INSTRUMENTATION

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Contents

Summary

Measurements and measurement processes are increasingly permeating all human activities. They not only they play an important role in modern scientific researches and activities, but they also have a great impact on industrial processes, business, health, environmental monitoring, etc.

The reason for this growth and dissemination is certainly the impressive development of measurement instrumentation, directly related to that of the electronic devices on which it is based, yielding an impressive improvement of the measurement performances, flexibility of use and cost reduction.

The big technological change from the analog to the digital techniques had a key role in this development, with similar effects of those clearly visible in other important technical fields, such as telecommunications, consumer electronics, etc.

Keeping this in mind, this chapter will cover the fundamental theoretical and technological background of this technical revolution, in order to provide the basic skills and knowledge required to allow the reader to understand the basic measurement methods and devices commonly employed in the measurement field, employ them in the correct way and advance in the study of more complex measurement instruments and systems.

In particular, the analysis of the way a measurement process can be planned and implemented will be first covered, and will be followed by the analysis of the required instruments as well as their metrological performance. The analysis of the proper terminology will be also covered.

Space is also given to the analog-to-digital (AD) and digital-to-analog (DA) conversion techniques and devices, since these have become fundamental elements of any modern instrument. Finally the some of the most popular and widely employed instruments are analyzed: digital voltmeters and multimeters and the digital oscilloscopes.

1. Measuring Instruments

Measurement is the process that is associated with a numerical value, a reference and its uncertainty in the case of a given physical quantity, called measurand, by means of a comparison of the same quantity to another one, having the same nature, and that is assumed as a reference. This process is put into practice by means of a measuring instrument or, more in general, by a measurement system, whenever it is necessary to measure a quantity as, for example, temperature (K), rotation speed (rad/s), power dissipation (W), etc. in an industrial process or a scientific experiment.

The scope of a measuring instrument is hence to provide quantitative information about the measurand. From a practical point of view, this means that the output of an instrument is usually a number, together with a proper reference that represents the quantity value attributed to the measurand.

Since any instrument is not a perfect artifact, it is easy to understand that the measurement process is not perfect too, so that an intrinsic measurement uncertainty is present in any measurement process. For this reason, a measurement result has to be considered as an estimate of the quantity value of the measurand. The uncertainty of a measurement result represents the quantitative evaluation of its capability to provide a better or worse estimate of the measurand. For this reason, every measurement result must include its uncertainty to be usefully employed in any subsequent activities. From an operational point of view, the uncertainty is determined by comparison of the quantity values provided by the instrument under test with those obtained by means of a reference instrument. This operation is called calibration.

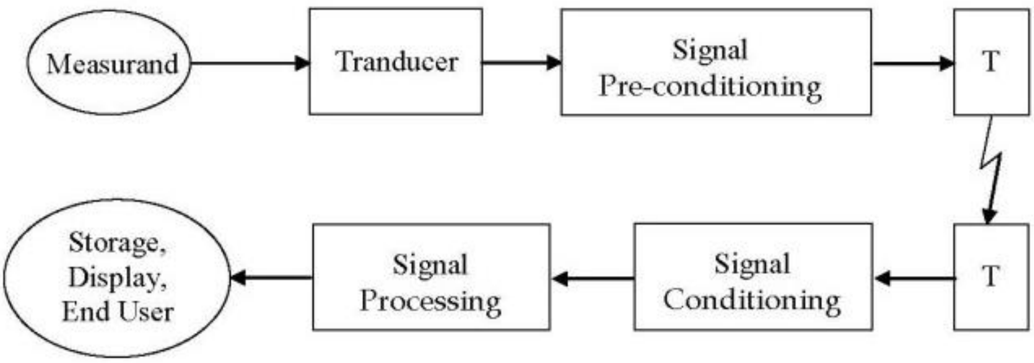

Figure 1. General structure of an electronic system of measurement. In this specific case a remote measurement is also provided (telemetry), transmitting the measured data: measurand and end user may be distant from each other .Tx: transmitter, Rx: Receiver.

