Contributed Paper

Tech Talk

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An Introduction

In conducting over many years the assessment of Control & Instrumentation (C&I) engineers applying for professional registration, it is apparent that significant gaps often existed in their fundamental technical and application knowledge. Notwithstanding the normal variations in the ability of individuals, the academic route chosen and the subsequent training offered by employers will play a major part in the development of a well-rounded engineer.

Professionals following the craft apprentice/Higher National Certificate (HNC) route through technician training and who are able to obtain employment in an engineering design capacity will usually possess good practical C&I application skills. In contrast, their university graduate counterparts, although better equipped mathematically, may struggle in their formative years with the broad spectrum of practical application knowledge required.

C&I engineers need a good working knowledge of many subjects, including the wide range of field instruments and control systems available in a fast changing marketplace, materials selection, piping mechanics, fluid physics, industry specific measurement, protection and control techniques/best practice, functional safety, hazardous area work, control systems architecture/application, data communications, installation design, engineering standards/codes of practice, inspection and testing, contractual awareness and much more. Large companies with accredited graduate training programmes will usually make use of both in-house mentoring and external training, whereas smaller organisations are often much more reliant on the haphazard self-learning process.

Tech Talk is a series of papers designed as a ‘pull out’ reference library. The aim is to disseminate knowledge of both the fundamentals of measurement and control and its practical application. To this end, experienced engineers and manufacturing companies are cordially invited to share their knowledge for the greater good by submitting for publication, further papers that will be of interest to practising C&I design engineers and technicians. Publication guidelines are available on request from: publications@instmc.org.uk

This first paper in the series addresses the basics of measurement. The co-authors are David W Otterson CEng, FInstMC and John E Edwards CEng, FIChemE, who have published several papers and books on process simulation, instrumentation and control.

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Tech Talk: (1) Instrument Measurement Basics

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I. The SI System of Measurement Units

The SI system has been adopted by most countries in the developed world, though within English-speaking countries, this has not been universal. The United Kingdom has officially adopted a partial metrication policy, with no intention of replacing imperial units entirely. The United States and Canada do not use metric units outside of science, medicine and the government and extensively use imperial units throughout the engineering disciplines.

The core of the SI system is built on seven base units defined in an absolute way without reference to any other units.

Property	Name	Symbol
Length	Metre	m
Mass	Kilogram	kg
Time	Second	s
Electrical current	Ampere	A
Temperature	Kelvin	K
Luminous intensity	Candela	cd
Quantity	Mole	mol

SI derived units with special names and symbols acceptable in SI

Property	Name	Symbol	SI units
Plane angle	Radian	rad	
Electrical capacitance	Farad	F	m^{-2} kg^{-1} s^4 A^2
Electrical charge	Coulomb	C	A s
Electrical conductance	Siemens	S	m^{-2} kg^{-1} s^3 A^2
Electrical inductance	Henry	H	m^2 kg s^{-2} A^{-2}
Electrical potential	Volt	V	m^2 kg s^{-3} A^{-1}
Electrical resistance	Ohm	Ω	m^2 kg s^{-3} A^{-2}
Force	Newton	N	kg ms^{-2}
Frequency	Hertz	Hz	s^{-1}
Power or radiant flux	Watt	W	kg m^2 s^{-3}
Pressure	Pascal	Pa	kg/(ms^2) = (N/m^2)
Radioactivity	Bequerel	Bq	s^{-1}
Work, energy, heat	Joule	J	m^2 kg s^{-2}

Commonly used SI derived units described in terms of acceptable SI units

Property	Symbol	SI base units
Acceleration	m/s^2	m s^{-2}
Area	m^2	m^2
Coefficient of heat transfer	W/(m^2 K)	kg $s^{-3}K^{-1}$
Concentration	mol/m^3	mol m^{-3}
Density (mass density)	kg/m^3	kg m^{-3}
Electrical charge density	C/m^3	m^{-3} s A
Force	N or J/m	m kg s^{-2}
Heat flow rate	W or J/s	m^2kg s^{-3}

