated

Connect the two phase-shifted outputs from the generator to Channel A and B of the PM 6681. If the output signals contain HF-noise and spurious signals, use two identical LP-filters (3 dB bandwidth at least 25 times above max. signal frequency) to reduce any trigger error caused by noise from the generator. See Figure 1, which shows a Fluke 5500A calibrator as an example, in which case LP-filters are recommended.

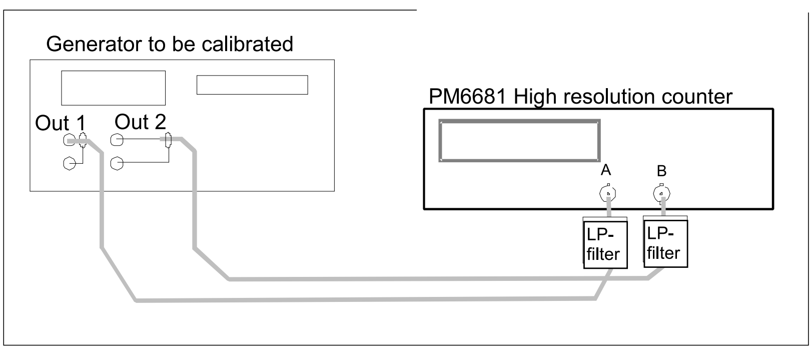

Figure 1

D. Set-up for Voltage to Current Phase measurements

Some generators produce a phase shift between a voltage output and a separate current output. The PM 6681 has no current input, and requires two input voltage signals. The current output of the generator must therefore be converted to a voltage using, for example, a shunt resistor with suitable resistance and power rating. For minimum uncertainty, keep input levels for both input channels in the same order of magnitude.

Example suitable for the Fluke 5500 Calibrator:

Aux output:	300 mA	2A	5 A
Shunt resistor Ri:	3 Ω, 0.5W	0.3 Ω, 10W	0.3 Ω, 10W

E. Procedure for high-accuracy measurements

Uncertainty levels below 0.5° require two series of measurements: first with normal connections and then with the input signals swapped, as shown in Figure 2 below.

1. First connect signal 1 to input A and signal 2 to input B, resulting in the mean value φ1-2.
2. Next connect signal 1 to input B and signal 2 to input A, giving φ2-1. Note: Do not use the internal SWAP A-B button.
3. Finally, calculate the average value of the results φ1-2 and 360°-φ2-1. This procedure will compensate for systematic uncertainties due to trigger level errors.

Figure 2

FLUKE

Appendix
Uncertainty calculations according to recommendation INC-1 (ISO, BIPM)

General
1. Identify all contributing uncertainty factors
2. Express the influence of all factors (whether random or systematic) on the measured value as one standard deviation. The standard deviation of a systematic uncertainty given as limit values ±A, is A / √3 for a rectangular distribution.
3. If all factors are uncorrelated, express Combined Uncertainty (u_c) as the root of the sum of the squares.
4. To obtain higher confidence level ('2 σ'), multiply u_c by 2 to get the total uncertainty (U).

Phase measurements
The phase (A-B) between the input signals that are connected to inputs A and B is measured in two consecutive measurements:
- Period (T) of signal on input A
- Time interval (TI) from set trigger levels (normally zero crossings) of input A to input B

The phase is then calculated as:

$$\Phi_{A-B} = \frac{TI}{T} \times 360°$$

The combined uncertainty of the phase is called u_Φ and the standard uncertainties in the period and time interval measurements are called u_T and u_{TI} respectively.
The relative uncertainty of the measurement can be expressed as:

$$\left(\frac{u_\Phi}{\Phi}\right)^2 = \left(\frac{u_{TI}}{TI}\right)^2 + \left(\frac{u_T}{T}\right)^2$$

Example
Phase between zero crossings of two sine-wave signals with Signal/Noise-ratio (SNR) = 60 dB, frequency = 1 kHz and UA = 2 Vrms, UB = 1 Vrms.