More instruments are extensively based on electronic devices to process input signals and retrieve the associated information needed to generate the measurement result. To differentiate these from older instruments, mainly based on mechanical and electromechanical interactions, they are called electronic measurement instruments.

Regardless of how elaborate and complex it may be, the essential structure of an electronic instrument can be represented by the blocks shown in Figure 1.

Some of the blocks shown in Figure 1 may not be always required in a measuring instrument; for example, the pre-conditioning block or the storage section may not be included. Anyway, irrespective of the number of the employed sections, all electronic instruments are characterized by the fact that the information travels from one block to the next in the form of electrical signals.

2. Static and Dynamic Behavior of an Instrument

To properly use an instrument, one must be aware of how it operates on the measurand in order to provide the measurement value. For this purpose, it is useful to briefly recall the electronic behavior and the input/output relationship that describe each block of the instrument. Each of them contributes to the overall characteristics of the measurement system.

In order to clarify this concept, let us consider a thermometer based on the reading of the resistance value of NTC (Negative Temperature Coefficient) thermistor, which provides an output voltage signal proportional to the measured temperature, expressed in Kelvin. Referring to the block diagram of Figure 1, one can identify some basic functional blocks of the measuring instrument: a thermo-resistive sensor (sensor) whose resistance R_T varies, as a function its temperature T, in accordance to the equation:

$$R_T = R_{T_0} e^{\left[\xi\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]} \tag{1}$$

where ξ is a parameter that depends on the particular material (typically a semiconductor) with which the thermistor is made, and T_0 is a reference temperature, usually chosen equal to 298 K, at which the sensor assumes the nominal resistance value R_{T0}. For example, for a 10 kΩ NTC sensor, typically used to control temperature of small objects such as semiconductor laser diodes, the two characteristic parameters are $R_{T0} = 10$ kΩ and ξ = 3775 K.

A pre-conditioning block that converts the electrical signal produced by the sensor, i.e. its resistance value, into a voltage signal, that can be more easily processed by the following sections of the instrument. This block may consist, for example, of a simple electronic circuit that injects a constant current I_0 into the thermistor and then retrieves the resulting voltage at its terminals:

$$V_T = R_T I_0 \tag{2}$$

This simple electronic pre-conditioning circuit causes a self-heating effect of the sensor, due to the current I_0, that, if not properly compensated, contributes to the uncertainty of the final measured value.

A signal conditioning block changes the electrical signal provided by the previous block, V_T, into a signal with characteristics more suitable for the next processing section. For example, signal V_T may feature a low level, so that it may be convenient or even necessary to amplify it (e.g. if it is necessary to transmit voltage V_T to a remote device using a shielded cable) before the subsequent processing operations. In this case, the new conditioning block is a voltage amplifier with gain $k > 1$ (k being a real number), whose effect is to provide the output signal

$$V_{T,\mathrm{c}} = kV_T \tag{3}$$

A signal processing block devoted, for example, to linearize and finely adjust the signal amplitude in order to make it suitable for the output stage and the end user. In the specific case of the NTC thermometer, as clearly shown by Eq. (1), the sensor presents an exponential relationship between temperature and the output electrical quantity. Generally, measurement instruments are required to provide an output value that is directly proportional to the value of the measurand. In the specific example of the considered electronic thermometer, combining equations from (1) to (3), we get:

$$V_{T,\mathrm{c}} = kR_{T_0} I_0 e^{\left[\xi\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]} \tag{4}$$

To linearize the relationship between the output signal $V_{T,\mathrm{c}}$ and the temperature, T, voltage $V_{T,\mathrm{c}}$ has to be processed by a logarithmic amplifier, such as that shown in Figure 2. The current flowing in the diode is:

$$I = \frac{V_{\mathrm{in}}}{R_{\mathrm{i}}} = I_{\mathrm{s}}\left[e^k - 1\right] \tag{5}$$

where current I_{s} and constant k depend on the component used to realize the logarithmic amplifier of Figure 2.

