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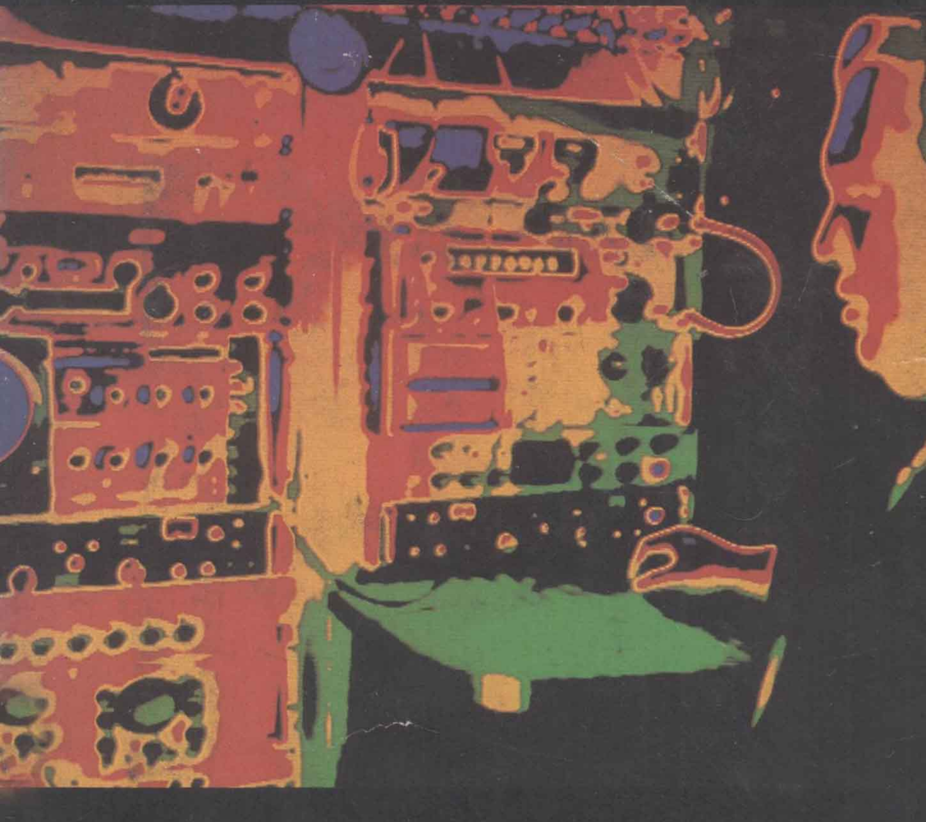

BY JOHN A. KUECKEN

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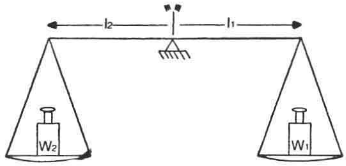
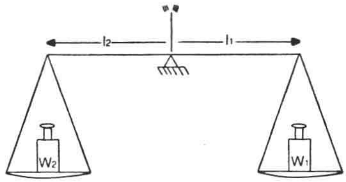




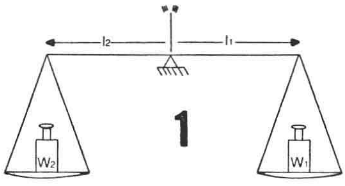
Introduction

There is very little question that the world has changed a great deal since the founding of the United States. If asked to describe this difference, the average person might cite such advances as the automobile, the airplane, television, telephone communications, frozen foods or a host of other wonders. The contrast between the homespun world of our founding fathers and our own sophisticated existence and society, in nearly every facet of everyday life, is startling and dramatic. Even the foods which we eat, as delivered by nature, such as oranges and apples have been changed dramatically. The seedless orange and the Red Delicious apple are man-developed products; they did not exist in nature in their present form. Most of our steaks and beef come from breeds and strains of cattle which did not exist in nature. The Whitefaced Hereford is a developed strain of beef cattle which has been optimized for converting grass and corn into flesh. Man has indeed shaped the world.

