INDUSTRIAL INSTRUMENTATION

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To the memory of JOHN ALDEN SETTLE

teacher, helper, friend, whose unswerving devotion to his students gave all who knew him an unparalleled example of those qualities we would have for our own

PREFACE

This book is based on material for a course in industrial instrumentation, part of the curriculum of the Ward School of Electronics, technical school division of the University of Hartford. Since its inception in 1949 by John Alden Settle, the course has been expanded to train students who desire to make a career in the field of instrumentation. The success of Ward School students in this field testify to its effectiveness.

Emphasis on broad general principles presented in simple, direct language is the result of experience with students at the technical school level. The use of calculus in the chapter on flow was deliberately introduced as a challenge to student and teacher alike and may be omitted if so desired.

Since this book shall also be used by many now employed as instrument men, and since most of these people will not have had the advantage of formal technical training, the necessary physics, mathematics, and mechanical engineering are included where required. This is the result of teaching the original completely integrated course which included these subjects along with report writing and sketching.

Electrical or electronic instrumentation are not dealt with in this book, although such instrumentation finds increasing use, particularly in the field of measurement. Our concern here is with pneumatic control, which comprises over eighty percent of today's instrumentation.

To the best of my knowledge, the section devoted to link and lever systems is unique.

All the instruments described (approximately fifty) are used in the laboratory. An instrumentation laboratory offers an exceptional chance to teach on an individual basis, and allows the student an opportunity to solve his own difficulties. Laboratory, then, should be emphasized, but not from the "hardware" point of view.

Without the whole-hearted cooperation of many companies this book would have been impossible to prepare. To these manufacturers I acknowledge my gratitude.

To Malcolm B. Hall of the Foxboro Company, the dean of teachers of instrumentation, whose encouragement and cooperation led to the writing of this text, I express my profound respect and admiration.

To Roland F. Lescarbeau, Director of Training, and Douglas M. Fellows, Administrative Director, of the Ward School of Electronics, I offer my thanks for their patience, understanding, and help.

Finally, I acknowledge the unfailing cooperation of the Bristol Company, the Foxboro Company, the Taylor Instrument Company, Manning, Maxwell, and Moore's Ashcroft Division, American Chain and Cable Company's Helicoid Gage Division, the Rockwell Manufacturing Company, Kieley and Mueller, and Farris Flexible Valve Company in supplying illustrative material.

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INSTRUMENTS AND INSTRUMENTATION

THE STUDY of physics tells us that everything about us has a level of energy. Since energy may take many different forms, it is not always easy for us to understand what the energy is. There is an energy of position—*potential energy,* the physicists call it—made evident by the dent in the floor when something heavy is dropped on it from a high position. Anything in motion must have received energy from somewhere or something; otherwise it would not move. The energy in a lighted match is equally obvious, if you let the match burn to your fingers. A silver spoon in a hot cup of coffee soon manages to transfer energy to your fingers.

Phyics also tells us that a transfer of energy will always take place in such a way that a higher level will be reduced to a lower level. The idea of transfer, however, suggests that there is an exchange of energy. If something is lost, then something must be received or gained by the other party to the swap; and this may go on until both loser and winner are at the same level. At this point, trade stops. A lighted match is momentarily at a higher energy level than the torch which it can light. The torch can ignite the burners in a large boiler. The boiler, now at a higher energy level than the water in it, boils the water and turns it into steam. The steam turns a turbine, the turbine turns a generator, and so on. Each step involves a swap of energy, always from the higher to the lower. The *quantity* of energy has nothing to do with it; the *level* is important.

The dictionary says that energy is *force* and that force is the *ability to do work.* Nowhere do we find that work *must* be done if energy is present; and we have found that energy in some form, of some kind, is always present. Work may be done under the right conditions; but the fact that work is not done, and thus not apparent, is no reason to assume that energy does not exist. We know, at least, that the ability to do work is there, and that work will be done if we can manage to set up the right conditions. And since man has a built-in reluctance to use his own energy, the measurement, direction, and control of other forces and energies play a very important part in his life.

We have names for the many different ways in which energy can be useful to us. Some of these are: pressure, temperature, flow, and humidity. We may also mention such things as acidity, velocity, level, and even simple counting. The list could go on and on, almost without end. *The measurement of the level of the various energies and the control of the energy exchanges which can take place is called* ***instrumentation.***

The end result of instrumentation, then, is control. Control may be direct and obvious. It may be merely an indication that things are going well—or badly. If things are going badly, the indication should at least tell us where the trouble is and give us an idea of what to do about it. In this case, we are the control.