Working in the zone of diode conduction, the exponential term e^k is much greater than 1 and therefore the output of this logarithmic amplifier will get a signal

$$V_{\mathrm{lin}} \cong -\eta V_T \ln\left(\frac{V_{T,\mathrm{c}}}{R_{\mathrm{i}} I_{\mathrm{s}}}\right) = -\eta V_T \ln\left(\frac{V_{T,\mathrm{c}}}{1\mathrm{V}}\right) + \eta V_T \ln\left(\frac{1\mathrm{V}}{R_{\mathrm{i}} I_{\mathrm{s}}}\right) = -\eta V_T \ln\left\{\frac{kR_{T_0} I_0}{1\mathrm{V}} e^{\left[\xi\left(\frac{T_0 - T}{TT_0}\right)\right]}\right\} + C' \tag{6}$$

where $C' = \eta V_T \ln\left(R_{\mathrm{i}} I_{\mathrm{s}} / 1\mathrm{V}\right)$.

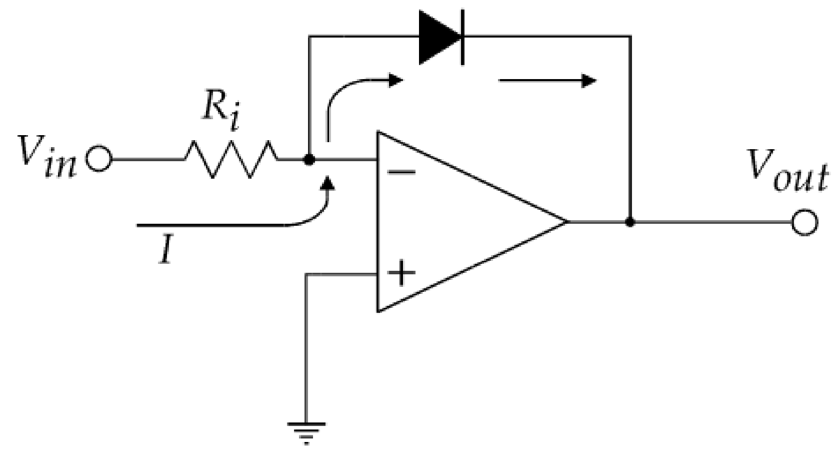

Figure 2. Logarithmic amplifier, built using an operational amplifier with a diode in the feedback branch, used to linearize exponential relationships.

For small temperature changes around the temperature T_0, Eq. (6) can be approximated as:

$$V_{\text{lin}} \cong \eta V_T \xi \frac{\left(T - T_0\right)}{T_0^2} - \eta V_T \ln\left(\frac{kR_{T_0} I_0}{1\text{V}}\right) + C' = BT + C \qquad (7)$$

where $B = \eta V_T \xi / T_0^2$ and $C = \eta V_T \xi / T_0 - \eta V_T \ln\left(kR_{T_0} I / 1\text{V}\right) + C'$.

At this point, having obtained the desired proportionality between the output signal and the temperature T, the processing block performs a final operation on the signal V_{lin}, in order to have the output signal V_{out} simply depending by the desired constant proportionality $K_{\text{instr}} = 1\ \text{VK}^{-1}$ to the physical quantity under measurement T. For this purpose, a simple electronic circuit can provide to translate (by subtracting the offset terms represented by the constant *C*) and to adjust the signal amplitude (in order to have a perfect match between the output voltage signal and input thermal signal).

Finally, a block provides the requested visualization (by means of a pointer deflection, a digital display, a scope-like display, etc.) and eventually stores the measurement result by printing it, sending it to a computer or other mass devices.

