THE APPLICATION OF ELECTRONICS TO HYDRAULIC RESEARCH

S. W. Grinnell

Stanford University, Palo Alto, California

The term "electronics" was coined as a means of referring to the construction and utilization of electrical devices which involve the passage of electrons through space, as distinguished from ordinary metallic conduction. Perhaps the most familiar example of a simple electronic device is the radio amplifying tube, which is capable of controlling currents up to a few hundredths of an ampere at voltages up to a few hundred volts in response to the extremely minute currents and voltages which are impressed on the grid of the tube.

By means of the thyratron, a representative of another class of electronic devices, large amounts of electric power, taken from the usual 60-cycle alternating-current mains, may be governed by a relatively small power input in such a manner as to enable smooth and efficient control in the operation of electrical equipment. X-Ray tubes, fluorescent lighting, the strobotron or high-speed flash light for photography, and the cathode-ray oscilloscope are but a few of a host of other electronic devices to which new additions are being made continuously. These have been utilized in an ever increasing number of applications, and during the recent war the allies were finally able to reach an overwhelming degree of superiority in their electronic equipment over that of their opponents.

As a rule, the designation "electronic equipment" or "electronic components" includes all the electrical parts, such as resistors, capacitances, inductances, transformers, batteries, etc., in addition to the purely electronic devices, which are combined to perform the desired service. The present cheapness and availability of these components is largely due to the support of research and development afforded by the public demand for long-distance telephone service and for broadcast entertainment.

With the removal of war-time secrecy restrictions, information on recent war-time developments in electronics, successfully applied in research and production as well as in the war zones, is continuously appearing in the technical journals and in the scientific reports of the many research organizations which worked at an accelerated pace during the war.

In the field of hydraulics, as in other lines of research, there is always a need for new instruments and equipment, and because of the similarity between the concepts of fluid flow and those of electricity it is not difficult for the hydraulic engineer to evaluate for himself the capabilities and limitations of a particular application of electronic equipment to the research in which he is interested. If he takes an active part in formulating the design and specifications of a new piece of equipment, even though leaving the circuit details to the electronicist or to the manufacturer, this interest will tend to result in a more profitable utilization of the almost unlimited electronic resources which are available today.

There is now, for example, a growing tendency to operate such power devices as wind-tunnel fans, towing-tank equipment, dynamometers, etc., directly from the 60-cycle alternating-current power lines, with relatively compact and highly responsive electronic equipment giving better control than the rheostats and direct-current motor-generator sets formerly considered necessary for this purpose. Similarly, where extremely steady currents and voltages are required, storage batteries can now be replaced with electronic power-supplies capable of maintaining currents and voltages to within a few hundredths or even thousandths of a percent of the desired value.

In regard to instrumentation, although there are many relatively simple and time-tested devices, both electrical and mechanical, for which the substitution of a new instrument would require considerable justification, many cases will come to mind where there is an excellent opportunity for the introduction of electronic methods. This may either increase the efficiency with which data already obtainable by other means may be collected and analyzed, or it may lead to the quantitative observation of phenomena beyond the practical range of the existing instruments.

The criteria for the successful performance of field instruments, such as would be used in extended hydrologic and meteorologic studies, may be entirely different from those for the performance of laboratory instruments. The former must operate dependably without skilled attention over long periods of time. They are subject to conditions which are not completely under the control of the operator, and their operation usually results in the accumulation and necessity for subsequent treatment of far more voluminous data than those obtained in normal laboratory procedure. Consequently effort which results in even minor improvements in field instruments will often be amply justified by cumulative savings in man-power or by more complete records, while the same degree of improvement in a laboratory instrument would only result in the saving of a few minutes of the operator's time or in preventing the loss of a few measurements which could easily be repeated.

The advantages peculiar to electrical, and hence to electronic, methods of measurement lie in the ease with which various physical quantities may be transformed into electric currents and voltages. These may then be amplified to operate the standard highly-developed electrical indicating and recording equipment. With the proper selection of instruments, the speed of response can be made extremely fast, and yet the power abstracted from the system undergoing measurement may be made extremely small. Moreover, there are a number of mathematical operations which can be performed by automatic electric means on these varying currents and voltages, thus allowing the measurements to be expressed in a final form that would otherwise require a virtually impossible amount of computation.