A – The uncertainty of the period measurement

Random uncertainty factors
1. Resolution (single-shot):
$u1$=50 ps (rms - value)

2. Start trigger point uncertainty due to noise:

$$u2 = \frac{\sqrt{(Internal\ noise)^2 + (External\ noise)^2}}{Signal\ Slew\ Rate\ at\ trigger\ point}$$

For small values of ΔU_A the signal slew rate is approx. equal to the slew rate at the zero crossing.
For a sine-wave signal $u = \hat{U} \cdot \sin(\omega t)$, the slew rate ($\frac{du}{dt}$) equals $\hat{U} \cdot \omega \cdot \cos(0) = 2\pi f \cdot U_{rms} \cdot \sqrt{2}$

$$u2 = \frac{\sqrt{(100\ \mu V)^2 + (External\ noise)^2}}{2\pi \cdot Freq \cdot U_{rms} \cdot \sqrt{2}} = \sqrt{\left(\frac{100\ \mu V}{U_{rms}}\right)^2 + (SNR)^2} \times \frac{1}{4\pi \cdot \sqrt{2} \cdot 1000} =$$

$$= \sqrt{0.00005^2 + 0.001^2} \times 56 \cdot 10^{-6} \approx 56\,\text{ns (rms - value)}$$

3. Stop trigger point uncertainty due to noise:

$$u3 = \frac{\sqrt{(Internal\ noise)^2 + (External\ noise)^2}}{Signal\ Slew\ Rate\ at\ trigger\ point} \approx 56\,\text{ns (rms - value)}$$

4. Combined uncertainty u_T for period:

$$u_T = \sqrt{0^2 + 56^2 + 56^2} \approx 79\,\text{ns (rms - value)} \Rightarrow \frac{u_T}{T} = \frac{79\,\text{ns}}{1\,\text{ms}} \approx 8 \cdot 10^{-5}$$

(This is reduced to 8 x 10^{-6} after statistical averaging with 100 samples, which is completely negligible.)

B – The uncertainty of the time interval measurement

Random uncertainty factors:
1. Resolution (single-shot):
$u1$ = 50 ps (rms - value)

2. Start trigger point uncertainty due to noise:

$$u2 = \frac{\sqrt{(Internal\ noise)^2 + (External\ noise)^2}}{Signal\ Slew\ Rate\ at\ trigger\ point}$$

For small values of ΔU_A the signal slew rate is about equal to the slew rate at the zero crossing.
For a sine-wave signal $u = \hat{U} \cdot \sin(\omega t)$, the slew rate ($\frac{du}{dt}$) equals $\hat{U} \cdot \omega \cdot \cos(0) = 2\pi f \cdot U_{rms} \cdot \sqrt{2}$

$$u2 = \frac{\sqrt{(100\ \mu V)^2 + (External\ noise)^2}}{2\pi \cdot Freq \cdot U_{rms} \cdot \sqrt{2}} = \sqrt{\left(\frac{100\ \mu V}{U_{rms}}\right)^2 + (SNR)^2} \times \frac{1}{4\pi \cdot \sqrt{2} \cdot 1000} =$$

$$= \sqrt{0.00005^2 + 0.001^2} \times 56 \cdot 10^{-6} \approx 56\,\text{ns (rms - value)}$$

3. Stop trigger point uncertainty due to noise:

$$u3 = \frac{\sqrt{(Internal\ noise)^2 + (External\ noise)^2}}{Signal\ Slew\ Rate\ at\ trigger\ point} \approx 6.3\,\text{ns (rms - value)}$$

$$u3 = \frac{\sqrt{(100\ \mu V)^2 + (External\ noise)^2}}{2\pi \cdot Freq \cdot U_{rms} \cdot \sqrt{2}} = \sqrt{\left(\frac{100\ \mu V}{U_{rms}}\right)^2 + (SNR)^2} \times \frac{1}{2\pi \cdot \sqrt{2} \cdot 1000} =$$

$$= \sqrt{0.00005^2 + 0.001^2} \times 11 \cdot 10^{-5} \approx 110\,\text{ns (rms - value)}$$

Combined random uncertainty $u_{TI(R)}$ for time interval:

$$u_{TI(R)} = \sqrt{0^2 + 56^2 + 110^2} \approx 120\,\text{ns (rms - value)}$$

(reduced to 12 ns after statistical averaging with 100 samples, which is totally negligible).

