An Introduction to Electrical Instrumentation

B. A. Gregory

LOW-PRICED EDITION

E L B S

An Introduction to

Electrical Instrumentation

A guide to the use, selection, and limitations of electrical instruments and measuring systems

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ENGLISH LANGUAGE BOOK SOCIETY
and
MACMILLAN

First edition 1973
Reprinted 1975 (with corrections), 1977

ELBS edition first published 1977

Published by
THE MACMILLAN PRESS LTD
London and Basingstoke
Associated companies in Delhi Dublin
Hong Kong Johannesburg Lagos Melbourne
New York Singapore and Tokyo

ISBN 0 333 14833 9

ISBN 0 333 23283 6 (ELBS paperback edition)

Printed in Great Britain by
Unwin Brothers Limited
The Gresham Press Old Woking Surrey.

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Preface

Our ability to measure a quantity determines our knowledge of that quantity, and since the measuring of electrical quantities – or other parameters in terms of electrical quantities – is involved in an ever expanding circle of occupations of contemporary life, it is essential for the practising engineer to have a thorough knowledge of electrical instrumentation and measurement systems. This is especially so since in addition to his own requirements, he may be called upon to advise others who have no electrical knowledge at all.

This book is primarily intended to assist the student following an electrical or electronic engineering degree course to adopt a practical approach to his measurement problems. It will also be of use to the engineer or technician, who now finds himself involved with measurements in terms of volts, ampères, ohms, watts, etc., and faced with an ever increasing variety of instruments from a simple pointer instrument to a complex data logging and processing system. Thus, the object of this book is to help the engineer, or instrument user, to select the right form of instrument for an application, and then analyse the performance of the competitive instruments from the various manufacturers in order to obtain the optimum instrument performance for each measurement situation.

During that period of my career when I was employed in the research department of an industrial organisation I was, at times, appalled by the lack of ability exhibited by some graduates in selecting a suitable, let alone the best, instrument to perform quite basic measurements. Since entering the field of higher education to lecture in electrical measurements and instrumentation, my philosophy has been to instruct students to consider each measurement situation on its merits and then select the best instrument for that particular set of circumstances. Such an approach must of course include descriptions of types of instruments, and be presented so that the student understands the functioning and limitations of each instrument in order to be able to make the optimum selection. Hence the general theme of this book is to describe various types of instrument and then compare their characteristics. Unfortunately there is a limit to the number of instruments that can be described in a book of realistic size, and I have therefore omitted specialised topics such as medical instrumentation, gas chromatography, radio frequency measurements, power system measurements, acoustic measurements, and high voltage instruments such as discharge detectors. Further, since some of the established methods are extensively covered elsewhere they are only summarised in this book; there is a list of references for further reading at the end of each chapter.

I would like to thank all the instrument manufacturers who have willingly assisted me in producing this volume by providing application notes, specifications, reproductions of articles, and also their obliging field engineers. I have endeavoured to acknowledge all sources of diagrams and other material, but I hope that any oversights will be excused. I should also like to thank my colleagues in the Department of Electrical and Electronic Engineering at Brighton Polytechnic for their assistance and encouragement; in particular my thanks are due to Dr B. H. Venning and Dr E. M. Freeman. Finally may I record my thanks and appreciation to my wife for her perseverance and courage in typing the manuscript.

B. A. Gregory

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Introduction

Scientific and technical instruments have been defined as devices used in observing, measuring, controlling, computing or communicating. Additionally the same volume* states that: 'Instruments and instrument systems refine, extend or supplement human facilities and abilities to sense, perceive, communicate, remember, calculate or reason'.

The principal concern of this book is to describe instruments capable of measuring and recording the magnitudes and variations in electrical and mechanical quantities, and to illustrate methods by which it should be possible to select the optimum instrument for any measurement situation. With this latter point in mind, and before describing any 'hardware' it is desirable to consider some of the factors that govern the choice of an instrument for a particular measurement situation.

Accuracy

The term 'accuracy' is really one of conversation and in a measurement situation the operator should be concerned with defining the limits of error that apply to a particular measurement. As an example consider a voltmeter that has a fiducial value† of 1 V and is a class 1.5 instrument. Then if this meter is connected across a pair of terminals between which there is a voltage such that the meter indicates 1 V, the 'conventional true value' of the voltage (providing the meter is of a suitable type) is somewhere between 0.985 and 1.015 of an absolute or standard volt. It should be noted that the error quoted is in terms of the fiducial value and the tolerance on a reading of 0.1 V on the same instrument would still be ± 0.015 V or ± 15 per cent of the reading if the measurement is performed at reference conditions†. This aspect is covered in more detail in chapter 7.