Against the above advantages of new or improved electronic equipment must be placed the time and expense required to develop it. At best the actual construction of the various electronic circuits is so complex that even when they are described in the literature they require considerable intelligent effort for their successful application. After a single unit has been constructed, however, the production of subsequent units becomes a simple matter. The complete interchange of information between various research organizations which have common instrumentation problems would result in considerably reduced duplication of effort and in improved instruments. It is not usually possible to conduct this exchange of information in a satisfactory manner via the literature, at least not without a large amount of experience in a particular field.

The various electronic techniques which are available to studies in hydraulics are distributed widely throughout journals dealing with such varied subjects as radio, biology, chemistry, electrical engineering, geophysics, etc. Furthermore it is frequently found that the title of the article bears little or no relationship to the particular phase of electronic instrumentation which is desired. Therefore, there is every advantage in maintaining a broad general interest in a variety of different fields, and in regarding a new instrument in an analytical manner by breaking it down into its various functional units. An understanding of these functional units and of their optimum design may then lead to their reassembly in an entirely different instrument which will play an indispensable part in an entirely different research project.

At first sight, the complete circuit diagram for even so familiar a device as a broadcast radio receiving set presents a bewildering array of resistors, capacitors, transformers, vacuum tubes, and perhaps other electronic components all interconnected by a maze of lines which represent the electrical wiring. On analyzing this circuit diagram, however, it can be seen to resolve itself into a group of functional units, such as radio-frequency amplifiers, an oscillator, a mixer, a detector, an audio-frequency amplifier, and a power-supply, each of which has a definite purpose and is constructed from the various electronic components just mentioned. By first understanding each of these functional units separately and synthesizing their actions, the circuit diagram then becomes clear. Circuits for other devices, not at all related to radio broadcast receiving, may employ similar units, but grouped with others in a different way.

New methods of doing things electronically are usually devised by considering first the various steps which must be performed and then assembling a set of functional units which fulfill as well as possible the requirements laid down for the new piece of equipment. The first step in this process is to have an appreciation of what the different functional units can do and which ones will most suitably conform to the problem at hand. After these are chosen, the success or failure of the new method will depend to a large extent on the skill and judgment with which the basic components are selected and the way in which they are put together.

Since, as has been mentioned before, there are very attractive possibilities in the further application of electronic principles to measuring instruments, the remainder of this discussion will be oriented chiefly in that direction. Most applications of electronics are inseparably connected with mechanical and other physical principles, and it is best for all these principles to be considered together at the same time. Therefore any survey of the possibilities of electronic techniques will necessarily also cover electrical techniques in general and some partly mechanical techniques.

There are three distinctive methods by which many measurements such as electrical measurements are made. The simplest is the deflection method, where the quantity undergoing measurement produces a force which moves a mechanism to which an indicator is attached and as the indicator is displaced an opposing force is developed in accordance with the position of the indicator. This final position, when the two forces are equal, shows on a graduated scale the magnitude of the initial quantity. Common instruments indicating by the deflection method are: Bourdon gages, simple liquid manometers, and ordinary direct-current voltmeters and ammeters. In the latter case the initial force is produced on the moving coil by the interaction between the current in the coil with an external magnetic field; the opposing force is supplied by the deflection of flat spiral springs.

The second method is usually called the null method or ''setback'' method. If the quantity actually measured is a force, pressure, or voltage, this quantity may be compared with a calibrated source of variable force, pressure or voltage by adjusting the latter until some sort of indicator (functioning by the deflection method) shows equality between the two opposing intensive quantities, that is, until a null indication is obtained. The calibrated source of the variable force, pressure, voltage, or other quantity can be adjusted to a far higher degree of precision than can ordinarily be maintained in a deflection type of instrument. The null indicator itself, which need detect only the equality between the opposing quantities or else the direction of the unbalance, need be designed primarily for sensitivity and simplicity and not for accuracy.

The null method is used in many types of instrument where extreme accuracy is required. It is slower than the deflection method and requires more attention on the part of the operator, since several successive readjustments are ordinarily required before a null balance is achieved. For the same reason it is best suited for the measurement of only reasonably steady values, where it has the great advantage over the deflection method in that at the balance point the measuring system is drawing negligible power from the system undergoing measurement, and in that it is usually a simple matter for the true position of this balance point to be known to a sufficiently high degree of precision. Good examples of the method are seen in analytical balances, the potentiometer method of measuring voltages, the torsion dynamometer, the Paulin-system aneroid barometer, and the differential manometer when it is balanced by varying the leveling of the instrument with a micrometer screw.