If one were to pursue the matter further and ask the question: *What is the single underlying advance that has contributed the most to this progress?* the answers are liable to become a little more varied. Some might cite a given invention such as the steam engine or electricity. Still others might wax more philosophical and cite advances such as the US Constitution with its concepts of equality, freedom and self-rule. Still others might advocate the position that the growth of science or the American inventor is responsible. It is relatively simple to make a good case for each of these positions and it is also relatively easy to argue against each. The question is not easy to decisively answer in a way which will satisfy everyone.

It is the position of this writer that the area in which advancement has contributed as an underlying factor to all of the other advances is the art of measurement. When one can measure, one can improve performance and as one can measure better, either more accurately or more easily or more cheaply, one can improve performance even more. Without measurement, it is very difficult to determine whether a change has been for the better or for the worse.

In this book we shall be showing some of the techniques whereby very nearly anything can be measured using electronics. The principal goal shall not be to explore the cutting edge of the drive toward greater and greater precision since this is not the usual goal of the person building a single instrument. Instead, we shall be treating the problems of creating instruments which are easy to use and accurate enough for the task at hand.



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Units of Measurement

Since the basic topic of this book is the subject of measurement, it seems appropriate that we spend some time at the outset discussing the subject of units. First we shall look at some mechanical units mainly because these are the easiest to visualize.

To begin with, we should make the distinction between *vector* and *scalar* quantities. This is really not so fancy as it sounds. A scalar quantity is simply a quantity which has no direction associated with it. For example ten jellybeans or three gallons of water have no direction associated with them. The number and the units suffice to tell us the facts.

On the other hand, a vector quantity does have direction associated with it. A reading such as "ten miles west" or "five flights up" has a definite direction. In the text we shall distinguish vector quantities by placing an arrow above the symbol; thus electric field strength will be given as $\vec{E}$. It should be noted that certain quantities can be either a vector or a scalar. For example the mileage on a car might be 25,000 miles as shown on the odometer however in this case the accumulated mileage is not a vector quantity since the mileage was accumulated traveling in all directions and the direction is unimportant. This will be accounted for in the text by showing the symbol without the arrow superscript; for example the voltage between two points on a circuit will be noted as E.

FORCE, MASS, AND ACCELERATION

For a coherent system of units we shall be using the MKS system of units. In this system lengths will be given in meters (m) or fractions or multiples of meters, such as centimeters (cm) or kilometers (km). The centimeter is of course 0.01 m and the kilometer is 1,000 m. One meter is equal to 39.370 inches.

The kilogram is the unit of mass in the MKS system. A gram is the weight of one cubic centimeter of water at 4°C which happens to be the point where water is densest. The kilogram (kg) is naturally the weight of a thousand grams of water. A kg is equal to 2.205 pounds (avoirdupois).

The unit of time is the second. This shall be noted as (sec.) in the text. The second is 1/60th of a minute and 1/3600th of an hour and 1/86,400 of a mean solar day.

The reason that the MKS system is attractive to engineers is the fact that some of the derived units come out evenly in practical terms, such as *volts, ohms, amperes*, and *watts*. The MKS system thus avoids the use of such units as abvolts and statvolts, slugs, poundals, etc. The MKS system was proposed in 1904 by L. Georgi for this reason and has been in wide use in engineering since; most particularly electrical engineering.

THE NEWTON

The first of the derived units is the *newton*. The unit stems from the Newtonian equation for the acceleration of a body:

$$F = Ma \tag{1-1}$$

One of the advantages of the MKS system is the fact that it uses the units of *mass* in kilograms. If we consider a to be acceleration in m/sec^2 and M in kilograms then F is given in newtons abbreviated (Nt). Assume that $a = 1\ m/sec.^2$ and $M = 1$ kg then $F = 1$ Nt. In some respects this is easier to deal with than a system in which the mass must be derived by dividing weight by the acceleration due to gravity so that force comes out in the same units as weight.