* *Encyclopedia of Science and Technology*, McGraw-Hill, 1971.
† see B.S. 89: Part 1:1970

Bandwidth

The bandwidth of an instrument relates to the maximum range of frequency over which it is suitable for use and is normally quoted in terms of 3 dB points. For example, an oscilloscope amplifier may have a specification quoting −3 dB points of 20 Hz and 50 MHz, indicating that at these frequencies the gain of the amplifier will be $1/\sqrt{2}$ or 0.707 of its midfrequency value (that is 29 per cent less, also there will be a 45° phase shift) so that measurements made at or near these values of frequency will have considerable errors.

Screening

Measurements made involving electrical quantities of small magnitude can be seriously affected by electromagnetic and electrostatic interference from external sources. Protection and screening from these effects must therefore be included in a sensitive measurement system. Chapter 4 gives the basic procedures which should be adopted to reduce these 'interference' problems.

Impedance effects

Almost any instrument when connected into a circuit will change the conditions that existed in the circuit prior to its inclusion. It is obviously important to ensure that this disturbance is a minimum or incorrect results will be produced. As a simple example consider a source of d.c. voltage which has an internal resistance of 100 Ω and an open circuit voltage of 2 V (see Figure I.1).

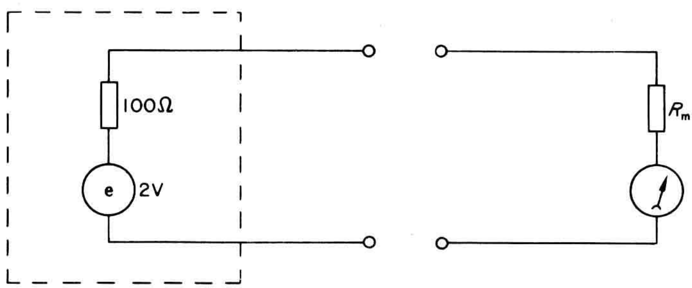

Figure I.1

Connecting across these terminals a voltmeter with an impedance (or resistance) of 100 Ω, a current of 2/200 or 0.01 A will flow and the voltage indicated by the meter will be 2−100 x 0.01 or 1.0 V. However if a meter of 1900 Ω resistance is used, the current flowing will be 2/2000 or 0.001 A and the indicated voltage becomes (2−100 x 0.001) or 1.9 V, which is a considerable improvement. Using a meter with say, a 10 000 Ω resistance would, of course, reduce the error in measurement still further.

A similar illustration of the effects of ammeter resistance is of interest, that is suppose the above source is passing current through a 10 Ω resistance and the current is measured with ammeters of 10, 1, 0.1 Ω resistance; the readings obtained would be 0.01667 A, 0.01802 A and 0.01816 A respectively; the correct value, or the value with no ammeter, being 0.01818 A. If alternating voltages are involved the impedance effects may not be purely resistive and phase angle errors may also be present.

Sensitivity

An instrument's sensitivity will be quoted as so many units for full scale, for example 1 A f.s.d., or as a unit of deflection, for example, 10 mm/μA. It should be noted that in order to obtain the least error in a particular measurement the instrument used must be such that the indicated value is near the full scale value of the most suitable range.

Display method

The display or recording method used in a measurement is usually governed by the purpose of the measurement, hence one must ask, is a pointer or analog instrument's deflection suitable for the application, or is the display in numerical form from a digital instrument more satisfactory? Alternatively, it may be that a permanent record is required, when the choice is from a graphical presentation, a printed output, punched paper tape, or a record on magnetic tape for later analysis.

Waveform purity

In a.c. measurements the quantity which is usually of greatest interest is the root mean square (r.m.s.) value or, expressed in another manner, its equivalent direct current magnitude. For a single frequency sinusoidal wave this presents little problem as the relationships between the peak value, the rectified average value and the r.m.s. value are constants. However, for waveforms with harmonic content these constant relationships are not valid and instruments which actually measure r.m.s. as opposed to those calibrated in r.m.s. quantities must be used.

From this preamble, which only indicates some of the influencing factors, it should be apparent that when making a measurement, it is not sufficient to pick up the nearest meter calibrated in the appropriate units and expect it to yield satisfactory results.

Thus the reason for the ever increasing number of different instruments to perform each type of measurement becomes a little clearer. A further source of confusion is in the use of symbols and units. This book uses the SI system (Système International d'Unités), and to assist the student a list of symbols, units and conversion factors between imperial, MKS and SI units is presented in appendix I.

1

Analog (Pointer) Instruments

Definition

An analog device is one in which the output or display is continuously variable in time and bears a fixed relationship to the input.