The above example has shown how the input-output relationship of the thermometer can be obtained by suitably combining the input-output relationships of the instrument single functional blocks, so that the simple more practical one is obtained:

$$V_{\text{proc,out}} = 1\left[\text{VK}^{-1}\right] T \qquad (8)$$

The above analysis, however, does only apparently explain the instrument operation in an extensive way. Indeed, it is based on a DC steady state analysis, in which the dynamical limits of the considered blocks to the changes in their input signals have not been considered. A further approximation is that the relationship between input and output is irrespective of the amplitudes of the signals. In general, each electronic block and also every physical system shows a response to the stimuli presented to its input which differs from the simple proportionality and the difference depends also on the speed with which these stimuli occur. In this context it is usual to characterize a system in terms of its transfer function. For the sake of completeness, it shall be noted that this analysis is valid only if the considered system is linear, or, at least, if it can be assumed to be linear about its operating point. It is worth nothing that the assumption is valid, at least to a first approximation, for most instruments.

The transfer function of the *i*-th block of a linear system $H_i(s)$ is analytically defined as the ratio of the Laplace transform of the output signal, $G_{i,\text{out}}(s)$ and the Laplace transform of the input signal to the same block, $G_{i,\text{in}}(s)$, in accordance with the formula:

$$H_i(s) = \frac{G_{i,\text{out}}(s)}{G_{i,\text{in}}(s)} \qquad (9)$$

$H_i(s)$ is in general a rational function of complex variable *s*. By considering in Eq. (9), instead of the whole variable *s*, only its imaginary part $j2\pi f$, where f is the frequency, the frequency response of the *i*-th block, $H_i(f)$ is obtained. The values taken by the $H_i(f)$ function are still complex numbers that describe the magnitude of the frequency response of the system, $|H_i(f)|$, and the phase relationship between input and output, $\Phi_i(f) = \angle H_i(f)$.

For the principle of causality, there is always a finite time delay in the response of a system to a stimulus at its input. For example, in the case of a linear system, excited by a sinusoidal signal at frequency f, the output is still a sinusoidal signal, with the same frequency as that of the input signal, but phase-shifted by an angle ϕ. At this phase shift corresponds a time delay between the input and output signal, which is obtained by the relation $2\pi f \tau = \phi$, and hence $\tau = \phi/2\pi f$. Therefore, each value of the phase response obtained from the frequency response allows one to readily retrieve also the time delay between the input and output signal. The above relationship can be generalized, and the time delay, or group delay, can be obtained from the phase response as:

$$\tau = -\frac{d\phi(f)}{df} \qquad (10)$$

The minus sign is a matter of convention, since systems whose output signal are lagging behind the input signal are supposed to feature a positive time delay.

In most electronic systems, the phase shift tends to increase in magnitude, as the frequency increases. In some cases, such as in a voltage amplifier, this effect can lead to distortion of the output signal when the input signal is characterized by the presence of spectral components of different frequencies (e.g., triangle waves, square waves, etc.). In this situation, the different spectral components suffer different delays, causing the output signal to change its shape with respect to the input signal. To avoid this distortion, called phase distortion, the system must feature a phase response varying linearly with frequency. In this case the group delay is constant and then all spectral components are equally delayed passing through the system, and, therefore, the output waveform preserves the same shape as that of the input waveform.

When the magnitude $\left|H_i\left(f\right)\right|$ and frequency f are represented on logarithmic scales, and phase $\Phi\left(f\right)$ is plotted on a linear scale, we obtain the well-known representation of the frequency response in terms of the two Bode diagrams (magnitude and phase, respectively). For example, Figure 3 shows the Bode diagrams of the frequency response of a band-pass voltage amplifier with cutoff frequencies of 10 kHz and 5 MHz. The cut-off frequencies are conventionally defined as the frequency values at which the amplitude of the transfer function is reduced by 3 dB compared to its value at center band.