Like all other games this one has rules. If we are to play the game intelligently, we must set down the rules—and stick to them. The very first rule is that we must measure or compare before we can control. It is thus important that we study measurement thoroughly since it is the basis of control and instrumentation.

Measurement implies some sort of a yardstick or standard with which we can compare that which we are trying to measure. The basic standards, again set by our friends the physicists, are:

1. Length
2. Mass
3. Time

These are fundamental ideas which would have the same meaning on the earth, the moon, the sun, or anywhere else under the heavens. The units used to describe these ideas are of minor importance compared with the ideas themselves. We see immediately that it is going to be difficult to measure volts with a foot ruler or amperes with a clock. Most of the measurements we will make, in fact, will be in terms of derived units which are familiar and easy to work with. It is a matter of convenience. Of course there must be some relationship between the derived units and fundamental units. Here is the rub: if this relationship is not maintained, then none of us will have the slightest idea of what the other is talking about. This is a clear case of having to play the game by the rules.

INSTRUMENTS

A measuring device—meter, gauge, instrument, or whatever you wish to call it—must have certain abilities if it is to be useful. The important ones are:

1. Accuracy
2. Repeatability
3. Sensitivity
4. Permanence

Since most instruments have a scale or other device to indicate how many units are involved, it is convenient to define accuracy in terms of that scale. Instrument manufacturers agree among themselves, and this is most unusual, that the full-scale length on a gauge or instrument should be used as a basis for figuring accuracy. *Accuracy* is expressed as the error, which in turn is the difference between the reading of the instrument and the true value of that which is being measured. Accuracy is expressed as a percentage of the top scale value regardless of where the reading is taken on the scale. Thus, on an instrument having a scale calibrated from 0 to 100 units, an error of 1 unit is called an accuracy of 1 per cent. Note that if a true value of 50 units is read as 49 units on the scale of our 0–100 gauge, the accuracy is still considered as 1 per cent, although in terms of the true value there is an error of 2 per cent. So let us agree right now that *when we speak of accuracy it will be in terms of full scale regardless of where the measurement is made on the scale.* That is, if we measure a true 2 volts on a 0–100 voltmeter and find that our scale says 1 volt, we will understand that this is an accuracy of 1 per cent, not an error of 50 per cent. Of course we know that no intelligent student would every try to measure 1 volt with a 0–100 voltmeter.

There is no specification that the error be positive or negative. This means that the manufacturer has an actual leeway of plus *and* minus 1 unit, a span of 2 units on our 0–100 meter of 1 per cent accuracy. An instrument having a guaranteed accuracy of 1 per cent and a scale of 0–500 units may have an error of plus or minus 5 units at any point on the scale except the extreme top and bottom and still be within its specified accuracy. Most of the instruments we will talk about carry a 1 per cent accuracy guarantee, and we will assume that this is the case for all industrial grade instruments unless otherwise specified.

Repeatability means that the instrument will stop at the same point on the scale when measuring the same value regardless of how the point of measurement is approached. This means that fast or slow, upscale or down, the measurement must be exactly the same when the motion stops. Suppose we measure a true 50-unit value starting from 0 and increasing toward 100. Suppose that the instrument reads 49 when we reach a true 50. We now do the same thing but in the opposite direction, from 100 downscale toward 0, and arrive at a reading of 51 units. Something is wrong. This error is called *hysteresis,* from the Greek word meaning "wandering." The cause of hysteretic errors is loss of energy within the instrument itself. Energy losses here are due to friction. If the friction losses are greater than the power available to move the indicator, hysteresis results. Another difficulty results from backlash or play in gears and other mechanical parts.

By *sensitivity* we mean the ability of the instrument to respond to a small change in the value being measured. It is the smallest change that will cause effective motion of the measuring element. Notice that no mention is made of your seeing this motion. A sensitive controller is quite capable of turning a switch on or off as the result of a motion so small that you could not possibly see it.

Please do not make the mistake of confusing sensitivity with accuracy. Sensitivity must be many times greater than the specified accuracy and is determined largely by friction and other losses in the moving mechanical parts of the instrument. You will see that a good controller can have a response to a change of less than 0.1 per cent of full scale to achieve an accuracy of ¼ per cent of full scale. The manufacturer must be able to make his instrument do this as a safety factor if he is to guarantee his instrument to, say, ½ per cent.