The third and last method of measurement is really a modification of the null method described above, but here the adjustment of the opposing force, pressure, voltage, or other quantity is made automatically in response to a signal from the null-indicator, and in such a direction as to make it more nearly equal to the quantity which is being measured. Systems of this type are sometimes called "follower systems", since the magnitude of the opposing quantity is made to follow that of the quantity being measured. As before, the null-indicator absorbs only an extremely small amount of power from the system undergoing measurement, or being "followed", but there is no limit to the amount of power that can be controlled by the position of the null-indicator. This power can be applied not only to the adjustment of the calibrated source of the opposing quantity, but also to moving other systems which are mechanically coupled to it.

When the motion of the mechanically coupled system assumes major importance, the follower system is usually called a "servo-system" or "torque-amplifier." The quantity being followed in this case may be, for example, the resistance of a delicate rheostat whose setting is determined by the position of the axis of a gyro-compass relative to its mounting. This resistance may be "followed" by that of another rheostat mechanically coupled to the steering mechanism of an airplane. The flight-path of the airplane will then follow the position of gyrocompass, and if the plane deviates from the direction set on the gyrocompass, the steering mechanism will respond automatically in such a direction as to correct the course.

Servo-mechanisms, and in fact all follower systems, must be carefully designed or else instead of accurately following the device producing the controlling signal, the output response will continuously oscillate about its proper value. Methods of avoiding this and at the same time obtaining a rapid response to any change in the controlling signal are now in a high state of development, as far as their application to many commercially or mass produced appliances is concerned. Their application to specific problems in pure research offers attractive possibilities, and numerous devices in this category have already been described in the literature.

Commercial and war-time applications include the following: automatic pilot systems for aircraft; radar-controlled anti-aircraft systems; control of gun fire on warships; automatically guided rockets and torpedos; automatic plotting of the course of a jeep in response to the azimuth indications of a magnetic compass and distance indications from the speedometer; speed governors of many types; a variety of electrical recording instruments; draft and fuel controls in furnaces; industrial temperature control; contouring machines such as those which accurately mill the form of large ship propellors in accordance with the motion of a pointer which traces over the contours of a small wooden model.

Essentially the same principle is used in the design of purely electrical amplifiers in which the output current or voltage is controlled with a high degree of accuracy by the input voltage. These are known as "negative-feed-back amplifiers".

Although extremely successful hydraulic and non-electronic follower systems have been worked out, electron tubes play an important part in the majority of applications of follower systems for purposes of measurement. Since the functional units of this class of follower systems are similar to those used with the deflection and null methods, the same scheme of classification will apply for all. As mentioned before, some such scheme can be very helpful both in dealing with unfamiliar instruments and in the selection of the principles on which to design new ones.

A logical approach to the useful classification of the different functional units is the resolution of the equipment into the following subdivisions:

(1) Responsive elements, which transform the variations of the

physical quantity under measurement into variations of one of the electrical quantities.

(2) Intermediate elements. These may provide amplification of the electrical signals from the responsive element, or they may transform the electrical data received by them into forms more suitable for the final expression of the measurements.

(3) Indicating elements. These may be one of the many varieties of instruments, readily available as completed units, for indicating or recording such electrical quantities as current, voltage, resistance, frequency, total number of electrical pulses, etc., or they may be cathode-ray tubes or more specialized instruments.

The instruments comprising the three types of element given above may in themselves frequently be broken down into still simpler elements, and finally into their basic electronic and mechanical components.

For example, a self-balancing potentiometer, used as a recording element, is in itself a complete follower system and it can be divided into the following parts: The null indicator, which is sensitive to the difference between the impressed emf and the opposing emf; the variable source of the opposing emf, which may consist of a wire-wound resistor provided with a sliding contact so that, with a constant current flowing through the resistor, the position of the contact determines the voltage which is opposed to that being measured; a pen which is mechanically coupled to the resistor contact so that its position is continuously recorded on the moving chart; a reversible motor to drive the variable resistor contact in response to the signal from the null indicator; a damping mechanism so that the motor will not coast beyond the point where the null indicator shows that the emf to be measured and the opposing emf are equal. The null indicator consists, in a number of commercial instruments, of an electronic amplifier whose output current passes through the field coils of the driving motor to produce the proper sense of rotation of the armature. Because the amplifier can rapidly control a relatively large amount of power the pen system will follow completely any change in the impressed emf within one second.