The use of analog instruments is very extensive and whilst digital instruments are ever increasing in number and applications, the areas common to both types are, at present, fairly limited and it is therefore likely that analog devices will remain in extensive use for a good many years, and for some applications are unlikely ever to be replaced by digital devices. Analog instruments may be divided into three groups: (a) electromechanical instruments (Section A); (b) electronic instruments (Section B) which, broadly speaking, are constructed by the addition of electronic circuits to electromagnetic indicators thus increasing their sensitivity and input impedance; and (c) electromechanical and electronic instruments having a modified display arrangement so that a graphical trace, that is a display of instantaneous values against time, is obtained (see chapter 2).

SECTION A. ELECTROMECHANICAL INSTRUMENTS

When an electric current flows along a conductor, the conductor becomes surrounded by a magnetic field. This property is used in electromechanical instruments to obtain the deflection of a pointer: (a) by the interaction of the magnetic field around a coil with a permanent magnet; (b) between ferromagnetic vanes in the coil's magnetic field; or (c) through the interaction of the magnetic fields produced by a number of coils.

Constraining these forces to form a turning movement a deflecting torque $= G\,.\,f(i)$ newton metres (N m) is obtained which is a function of the current in the instrument's coil and the geometry and type of coil system. To obtain a stable display it is necessary to equate the deflection torque with an opposing or control torque. The magnitude of this control torque must increase with the angular deflection of the pointer and this is arranged by using spiral springs or a ribbon suspension so that the control torque = $C \times \theta$ N m, where θ is the angular deflection in radians and C is the control constant in newton metres per radian and will depend on the material and geometry of the control device[1].

The moving parts of the instrument will have a moment of inertia (J) and when a change in the magnitude of deflection takes place an accelerating torque ($J.\mathrm{d}^2\theta/\mathrm{d}t^2$ N m) will be present. As the movable parts are attached to a control spring they combine to form a mass–spring system and in order to prevent excessive oscillations when the magnitude of the electrical input is changed, a damping torque ($D.\mathrm{d}\theta/\mathrm{d}t$ N m) must be provided that will only act if the movable parts are in motion. The method by which this damping torque is applied may be:

(a) eddy current – where currents induced in a conducting sheet attached to the movement produce a magnetic field opposing any change in position

(b) pneumatic – in this method a vane is attached to the instrument movement, and the resistance of the surrounding air to the motion of the vane provides the required damping. Fluid damping is an extension of this principle, a small vane then being constrained to move in a container filled with a suitably viscous fluid (see page 52).

(c) electromagnetic – movement of a coil in a magnetic field produces a current in the coil which opposes the deflecting current and slows the response of the instrument. The magnitude of the opposing current will be dependent on the resistance of the circuit to which the instrument is connected.

Combining the above torques, the equation of motion for a pointer instrument becomes:

$$J.\frac{\mathrm{d}^2\theta}{\mathrm{d}t^2} + D.\frac{\mathrm{d}\theta}{\mathrm{d}t} + C.\,\theta = G.f(i) \tag{1.1}$$

which will have a steady state solution[3],

$$C.\theta = G.f(i) \tag{1.2}$$

and a dynamic or transient solution of the form (see appendix II),

$$\theta = A.e^{\lambda_1} + B.e^{\lambda_2} \tag{1.3}$$

where A and B are arbitrary constants and

$$\lambda_1 = \frac{-D}{2J} + \left(\frac{D^2}{4J^2} - \frac{C}{J}\right)^{\frac{1}{2}} \tag{1.4}$$

and $$\lambda_2 = \frac{-D}{2J} - \left(\frac{D^2}{4J^2} - \frac{C}{J}\right)^{\frac{1}{2}} \tag{1.5}$$

For a particular instrument C and J are fixed in magnitude during manufacture, but D (the amount of damping) may be varied. This results in three possible modes of response to a transient:

(a) when $D^2/4J^2 > C/J$ – for which the roots λ_1 and λ_2 are real and unequal, and is known as the overdamped case, curve (a) in figure 1.1.

(b) when $D^2/4J^2 = C/J$ – for which the root are real and equal, and D has a value termed the critical value, curve (b) in figure 1.1.

(c) when $D^2/4J^2 < C/J$ – which gives roots that are conjugate-complex quantities and the system is underdamped, curve (c) in figure 1.1. The frequency of the decaying oscillations being:

$$\omega = \left(\frac{C}{J} - \frac{D^2}{4J^2}\right)^{\frac{1}{2}} \qquad (1.6)$$

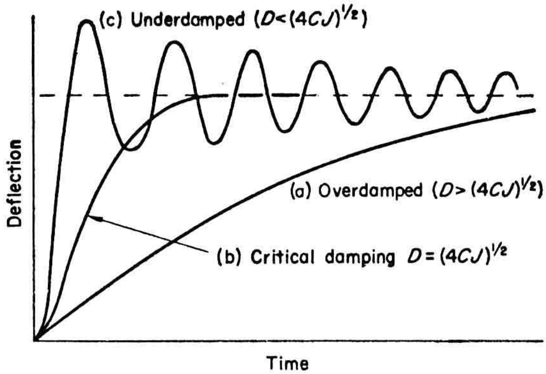

Figure 1.1. The effects of damping magnitude on the movement response

Thus it is apparent that the magnitude of the damping applied to a movement has an important effect on the dynamic performance of an instrument; it being general practice to operate pointer instruments with slightly less than critical damping to ensure that the pointer changes rapidly from one position to another with the minimum chance of sticking.