Systematic uncertainty factors:

4. Start trigger point uncertainty due to trigger level offset (T.L. Setting Error)

$$u4 = \frac{\Delta U_A}{\textit{Signal Slew Rate at start trigger point}}$$

After a hysteresis calibration, the uncertainty in the 0 V trigger level setting ΔU_A is 2.5 mV or less.
For small values of ΔU_A the signal slew rate is approx. equal to the slew rate at the zero crossing.
For a sine-wave signal $u = \hat{U} \cdot \sin(\omega t)$, the slew rate ($\frac{du}{dt}$) equals $\hat{U} \cdot \omega \cdot \cos(0) = 2\pi f \cdot U_{rms} \cdot \sqrt{2}$

$$u4 = \frac{\Delta U_A}{2 \cdot \pi \cdot Freq \cdot U_{rms}(A) \cdot \sqrt{2}} = \frac{2.5\,\text{mV}}{2\pi \cdot 1000\,\text{s}^{-1} \cdot 2\,\text{V} \cdot \sqrt{2}} \approx 0.14\ \mu\text{s}\ \ \text{(limit value)}$$

5. Stop trigger point uncertainty due to trigger level offset (T.L. Setting Error)

$$u5 = \frac{\Delta U_B}{2 \cdot \pi \cdot Freq \cdot U_{rms}(B) \cdot \sqrt{2}} = \frac{2.5\,\text{mV}}{2\pi \cdot 1000\,\text{s}^{-1} \cdot 1\,\text{V} \cdot \sqrt{2}} \approx 0.28\ \mu\text{s}\ \ \text{(limit value)}$$

$$u5 = \frac{\Delta U_B}{\textit{Signal Slew Rate at stop trigger point}}$$

6. Channel asymmetry uncertainty (500 ps)
*u*6=500 ps (limit value)

Combined systematic uncertainty uTI(S) for time interval:

$$u_{TI(S)} = \sqrt{\frac{0.14^2 + 0.28^2 + 0^2}{3}} \approx 0.18\,\mu\text{s (rms - value)}$$

(Can NOT be reduced by statistical averaging)

Total uncertainty (2σ)
The analysis above shows that when making a phase A-B measurement and averaging the result (N = 100), the overall dominant source for uncertainty is the systematic uncertainty of the time interval measurement, due to a small zero-level offset:
Combined uncertainty for period measurement:
8 ns (rms) (⇒ 0.003° uncertainty)
Combined random uncertainty for time interval meas.:
12 ns (rms) (⇒ 0.009° uncertainty)
Combined systematic uncertainty for time interval meas.:
180 ns (rms) (⇒ 0.13° uncertainty)
For a given phase measurement, the period can be regarded as constant and invariable and all uncertainty is associated with the time interval measurement. Thus ΔΦ can be expressed as:

$$\Delta\Phi = \frac{\Delta TI}{T} \times 360°$$

This leads to a total uncertainty *U* (2 σ) in this example of:

$$U = 2 \times \frac{180\,\text{ns}}{1\,\text{ms}} \times 360° = 0.13°$$

C – Reducing the systematic uncertainty by swapping the inputs

As found in the previous calculations, uncertainties well below 0.1° are difficult to reach without special precautions. A two-step procedure, where the result is obtained from two consecutive measurements with the signal swapped in the second measurement, will significantly improve the uncertainty.

The timing uncertainties in the trigger points (1…4) caused by the trigger level uncertainties can be expressed as follows:

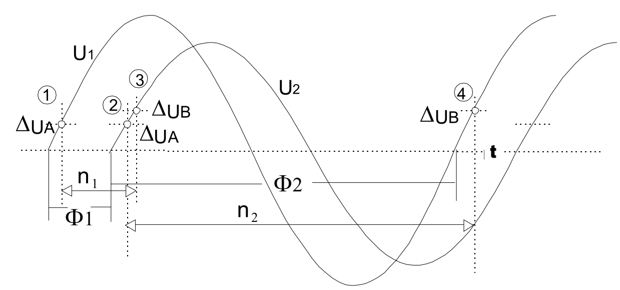

Figure 3

Figure 3 above shows the input signals with amplitudes U1 and U2 respectively with a fixed phase relation of Φ1 (U2 –U1), and Φ2 (U1– U2) (the "true" values), where Φ2 = 360° – Φ1. The actual measured values are φ1 between trigger point 1 and 3 for Φ1 and φ2 between trigger points 2 and 4 for Φ2.