The Nt differs from weight by the factor of the acceleration due to gravity. For example, to suspend a mass of 1 kg against the force of gravity we would have to supply exactly as much force as is required to accelerate the same body at the rate that gravity would. The accepted value for the acceleration due to gravity is 9.8 m/sec^2 at sea level and in mid latitudes. Therefore we obtain:

$$F = 1\ kg \times 9.8\ m/sec^2$$
$$= 9.8\ Nt\ (newtons)$$

To convert newtons to pounds of force multiply by 0.2248. The Nt is between a quarter and a fifth of a pound of force.

Pressures are often stated in terms of newtons per square meter (Nt/m^2). The newton per square meter has been given the title the *pascal*. In order to convert pascals to pounds per square inch, divide by 6.895×10^3. To get a feel for the size of the pascal, the pressure in the tires of a typical car is 28 psig which is equal to 28 psig $\times 6.895 \times 10^3 = 1.93 \times 10^5$ pascal (gauge).

The term *gauge* in the pressure reading refers to the fact that the ordinary pressure gauge reads not the absolute pressure but rather the difference between the pressure inside the tire and the pressure of the atmosphere outside of the tire. Pressures are very often quoted in terms of *atmospheres*. One standard atmosphere is equal to 1.0133×10^5 pascals. The use of the pascal is not too common in the literature at the present although one does see a certain amount of use of newtons per square meter. Considered as force, the newton is small, being a fraction of a pound; however the square meter is a pretty large area over which to consider the pressure which means that ordinary pressures like one atmosphere come out to a large number of pascals.

WORK AND POWER

Power is expended when a force is applied to a moving body and is the product of the force times the distance of movement. If the body does not move there is no power expended. For example, a clock with the spring wound but which was not running would have *potential energy* stored in the clock spring but the spring would be doing no work and expending no power. Until the clock was given a shake to start it ticking, the potential energy would lie dormant in the spring of the clock indefinitely. Once the clock starts ticking the spring would give up power and would begin to "run down". The MKS system has the advantage that the units for power come out very conveniently. The unit of power is the *watt*. One watt (w) is the power expended when a force of one newton lifts a body at the constant rate of one meter per second. The watt therefore has the units *newton-meters/sec*. A body which required 5 Nt to lift (or slide) at a rate of 15 m/sec would be absorbing $5 \times 15 = 75$ watts and the machine doing the work would be outputting a similar amount.

Note that the above equations had nothing to do with time. The power is constant whether the machine does the job for 1 second or 100 years. However the amount of *energy* expended is a function of the time that the work goes on. The measure of energy in small quantities is the joule or the watt- sec. This is the product of the amount of power being expended multiplied by the time during which the power is expended. In practical electrical work, the joule is a rather small unit and it is usual to quote energy in *kilowatt hours*. Since there are 3,600 seconds in an hour and 1000 watts in a kW the kWh is 3.6×10^6 joules.

It is noteworthy that the energy in joules or kWh tells us nothing about the rate at which the power is expended. For example a condenser in a laser storage system could be charged over a period of 30 sec to an energy of 100 joules and then discharged thru the laser in 10^{-9} sec. During the charge period, the condenser would be absorbing energy from the power source at a rate of 100 W-sec/30 sec = 3.33 W. During the discharge it would be giving up the energy at the rate of 100 W-sec/ 10^{-9} sec = 10^{11} W.

The common measure of power in large quantities used in mechanical engineering is the *horsepower*. One horsepower (hp) is equal to 550 foot pounds per second which is equal to 745 W. In electrical engineering the mechanical wattage rating is frequently used for electric motors less than one horsepower and the horsepower rating is frequently used for motors larger than one horsepower although the ratings for generating plants are always given in watts or kW.