In order to give an example of the application of the particular classification scheme mentioned above, Tables I and II, dealing with two types of responsive elements, those to position or motion, and those to temperature, and Tables III and IV, dealing with intermediate elements and with indicating elements have been prepared. These are by no means complete, and although a few references are given to illustrate some interesting applications, limitations in space prevent even an initial discussion of the many ways in which these elements have already been applied in making fundamental contributions to hydraulic research. Nielson [1] has given an excellent summary of the capabilities of different electrical instruments according to this scheme.

In the application of the above tables to various measurement problems in hydraulics, the quantity under measurement can often be transformed mechanically into such form that it will act on one of the responsive elements listed. Three types of measurement frequently desired are those of pressure, of fluid velocity, and of fluid height.

Variation in pressure may be transformed into variation in position by means of the fluid manometer, by means of a flexible diaphram, or by means of a flexible bellows. If a relatively large volume change can be tolerated, together with a response time of a second or longer, a number of the position elements listed in Table I may be employed, and the simplest is probably the mechanical coupling to the bellows of a variable resistor with sliding contact. Large pressure variations in a pipe could be measured by attaching a resistance-wire strain gage directly to the outside of the pipe. Pressures of a few inches of water can be measured by using a follower system where the null indicator is the liquid level inside a water manometer together with an electrolytic contact or action on a pair of photoelectric cells. These would control a source of variable air pressure to balance out that being measured. In the measurement of rapid fluctuations in wind-velocity a diaphram-type pressure plate has been employed together with a balanced inductance-coil strain gage to respond to very small motions of the diaphram.

Other methods of measuring fluid velocity consist of a rotating vane or cup system together with a position element to translate the number of rotations per minute into a frequency. The intermediate element can then be a frequency meter, and the indicating element a recording milliammeter. When using an extremely light cup or vane system in air at low velocity, the position element must extract no power at all from the rotating system. This requirement has been nearly met by the use of magnetic contacts, and has been completely met at the expense of somewhat more complicated auxiliary equipment by the use of a photocell with amplifier.

Another method of the measurement of fluid velocities consists of the hot wire anemometer, where a resistance-type temperature element, heated by an electric current responds to changes in the heat-transfer properties between the fixed wire and the moving fluid. The use of this method in the measurement of turbulence in wind-tunnels is now well known. Uniform time-response characteristics are obtained by the use of a capacitative or inductive compensator as an intermediate element. The application of the hot wire to measurement of turbulence in liquids has so far been less successful, but several methods, including a variant of the follower system, show promise.

The velocities of conducting liquids [15] have also been measured by using the principle of the moving conductor in a magnetic field. The voltage generated by this responsive element, of which the liquid itself is a part, is proportional to the velocity component of the liquid.

Unlimited extensions of the above discussion can easily be imagined. Literally hundreds of entirely feasible combinations of the elements and methods described can in some cases be synthesized as the answer to a given general instrumentation problem. The large number of degrees of freedom which are thus allowed makes it possible to conform to a large number of specifications in the selection of the design. The rapidity of response, the interaction of the initial responsive element with its physical environment, the sensitivity and accuracy requirements, the availability of the component parts, the experience which the designer has had with a particular type of equipment, whether the equipment is intended for field or laboratory use, and the type of power-supply on which the equipment is operated will all contribute to the final decision on its design.

By summarizing the properties of the different elements, functional units, and components in systematic form, their present application to the various phases of hydraulic research becomes easier to follow and future possibilities become easier to evaluate. Accordingly the attempt has been made in this paper to outline a process of thinking which leads, as far as electronics is concerned, to an efficient utilization of some of the instrumental resources which are available today.