Permanence, the ability of an instrument to read without change in accuracy for days, weeks, and months, is important. Permanence means that our instrument must be built of materials which will not corrode, which will show little wear, and which do not change in physical characteristics. By physical characteristics we mean such properties as tensile strength, ability to resist fatigue, and ability to stand up under temperature changes. A spring made of lead is not useful since it will not return to its original shape once it has been stretched or compressed. There is no one standard for permanence; in fact, an instrument which may be perfectly satisfactory under most conditions is completely worthless under other conditions. Permanence is measured by drift over a period of time which might be caused by any or all of the three factors we have mentioned. We could use the same scale device that we used to specify accuracy and say that a good standard industrial instrument must not drift more than 1/10 scale division over, say, a three-month period. The fact is that there are so many different ways of using so many different types of instruments that it is not practical to make one rule to fit them all.

Now that we have established our requirements for a measuring device, we can proceed to find out how some of them work. Some are simple and many are complex; all give us useful information which we will need later on when we start to control.

SUMMARY

Everything about us is in a state of continual energy change, the level either increasing or decreasing.

Instrumentation is the measurement of energy levels and the control of energy exchanges for useful purposes.

Four requirements for a satisfactory measuring device are:

1. Accuracy
2. Repeatability
3. Sensitivity
4. Permanence

Instrument accuracy is specified in terms of a percentage of full-scale value. Accuracy is error expressed as a per cent of full scale regardless of where the error is found.

1 PRESSURE

MEASURING INSTRUMENTS provide us with numerical information—numbers. Since numbers by themselves have no significance except as a means of counting, we must give the numbers names. It means little for you to say that you received 100 on pay day. It makes a considerable difference if you are talking in terms of nickels, dimes, or dollars, and this is especially true of forces. There are several systems of measurement, all described by numbers, but the values represented by the numbers vary widely. Since we will be dealing with forces from now on, it is important that we understand values and be able to convert values from one unit to another without trouble.

1.1 THE NATURE OF PRESSURE

Again we are in debt to the physicists for the definition of pressure. *Pressure is defined as force per unit area.* We note right here that the *kind* of force is not specified, and that the unit of area is not stated. In a way this is fortunate because it leaves us a lot of leeway. In another way it is unfortunate because there are hundreds of values with different names, all of which describe the same basic idea—force per unit area.

Force is defined by the physicists in terms of mass and motion. But weight is the attraction of gravity for a mass. Fortunately, weight and mass are practically identical at the earth's surface. Weight, then—at least at sea level—can be substituted for mass, and is more easily and conveniently measured. We can measure force in familiar terms: pounds, grams, ounces, kilograms, tons, or any other convenient unit of weight. These are definite units for which standards are readily available.

Area is square measure, two lengths multiplied together. We are free to use any unit of length we please—inches, feet, yards, millimeters, miles, or any other. Area becomes square inches, square feet, and so on. There is no problem here.

Pressure, then, is a force divided by the area over which the force is applied. If we let $P =$ pressure, $A =$ area, and $F =$ force, we can write

$$P = \frac{F}{A} \tag{1}$$

The most widely used pressure unit is pounds per square inch. Also used is pounds per square foot. We abreviate these to psi and psf respectively. We may also write lb/in.^{2} or lb/ft.^{2}

PRESSURE CALCULATIONS

Consider the block in Figure 1.1. It is a cube one foot long on each edge, weighing 288 pounds. It rests on a flat surface on one of its foot-square faces. To find the pressure this weight produces on the surface, we substitute in equation (1):

$$P = \frac{288 \text{ lb}}{1 \text{ ft}^2} = 288 \text{ lb/ft}^2$$

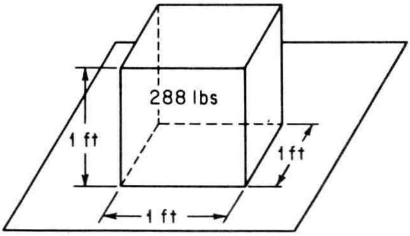

Fig. 1.1.

Suppose that for some reason we wanted to know the pressure in pounds per square inch or psi. All we have to do is to substitute 144 square inches for the square foot, giving 2 psi.

We can solve equation (1) for any of the three unknowns if the other two are known. Just remember that when force is involved it is *all* the force, not a part on a small unit area. We usually speak of *total force* rather than simply *force* to make this more clear. Note, too, that the area involved is the entire area which transmits the force regardless of its shape.