In much of physics, a much smaller unit of energy is used. This is the *erg* which is equal to 10^{-7} joule. The smaller force unit used is the *dyne*. One dyne is equal to 10^{-5} newtons.

ELECTRICAL UNITS

The following electrical units are intimately involved in modern measurement procedures.

The Ampere

The *ampere* is named after Andre Maria Ampere, a French physicist. The ampere can be defined in two entirely different ways. One of these is electrical/mechanical and the second is electrochemical. The electromechanical definition is based upon the property discovered by Ampere that a pair of wires which are parallel will experience a force tending to pull them together if the current is in the same direction in each wire and will tend to push them apart if the current is in the opposite direction. For example the cord on your table lamp is always experiencing a force trying to push the wires apart when the lamp is turned on since the current is traveling in opposite directions in the two wires at any instant in time. For a current of 1 ampere (A), if the wires are 1 meter apart the force will be 2×10^{-7} Nt per meter of length. For other distances the force is given by:

$$F = \frac{2 \times 10^{-7}\, i^2}{r} \quad \text{newtons} \qquad (1\text{-}2)$$

where r is the spacing between the parallel wires in meters and i is the current in amperes. In actual practice, the force is measured between closely spaced parallel coils of wire with a very sensitive scale.

The electrochemical definition of the ampere stems from the property discovered by the English physicist Michael Faraday that the weight of material deposited on one of the electrodes in an electroplating operation is directly proportional to the total charge used in the operation, that is the amount of current times time. More precisely, it was found that 95,521.9 ampere seconds of current would deposit one gram molecular weight of a monovalent substance. One definition of the ampere was the steady state current which will deposit silver at the rate of 0.001118 gm/sec.

The Coulomb

One of the quantities derived from the definition of the ampere is the *coulomb* which is equal to one ampere second. Thus, it requires 95,521.9 coulombs of electricity to deposit or electroplate one gram molecular weight of a monovalent substance. The coulomb is also involved in the definition of the capacitor since the coulomb describes the amount of electricity deposited in a capacitor. The charge of an electron is also measured in coulombs. An electron has a charge of 1.602×10^{-19} coulombs. If a capacitor has a charge of 1 coulomb, the negatively charged plate carries an excess of 6.242×10^{18} electrons. The single electron is the smallest amount of electric current and it is very small indeed.

The Ohm

The *ohm* is related to the ampere on the basis of heating effect. The power dissipated in a resistor is proportional to the resistance and the square of the current flowing through the resistance. One ohm is that resistance which will dissipate one watt when a current of one ampere is flowing through it. This definition was adopted at the Paris Congress of Electricians in 1881.

The reason for tying the legal definition of the ohm to the heating effect was the fact that by so doing it is possible to equate electrical work to mechanical work. A heating value of one watt can be generated by an apparatus which measures the Joule effect. A known mass or weight is allowed to slowly fall, thereby giving up known amounts of energy. The energy is extracted by allowing the falling weight to stir water, thereby heating the water. Similarly, the electric current can be used to heat the water. If the water flows through the apparatus at a known steady rate, the temperature rise can be measured and, using the known specific heat of water, and the known mass which is heated every second, the power in watts can be calculated. This is not a very easy experiment to set up and operate, therefore the U.S. National Bureau of Standards has developed carefully calibrated standards consisting of spools of platinum wire whose coefficient of resistance variation with temperature is well known. These standards may be compared with other resistors to be calibrated by electrical methods very quickly and easily. However, the basic definition remains and it does serve to tie electrical quantities precisely with mechanical quantities.

The Volt

The *volt* is defined as the potential drop across a one ohm resistor when a current of one ampere is flowing. The virtue of this definition is the fact that it is tied to the definition of the ampere and the ohm both of which can be precisely determined from mechanical considerations as described earlier.