TABLE I

RESPONSIVE ELEMENTS — POSITION, MOTION, OR DISTANCE

Contacts:	Balanced inductance coils
spring	[2] [5]
magnetic	Resistance wire
mercury switch	(strain gage)
with relay	Piezo-electric effect
with vacuum tube	(strain gage)
with gas-filled tubes	Magneto-striction effect
electrolytic [2] [3]	Moving conductor in magnetic field
Resistor with sliding contact	Change in mechanical or electro-
Interrupted light-beam	magnetic characteristics of medium.
with photocell	(as in Radar and depth-recorders)
De-tunable oscillator [4]	Change in heat-transfer
Capacitance changes	(as in hot-wire anemometer)

TABLE II

RESPONSIVE ELEMENTS — TEMPERATURE

Thermocouples [6]	Mercury column
Resistance wire [6]	Bi-metallic strips
Carbon-type resistors	Sputtered metal films
Liquids [7]	(as resistance elements)
(as resistance elements)	

TABLE III

INTERMEDIATE ELEMENTS

Bridge circuits	Capacitative or inductive compensator
Frequency meters [8]	(as used in the hot-wire anemometer)
Photoelectric galvanometer	Differentiating and integrating
amplifier [9]	circuits [12]
Direct-current amplifier	Hot-wire with thermocouple
(stabilized) [10]	Dynamometer AC current-meter
Alternating-current amplifier	Photocell with light-modulator
AC amplifier with chopper for	(filament or gaseous)
DC response [11]	Intermediate recorders
Electronic pulse-counter	(as magnetic wire-recorders) [13]
(as developed in radio-activity	Phase-shift meter (used in remote-
studies)	indicating radio transmission)

TABLE IV

INDICATING ELEMENTS

Visual:	Photographic:
Moving-coil milliammeter	Magnetic oscillograph
Cathode-ray oscilloscope	All visual elements
Counter	Variable density recording
Permanent Immediate Record:	Conduction-writing paper with electrical stylus [14]
Spark-writing	Mechanical self-balancing potentiometers
Soot-writing	Electronic self-balancing potentiometers
Pressure-printing (intermittant)	Moving-coil with mirror and photocell follower with pen
Pencils and self-contained pens with ink supply	
Moving-coil with siphon ink-supply to pen	

REFERENCES

1. Nielsen, D. M., ''Electrical Measuring Instruments'', *Electrical Engineering,* Vol. 65, No. 2, 1946.
2. Woodman, E. H., ''Electronic Aids in Waterway Development'', *Electronics,* Vol. 18, No. 9, 1945.
3. Ware, L.A., ''Water Level Indicator'', *Electronics,* Vol. 13, No. 3, 1940.
4. Agnew, W. B. R., ''Laboratory Oven Temperature Control'', *Electronics,* Vol. 17, No. 10, 1944.
5. Sherlock, R. H., and Stout, M. B., University of Michigan *Engineering Research Bulletin No. 20,* Ann Arbor, 1931.
6. ''Temperature — Its Measurement and Control in Science and Industry'', Reinhold Publishing Corp., New York, 1941.
7. Weiller, P. G., and Blatz, I. H., ''Electronic Thermometer'', *Electronics,* Vol. 17, No. 7, 1944.
8. Case, N. P., ''A Precise and Rapid Method of Measuring Frequencies from 5 to 500 Cycles per Second'', *Proc. Institute of Radio Engineers,* Vol. 18, page 1586, 1930.
9. Asset, G., ''A Photoelectric Galvanometer-Amplifier'', *Electronics,* Vol. 18, No. 2, 1945.
10. Artzt, M., ''Survey of D.C. Amplifiers'', *Electronics,* Vol. 18, No. 8, 1945.
11. Williams, J. A., ''Crystal Drive Modulator for D.C. Amplifier'', *Electronics,* Vol. 18, No. 12, 1945.
12. Clarke, J. G., ''Differentiating and Integrating Circuits'', *Electronics,* Vol. 17, No. 11, 1944.
13. Shaper, H. B., ''Frequency Modulated Magnetic-Tape Transient Recorder'', *Proc. Institute of Radio Engineers,* Vol. 33, No. 11, 1945.
14. Redemske, R. F., ''Electronic Shutter Testers'', *Electronics,* Vol. 19, No. 2, 1946.
15. Kolin, Alexander, ''Electromagnetic Velometry. I. A Method for the Determination of Fluid Velocity Distribution in Space and Time'', *Journal of Applied Physics,* Vol. 15, No. 2, pp. 150-164, 1944.