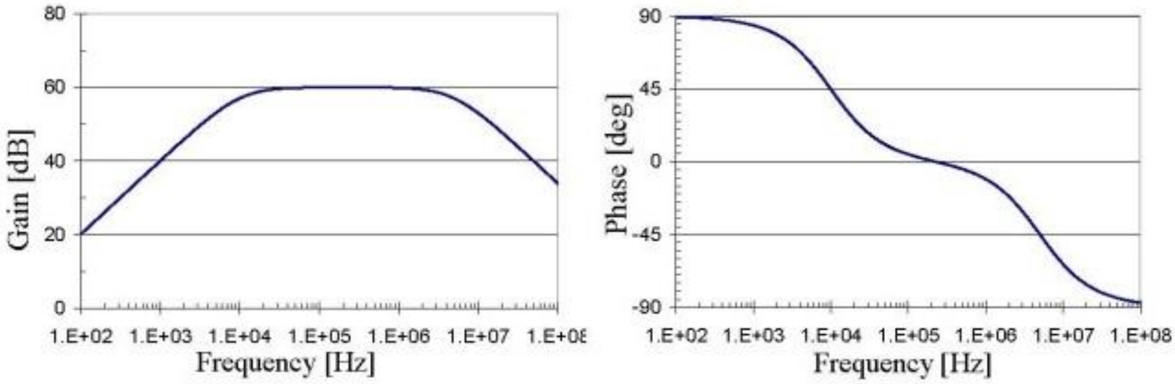

Figure 3. Amplitude and phase frequency response (Bode plots) of a band-pass voltage amplifier.

The frequency response is not the only available tool to characterize the dynamic behavior of an instrument. Alternative methods are the transient and impulse response. In the first case, it is necessary to provide a quick variation (ideally a step variation) in the input signal and analyze the subsequent evolution of the output. In the second case, the system response to an input pulse stimulus (signal of very short duration) is analyzed. For example, Figure 4 shows the impulse response of a coaxial cable. In a typical band-limited system, the impulse response shows a finite rise time followed by an exponentially decaying part. It is worth nothing that in linear, time-invariant systems, the frequency response and the impulse response are mathematically related, the frequency response being the Fourier transform of the impulse response. Therefore the selection of one of these two methods to characterize the dynamic response of an instrument is a matter of convenience and depends on the readiness of implementation and the expected accuracy.

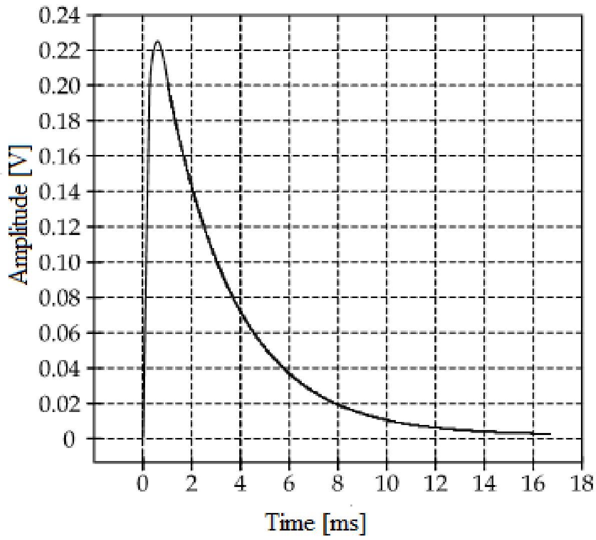

Figure 4. Impulse response of a coaxial cable

In general, real systems cannot be expected to respond to different amplitude input signals in the same way. The minimum detectable signal by a measurement system is defined as the minimum value of the input signal that is reflected in a corresponding detectable change in the output signal. When the input signal falls below the limit of insensitivity of the instrument (typically comparable to the level of noise, that is any signal not carrying any useful information) it is no longer possible to detect changes in the output signal that are correlated with changes in the input. On the other hand, it can be also noted that the input and output signals must not exceed a certain threshold to avoid saturation phenomena or damage to the device.