Property	Symbol	SI base units
Magnetic field strength	A/m	A m^{-1}
Molar energy	J/mol	m^{-2} kg s^{-2} mol^{-1}
Molar entropy	J/(mol K)	m^{-2} kg s^{-2} K^{-1} mol^{-1}
Moment of force (or torque)	N m	m^{2} kg s^{-2}
Moment of inertia	kg m^{2}	kg m^{2}
Momentum	kg m/s	kg m s^{-1}
Power	kW	10^{-3} m^{2} kg s^{-3}
Pressure	kPa	10^{-3} m^{-1} kg s^{-2}
Specific heat capacity	J/(kg K)	m^{2} s^{-2} K^{-1}
Specific volume	m^{3}/kg	m^{3} kg^{-1}
Stress	MPa	10^{-6} m^{-1} kg s^{-2}
Surface tension	N/m	kg s^{-2}
Thermal conductivity	W/(m K)	m kg s^{-2} K^{-1}
Torque	N m	m^{2} kg s^{-2}
Velocity	m/s	m s^{-1}
Viscosity, absolute or dynamic	Pa s	m^{-1} kg s^{-1}
Viscosity, kinematic	m^{2}/s	m^{2} s^{-1}
Volume	m^{3}	m^{3}
Work	J or N m	m^{2} kg s^{-2}

II. SI Prefixes

Numbers in the form 10^7 cannot be conveniently represented in computer programs, so the scientific notation is used where the 10^7 is now E07. Note E is not related to the mathematical constant e or the exponential function.

The following conventions avoid errors in allocating the correct number of zeros where fractions such as $1/10 = 10^{-1}$, $1/100 = 10^{-2}$ and so on.

Factor		Prefix	Symbol
10^{18}	E18	Exa	E
10^{15}	E15	Peta	P
10^{12}	E12	Tera	T
10^{9}	E09	Giga	G
10^{6}	E06	Mega	M
10^{3}	E03	Kilo	k
10^{2}	E02	Hecto	h
10^{1}	E01	Deca	da
10^{-1}	E-01	Deci	d

Factor		Prefix	Symbol
10^{-2}	E-02	Centi	c
10^{-2}	E-03	Milli	m
10^{-6}	E-06	Micro	µ
10^{-9}	E-09	Nano	n
10^{-12}	E-12	Pico	p
10^{-15}	E-15	Femto	f
10^{-18}	E-18	Atto	a

Note 1 Caution: Refinery industry sometimes uses MM to signify 10^6.

III. Unit Equation

In an equation, the units on each side are the same and should be checked for consistency. Consider an object uniformly increasing its speed (m/s) from u to v in t s, (v – u)/t represents the change in speed over t seconds defined as acceleration a (m/s^2).

Acceleration formula	$a = (v - u)/t$	LHS $m/s^2 (m\ s^{-2})$ = RHS $m/s \times 1/s = m/s^2$
Distance travelled s in time t	$s = ut + t(v - u)/2$	LHS m = RHS $(m/s \times s) + (s \times m/s) = m$
Substituting for (v – u)	$s = ut + ½at^2$	LHS m = RHS $(m/s \times s) + (m/s^2 \times s^2) = m$

IV. Unit Conversion

Unit converters are available from many sources so are not shown here. A typical example for energy is shown. The unit to be converted from is multiplied by the factor shown in column with the desired unit.

From	To			
	Btu	Joule	kWh	therm
Btu	1	1.055E03	0.2931E–03	10E–06
Joule	0.948E–03	1	0.2778E–06	9.48E–09
kWh	3.412E03	3.6E06	1	34.12E–03
therm	100E03	105.5E06	29.31	1

1000 Btu = 10^3 Btu = 1E03 Btu = 1.055E06 joule = 0.2931 kWh = 10E–03 therm

A. Temperature Conversion

To convert from °F to °C we have: °F = 9/5 °C + 32

A temperature of –10 °C is equivalent to °F = (1.8 × –10) + 32 = 14

B. Pressure Conversion

Absolute pressure p_a is the pressure above a total vacuum and gauge pressure p_g is the pressure above or below atmospheric pressure p_{atm} giving:

$$p_a = p_g + p_{atm} \text{ for } p_g > p_{atm}$$
$$pa = p_g - p_{atm} \text{ for } p_g < p_{atm}$$