The trigger level was set to 0 V and a hysteresis calibration made.

As illustrated (greatly exaggerated), the actual trigger levels have some offset associated with each input channel, ΔU_A and ΔU_B (V) causing a systematic difference between Φ1 and φ1 and Φ2 and φ2 respectively.

The influence of the systematic trigger level setting uncertainty can be significantly reduced if the measurement is made in two steps; first measure and obtain the reading φ1 (U2 –U1), and thereafter φ2 (U1– U2). Finally, calculate the average value

$$\varphi = \frac{\varphi 1 - \varphi 2 + 360°}{2}$$ as described previously.

We have ignored all other uncertainties except those due to systematic trigger level offsets. We have also assumed that these offsets (ΔU_A and ΔU_B) were fixed and stable for the PM 6681 during the complete measurement sequence. This means that the correlation coefficient ρ=1. We have identical systematic uncertainty u_φ in both measurements φ1 and φ2. According to uncertainty calculation theory, the combined uncertainty of the expression

$\varphi = \frac{\varphi 1 - \varphi 2 + 360°}{2}$ is then $u_{\varphi} - u_{\varphi} = 0$,and not $\sqrt{u_{\varphi}^2 + u_{\varphi}^2}$
as would be the case with uncorrelated variables (ρ=0).

With reference to Figure 3, the relation between the 'true' phase, the measured phase and its residual error is:

$$\varphi 1 = \Phi 1 + \left(\frac{\Delta U_B}{2\pi \cdot freq \cdot U_B \cdot \sqrt{2}} - \frac{\Delta U_A}{2\pi \cdot freq \cdot U_A \cdot \sqrt{2}} \right) \times \frac{360°}{period} = \Phi 1 + \left(\frac{\Delta U_B}{U_B} - \frac{\Delta U_A}{U_A} \right) \times \frac{180°}{\pi \cdot \sqrt{2}}$$

$$\varphi 2 = \Phi 2 + \left(\frac{\Delta U_B}{2\pi \cdot freq \cdot U_B \cdot \sqrt{2}} - \frac{\Delta U_A}{2\pi \cdot freq \cdot U_A \cdot \sqrt{2}} \right) \times \frac{360°}{period} = \Phi 2 + \left(\frac{\Delta U_B}{U_B} - \frac{\Delta U_A}{U_A} \right) \times \frac{180°}{\pi \cdot \sqrt{2}}$$

This leads to:

$$\varphi = \frac{\varphi 1 - \varphi 2 + 360°}{2} = \frac{\Phi 1 - \Phi 2 + 360°}{2} + \frac{1}{2} \times \left(\frac{\Delta U_B}{U_B} - \frac{\Delta U_A}{U_A} \right) \times \frac{180°}{\pi \cdot \sqrt{2}} - \frac{1}{2} \times \left(\frac{\Delta U_B}{U_B} - \frac{\Delta U_A}{U_A} \right) \times \frac{180°}{\pi \cdot \sqrt{2}}$$

$$\varphi = \Phi 1 \quad (= \frac{\Phi 1 - \Phi 2 + 360°}{2})$$

Although the trigger level setting is the major source of (systematic) uncertainty, we recommend making a complete uncertainty calculation, also based on other sources of uncertainty (like random variations due to the SNR and resolution, and systematic channel delay mismatch). See the Operator's Manual for the PM 6681.

Please remember that uncertainties caused by external and internal noise can be reduced by statistical averaging to a level far below the uncertainty caused by the trigger level offset.

Fluke Corporation
P.O. Box 9090, Everett, WA 98206

Fluke Europe B.V.
P.O. Box 1186,
5602 BD Eindhoven,
The Netherlands

For more information call:
In the U.S.A.: (800) 443-5853
or Fax: (425) 356-5116
In Europe/M-East:
+31 (0)40 2 678 200
or Fax: +31 (0)40 2 678 222
In Canada: (905) 890-7600
or Fax: (905) 890-6866
From other countries:
+1(425) 356-5500
or Fax: +1 (425) 356-5116
Web access: http://www.fluke.com