Capacitance

The unit of capacitance is measured in *farads* which represents a relationship between the voltage and the charge on a condenser. A one farad capacitor with one joule of charge will have a voltage of 1 volt across the terminals. Many of the small capacitance measuring testsets, particularly the digital models make use of this definition. A known current is applied to a capacitor until the voltage reaches a fixed level and the time required for the charging is measured. For example, suppose that the instrument supplies one microampere to the capacitor and the process is stopped when the voltage reaches one volt. The time in seconds required to charge the capacitor to one volt is equal to the capacitance in microfarads or (μf) as usually written. The farad is a very large unit which is not very practical for most electrical engineering problems.

Surprisingly, even a vacuum has a certain amount of capacitance. If two parallel plates are placed in a vacuum or in outer space the capacitance between them is given by

$$C = \frac{1}{36\pi} \times 10^{-9} \times A/h \text{ farads} \qquad (1\text{-}3)$$

where: A is the area of the plates in square meters
h is the spacing between the plates in meters.

The constant $1/36\pi \times 10^{-9}$ farads/meter is called the dielectric constant of free space. For air the dielectric constant of free space is nearly identical to that for a vacuum. Most denser materials have a higher dielectric constant, that is, the capacitor would measure a higher number of farads if the material completely filled the space between the parallel plates. The ratio between the capacitance which would be given for the material filling and the capacitance for the plates in a vacuum is called the relative dielectric constant of the material and is usually abbreviated as e_r. This is the value usually shown on tables of dielectric properties of insulators. To obtain the absolute dielectric constant, it is necessary to multiply the e_r by the dielectric constant of free space.

Inductance

The unit of inductance is the henry. It is the property of inductors that they behave like a mass, that is it takes a certain amount of force (voltage) to cause a change in the flow of current (akin to velocity) and the energy is stored as kinetic energy in the magnetic field of the inductor. An inductance of one henry (H) which is exposed to a voltage of one volt will have a current change of one ampere per second. Suppose that a one volt battery were applied to terminals of an inductor which initially had no current flowing through it. At the instant that the switch was closed, the current would be zero, however it would begin to rise at the rate of one ampere per second. If neither the battery nor the inductor had any resistance, at the end of one second the current would pass the one ampere mark and the current would continue to climb at the rate of one ampere per second toward infinity.

Unlike the capacitor, this definition does not make for a good way to measure inductors. Except for a superconducting magnet, there is always some resistance in an inductor which will ultimately limit the current and cause the charging rate to roll off, therefore the rate of change would only be approximately constant and then only at the time of closing of the switch. Secondly, as the current keeps climbing there would have to be some place where the process stopped. If one were simply to open the switch, this would attempt to make the current fall to zero in an infinitely short period of time and the inductor would attempt to develop an infinite voltage in a direction or polarity opposed to the original voltage as the magnetic field collapsed. In practice what usually happens is that the voltage simply climbs to a level high enough to strike an arc across the switch contacts. Inductors are generally measured using an alternating current which slows up in one direction, stops and then reverses. If a saw tooth wave of current changing, for example, at one ampere per second were fed into the inductor until the current reached one ampere and the current were then ramped down at minus one ampere per second to zero, a one henry inductor would show a +1V reading during the ramp up and a −1V reading during the ramp down.

As is the case with a dielectric, it turns out that free space or a vacuum has magnetic properties, that is it is possible to have a magnetic field in a vacuum. The *magnetic permeability* of free space is $4\pi \times 10^{-7}$ henrys per meter. Where the dielectric constant of free space is denoted by ϵ_0 the magnetic permeability of free space is given by μ_0. If a coil of wire is wrapped into a toroidal spiral which is closed on itself like a donut, the inductance is given by:

$$L = 4\pi \times 10^{-7} N^2 A/1 \text{ henrys} \qquad (1\text{-}4)$$

where; A is the cross sectional area of the coils (cut thru the donut) in square meters.