1.1 MOVING COIL INSTRUMENT

The principle used in the construction of this type of instrument is that current passing through a conductor generates a magnetic field around the conductor and if this field is arranged to interact with a permanent magnetic field, a force acts on the current carrying conductor. If the conductor (that is the coil) is constrained to move in a rotary manner an angular deflection or movement proportional to the current may be obtained, resulting in an instrument that has a linear scale but which, due to its inertia, can only respond to steady state and slowly varying quantities. The linearity of scale is an extremely useful feature and accounts for the use of moving coil instruments as the display in many complex electronic instruments.

The general arrangement of the moving coil instrument is indicated in figure 1.2. The permanent magnet system has over the years been considerably reduced in size due to the improvements in magnet design as better materials have become available.

The coil may be air cored or mounted on a metal former; if the latter is

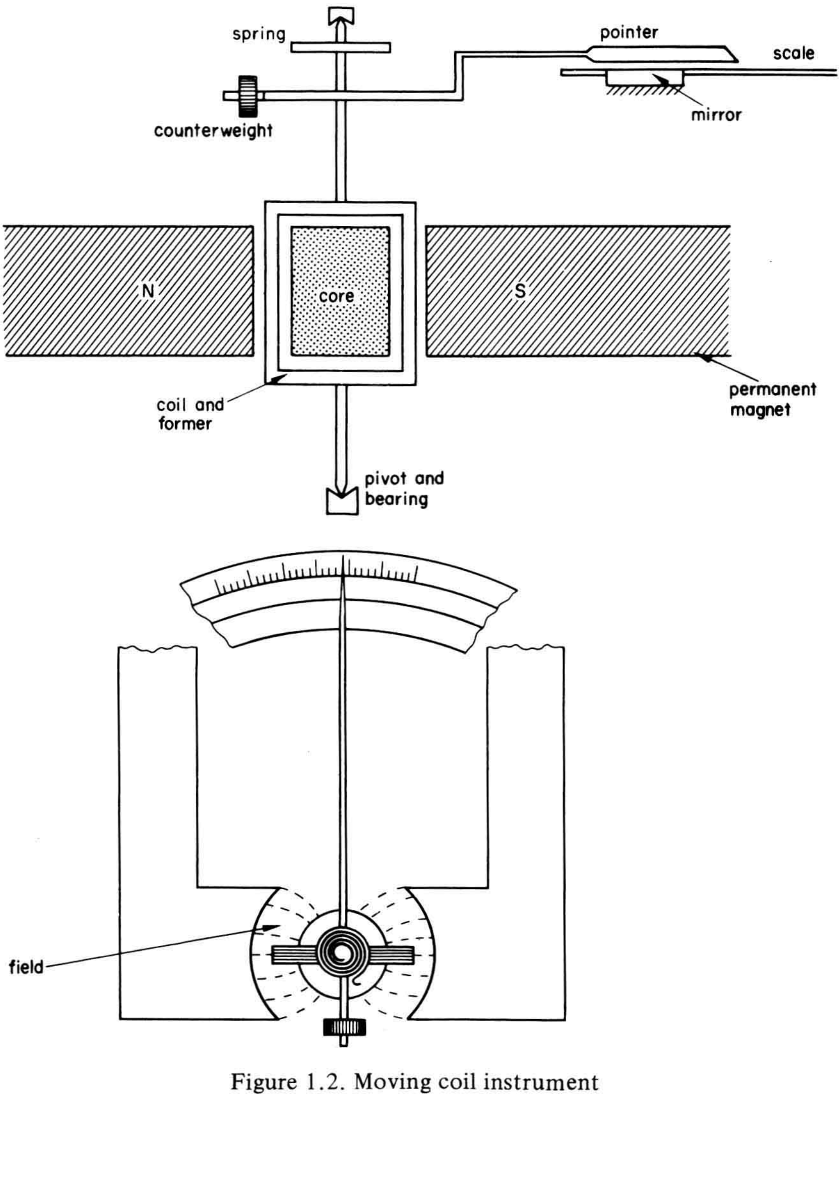

Figure 1.2. Moving coil instrument