**STANDARD OF TIME AND MEASURING INSTRUMENTS**

- **Definition of One Second**
  Frequency $f$ is expressed as shown below if the number of times a phenomenon repeats per second is represented by $N$.

  $$f = \frac{N}{T} \left[\frac{1}{s}\right] = \frac{1}{T} \left[\text{Hz}\right]$$

  $T$ is the time for which the phenomenon occurs once and is called a period. The frequency and the period (time) are related as inverses of each other and represent essentially the same physical quantity.

  The time we define as "one second" derived from the time it takes the earth to make one revolution around the sun. That is, one second is determined to be $1/31,556,925.9747$ of the time taken by the earth to revolve around the sun one time. However, this is inconvenient for use as a standard since a sufficient frequency stability cannot be obtained unless observation is made over several years because this determination is based on long periods of celestial body movements. For this reason, a method to utilize the inherent electromagnetic waves of atoms has been in practical use since the 1960's. It is known that atoms have inherent discrete energy levels. In transition of these atoms between two energy levels, the difference between these energies is absorbed or emitted as an electromagnetic wave.

  At present, $9,192,631,770$ periods of the frequency emitted by $^{133}$Cs atoms are defined as one second and Cs atom frequency standards are used as national standards. This time standard of using atoms has a precision of $10^{-13}$ because it utilizes an invariable high frequency.

- **Various Time Measuring Instruments**
  Instruments which measure time or frequency are generally called electronic counters and have been used in various fields because of their easy handling. Several types of electronic counters are shown below.

  - **Tachometers**
    A tachometer measures the number of revolutions of a mechanical rotating body and is generally composed of a sensor to detect the rotating motion and a display to indicate the number of revolutions.

  - **Frequency Counters**
    A frequency counter is the most basic instrument and its main purpose is to measure the frequency or period of electric signals. As their measuring functions are limited, most frequency counters are relatively small. Some models can measure frequencies in burst waveform oscillations.

  - **Microwave Counters**
    A microwave counter is one type of frequency counter and its input frequency band is limited to microwave bands. This is classified apart from general frequency counters because the field of use is different and the signal processing of microwaves requires special techniques.

  - **Universal Counters**
    A universal counter is provided with functions which can measure the time interval between two input channels and the ratio of two input frequencies in addition to frequency and period, and thus, can measure many time parameters. It is widely used in the "mechatronics" field in the electric and electronic fields.

- **Time Interval Analyzers**
  This is the newest type of time measuring instrument and is designed to be capable of analyzing jitter which is variations in measured values with time or frequency changes with time from many data by storing measured values of time and frequency in memory, in addition to the functions of universal counters. One of the features of this type of instrument is that it has a display that can present analyzed results graphically.

**COUNTER ACCURACY AND RESOLUTION**

Since electronic counters make very accurate measurements possible, the accuracy is affected by various errors in their measured values. This makes the measuring accuracy and resolution complicated.

- **Errors that determine accuracy**
  There are the following errors:

  1. ±1 count error
  2. Trigger error
  3. Time-base error
  4. Trigger level timing error
  5. Inter-channel error

  The error of a measured value is expressed as the sum of these errors. The ±1 count error and trigger error determine the resolution and they appear as a dispersion of the measured value. Also, the time-base error, trigger level timing error and inter-channel error are systematic errors and only affect the accuracy. They appear as a deviation from the true value. Figure 1 shows the relationships between them. In addition, these errors are divided into two: errors that have an effect and those that have no effect on the measuring objects depending on the measurement function (Table 1). For example, only the ±1 count error, trigger error, and time-base error affect a period measurement and appear as an error, but the inter-channel error has no effect. It affects the time interval measurement only.
The effect of random errors that determine the resolution can be reduced by taking many samples and averaging them. However, systematic errors cannot be reduced if averaging is done. This type of error can be reduced by performing a calibration. A simple explanation is given below for each type of error.

In counters whose ± 1 count errors have been made very small using the above described interpolation technique, the noise generated may become larger than the error and the actual measured resolution may be dispersed. In such a case, a single-shot resolution may be employed using the standard deviation. An expression as ± 10 ps rms represents the standard deviation (Figure 3).

**Errors that determine resolution**

- **± 1 count error**
  As the internal clock of a counter which measures time is completely asynchronous with input signals, it is unavoidable for the quantizing error for ± 1 clock to be generated depending on the time between them (Figure 2). This is called a “± 1 count error” and corresponds to “single-shot resolution” in product specifications.

![Fig. 2 ± 1 Count Error](image1)

The trigger error is expressed by the size of the noise and the signal rise time. This relationship is represented as shown below using the slew rate (SR) of the signal = V/t.

\[
\text{Trigger error [s]} = \frac{\Delta V}{\Delta t} = \text{SR [V/s]}
\]

(1)

This shows that the smaller the noise and the larger the SR, the smaller the error. The signal noise includes noise which the input signal has that is superimposed inside the counter.
• Errors that only affect accuracy
  - Time-base error
    Frequency or time measured by counters is determined based on the frequency of an incorporated crystal oscillator. The crystal oscillator, even if it is highly stable under the control of its temperature, has an aging property (secular change) and, thus, its frequency changes with time (Figure 5).

    ![Fig. 5 Aging Characteristics of Crystal Oscillator](image)

For example, a crystal oscillator whose oscillating frequency is 10 MHz having an

\[
\text{Aging rate} = \pm 2 \times 10^{-8} \text{year}
\]

has the possibility of a maximum change in its frequency of \(\pm 0.2 \text{ Hz}\) after a year. An error generated by the shift in the reference frequency is called a time-base error.

To eliminate the time-base error, it is necessary to adjust the oscillator frequency periodically. Otherwise, as almost all counters are provided with an external reference terminal (EXT REF IN) and can be operated with a time-base other than the internal clock, the time-base error can be eliminated by connecting a Cs atomic standard to the external reference signal terminal.

- Trigger level timing error
  This is a measuring error that occurs in time interval or pulse width measurement and has an effect on the measuring accuracy only.
  As the input comparator includes hysteresis, a set trigger voltage differs from an actual trigger voltage. For this reason, if there is a difference between the start and stop slopes, that difference appears as an error.

- Inter-channel error
  This is an error due to skew between channels inside a counter having A and B inputs as interpreted literally. This affects the accuracy only when time intervals are measured. This error cannot be ignored for high-resolution counters.

- Gate time and frequency resolution
  In reciprocal counters, if frequency is measured by gating, its resolution is averaged by input frequencies within the gate time and so the \(\pm 1\) count error and trigger error can be reduced. In other words, resolution improves if the gate time is prolonged and the frequency resolution is expressed as shown in equation (2).

\[
\text{Frequency resolution} = \frac{\text{\(\pm 1\) count error} \pm \text{trigger error}}{\text{gate time} \times \text{measuring frequency}} \tag{2}
\]

The fraction on the left side of the multiplication operation denotes the effective number of digits, and the minimum effective digit or resolution is expressed by multiplying this by the measured frequency. It is clear that the resolution improves as the \(\pm 1\) count error and the trigger error become smaller and the gate time becomes longer.