The entire range of amplitude values between the level of insensitivity and the maximum allowed level is called measurement range of the measurement system. It is worth nothing that the instrument can be safely operated within its accuracy specifications only if the input signal remains within the measuring range. If the input signal is outside this range, and its variation range is at least approximately known, it is possible to extend the instrument measurement range by pre-processing the input signal by means of simple attenuators (to extend the upper limit of the range) or low-noise amplifiers (to extend sensitivity towards low level signals).

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Biographical Sketches

Alessandro Ferrero was born in Milan, Italy, in 1954. He received the M.Sc. degree in electrical engineering from Politecnico di Milano in 1978. From 1980 to 1983 he worked as an R&D engineer with Daco Systems (an Italian division of Landys & Gyr). In 1983, he joined the Dipartimento di Elettrotecnica, Politecnico di Milano, as an Assistant Professor of electrical measurements. From 1987 to 1991, he was with the University of Catania, Catania, Italy, as an Associate Professor of measurements on electrical machines and systems. From 1991 to 1994, he was with the Dipartimento di Elettrotecnica, Politecnico di Milano, as an Associate Professor of electrical measurements. He is presently a Full Professor of electrical and electronic measurements at the Dipartimento di Elettronica, Informazione e Bioingegneria at Politecnico di Milano. His current research interests include new mathematical approaches to uncertainty evaluation based on the theory of evidence, the application of digital signal processing based methods to electrical measurements and measurements on electric power systems under non-sinusoidal conditions. In this last field he has contributed to the definition of non-active power components under non-sinusoidal conditions and the development of measurement methods to identify the sources injecting periodic disturbances.

Prof. Ferrero is a member of the Italian Association of Electrical and Electronic Engineers, the Italian Association for Industrial Automation and the Italian Association for Electrical and Electronic Measurements (GMEE). He is a Fellow of the IEEE. He has chaired the Italian Association for Electrical and Electronic Measurements for the three-year term 2004–2007 and he has been the President of the IEEE Instrumentation and Measurements Society for the 2008 – 2009 term. He is the recipient of the 2006 Joseph F. Keithley IEEE Field Award for Instrumentation and Measurement. Since 2011 he has been Foreign Member of the Class of Technical Sciences of the Royal Flemish Academy of Belgium for Science and the Arts. In 2014 he received the Doctor Honoris Causa degree from the Polytechnic

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Roberto Ottoboni graduated in Electronics Engineering and PhD in Electrical Engineering at the Politecnico di Milano. From 1992 to 1997 he was a researcher in the field of Electrical Measurements and then, from 1998 to April 2002, he was Associate Professor at the Department of Electrical Engineering at the Politecnico di Milano.

Since May 2002 he has been Full Professor in Electrical and Electronic Measurements at the same Department. From January 2003 to December 2008 he was Chairman of the Electrical Engineering Study Program of the Politecnico di Milano and, in the same period, Deputy Director of the Department of Electrical Engineering. From January 2009 to December 2012 he was Chair of the Electrical Engineering Department. Since 2013, he is Deputy Director of the Department Elettronica, Informazione e Bioingegneria at Politecnico di Milano. From 2003 to 2007 he was head of the Electrical Calibration Laboratory of SIT Center 104 at Politecnico di Milano and was also scientific consultant at the Calibration Center of Politecnico di Milano for the accreditation to the Italian Calibration Service (SIT). Since 2006 he is IEEE Fellow. He is a member of the Committee CT85 / 66 of the CEI (Measurement, Control and Laboratory Instrumentation) and serves on the board of ASTRI. His research fields range from the study and analysis of digital signal processing techniques for measurement to the study and implementation of sensors, transducers and measurement systems for electrical quantities in industrial applications, with particular attention to innovative sensors for high voltages and high currents.