At atmospheric pressure p_{atm} (kg/m^2), the absolute pressure p_a (kg/m^2) at the bottom of a column of liquid with a density ρ (kg/m^3) and height H (m) is:

$p_a = H\rho + p_{atm}$, check units RHS = $kg/m^3 \times m = kg/m^2$ = LHS

To convert p_a from kg/m^2 to bar:

We know 1 kg/cm^2 = 0.98065 bar and 1 $cm^2 = 0.0001\ m^2$ giving $10^4\ kg/m^2$ = 0.98065 bar, and $1.0197 \times 10^4\ kg/m^2$ = 1 bar leading to $p = H\rho/(1.0197 \times 10^4)$ bar. And p_{atm} = 1.01325 bar, so a p_g of 5 barg is equivalent to p_a of 6.01325 bar and a vacuum p_g of 0.5 barg is equivalent to p_a of 0.51325 bar.

V. Accuracy

The accuracy of a measurement relates to the nearness of that measurement relative to a National or International Standard. Measuring instrument accuracy is expressed in a variety of ways:

- As a percentage of the full-scale reading at any reading;
- As a percentage of the calibrated span at any reading;
- As a percentage of the actual reading.

Consider a flow transmitter, with a calibrated range of 100–1000 Nm^3/h, reading 800 Nm^3/h with an accuracy of 1% (basis unspecified):

As a percentage of the full-scale reading at any reading;

Full scale = 1000 Nm^3/h giving ± 1% of 1000 = ±10 Nm^3/h;

As a percentage of the calibrated span at any reading;

Calibrated span is 1000 – 100 = 900 Nm^3/h ± 1% of 900 = ±9 Nm^3/h

As a percentage of the actual reading at any reading

1% of 800 = ±8 Nm^3/h

It can be seen from the above that the best accuracy is obtained as a percentage of the actual measurement reading.

VI. Measurement Loop Accuracy

Where a number of devices are connected in series, the overall loop accuracy can be obtained by the root mean square method ensuring all device accuracies are on the same basis.

Primary measuring element accuracy = ±2%

Transmitter/Converter accuracy = ±1%

Analogue input card channel accuracy = ±0.5%

$$\text{Loop accuracy} = \sqrt{(2^2 + 1^2 + 0.5^2} = \pm 2.29$$

VII. Repeatability or Reproducibility

This is an important factor to consider for production processes in the application of a measuring instrument over its service life. Calibration errors and drift can be caused by physical changes affecting the sensor and its electronics. Factors to consider are ambient conditions, the effect of process fluid adhesion and wear or stress on wetted or moving parts may all influence the measurement uncertainty over time, often indicating the need for frequent calibration checks.

The repeatability coefficient is a precision measure which represents the value below which the absolute difference between two repeated test results may be expected to lie with a probability of 95%. The standard deviation under repeatability conditions is part of precision and accuracy.

VIII. Instrument Scaling

Electronic transmission in instrumentation almost universally uses an elevated zero signal of 4 mA dc with a span of 16 mA dc giving a full-scale signal of 20 mA dc. Below are some examples of applied scaling:

- A temperature transmitter calibrated 50–250 °C is reading 75 °C

The % calibrated range = 100 × 75/(250 — 50) = 37.5%

The transmitted signal will be (20 — 4) × 37.5/100 + 4 = 10 mA.

- A flow transmitter, with an orifice plate primary element, is calibrated 0–2500 mm wg for 0–25,000 kg/h has a reading of 12,500 kg/h on a receiving device having a square root scale. The orifice plate differential pressure (dp) and the transmitted signal are determined as follows:

At maximum flow (W_{Max}) the orifice plate dp is 2500 mm wg (referred to as h_{Max}). For a transmitter signal of 4 – 20 mA the following relationship applies:

$W/W_{Max} = \sqrt{(h/h_{Max})}$ which leads to $h = h_{Max} (W/W_{Max})^2$

$h = 2500\ (12{,}500/25{,}000)^2 = 625$ mm wg

The resulting transmitter signal is therefore = (0.25 × 16) + 4 = 8 mA.

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