1 is the circumference length of the donut in meters

N is the number of turns of wire.

If the donut were filled with a donut shaped core of iron and the wire wrapped on this new donut, the inductance would increase. The ratio between the iron filled torroid and the air or vacuum filled torroid would be the *relative permeability* of the iron which is usually written as μ_r.

There are similarities and there are differences between the capacitive and the inductive phenomena. If one were to keep pouring coulombs into a capacitor, the voltage would rise higher and higher until it eventually ruptured the dielectric material with a spark. On the other hand if a constant and high voltage were maintained across an inductor, the current would climb higher and higher and the magnetic field would follow it until a certain point is reached. Most ferromagnets magnetize by aligning *domains*, parts within the crystaline structure which are originally randomly oriented so that to the outside world there was no net magnetism. When the last domain lines up, the magnet becomes *saturated*. There is no phenomenon which parallels dielectric breakdown in magnetism and similarly there is no phenomenon akin to saturation in dielectric behavior.

In general all nonconductors have some relative dielectric constant which is larger than that of free space or vacuum. The values generally vary from 1.0 for air to 80 for distilled water. A few of the ceramics such as barium titanate have a dielectric constant of several thousand, but most materials lie between 2 and 8. Conversely, the vast majority of materials are no more magnetic than a vacuum. Only a few of the ferrites are more magnetic. A good grade of transformer iron will be as much as 10,000 times as magnetic and some of the magnetic alloys can be 100,000 times as magnetic.

RE-STANDARDIZING

Suppose, for example, that in some form of holocaust or upheaval that all of the standards of the world, and all of the laboratories were destroyed and that it became necessary to re-establish our standards for the volt, the ampere, etc. How would it be possible to reestablish these quantities at the precise same values they now have?

The surprising answer is the fact that it would be possible to reestablish standards for each of these quantities starting with nothing at all. The technique would be something like the following scenario.

Of all of the quantities described, only the meter is arbitrary. Originally, the meter was simply defined as the distance between two marks etched into a platinum-iridium bar and kept in a vault in Severes France, with the bar measured at a temperature of 0°C. However, the definition has been changed to state that the meter is equal to 1,650,763.73 wavelengths of the orange-red light given off by a discharge lamp containing the isotope Krypton 86. This is a very stable natural phenomenon which could be used to reestablish the length of the meter to a suitable degree of precision without any other standard available.

The kilogram is simply established as the weight of 1,000 cubic centimeters of distilled water at a temperature of 4° Celsius. The Celsius temperature scale is easily obtained by dividing the temperature difference between the melting point of water and the boiling of water into 100 equal segments.

The second is easily reestablished as 1/86,400 of a mean solar day. This could be determined with very good accuracy by noting the time interval between the passage of two stars of known position through the meridian. A more accurate definition of the second could be obtained from the measurement of the oscillations in a Cesium vapor cell. The second is defined as that period of time occupied by $9.192+ \times 10^9$ oscillations (to 13 significant figures) of the cesium vapor. In actuality, the cesium beam absorbs energy at resonance from a microwave oscillator whose oscillations can then be counted electronically to give more tractable units of time.

It is not here suggested that it is really very easy to do these things nor that it does not take a very considerable effort on the part of even a highly technical nation, however the point remains that it is possible to precisely reestablish the values of the meter, kilogram and second from natural phenomena without recourse to any arbitrary standards using only unchanging natural phenomena. With these fundamental units reestablished it would be possible to reestablish the derived units such as the newton, the watt and the ampere.

SUMMARY

This chapter has by no means exhausted the subject of units. There are a good many more units which we shall be using in the remainder of the text. It was the purpose of the chapter to introduce some of the units which will be used throughout the text and to convey a feeling for the techniques whereby the electrical units may be related to the mechanical units, etc. In the chapters to follow, some additional units of measurement will be discussed along with the measurement procedure and apparatus.