

RECENT DEVELOPMENTS IN ELECTRONIC INSTRUMENTATION

by

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At the Third Hydraulics Conference in 1946, Dr. S. W. Grinnell presented a paper [1] in which he discussed the role of electronics in hydraulic research and the work of some of the pioneers in the field up to that time. He analyzed the particular virtues and deficiencies of electronic instruments and reviewed current techniques in the field as a guide to those who found it necessary to supplement traditional methods of measurement. Nearly a decade has passed since that time, and a review of developments during this period is considered in order, both as a guide to those who wish to take advantage of current knowledge and equipment and as a clue to those who intend to participate in future developments along this line. For the sake of brevity, the title of this paper has been made much broader than the actual subject matter, and limitations can now be fully stated: Recent developments are those which have arisen or matured within roughly the last decade; only instrumentation which is closely related to hydraulic engineering will be included; and finally, the topics to be considered are meant to be only representative, certainly not exhaustive. In particular, instruments and techniques which are being presented in other papers of the present conference will be omitted or only mentioned briefly, for obvious reasons.

GENERAL OBSERVATIONS

For the research worker confronted with the problem of devising methods to measure various physical quantities under laboratory conditions, the required understanding of the details of electronic circuitry has been greatly decreased during the last decade. Because of the demands of industrial research, particularly in the aircraft and flow-process industries, a multiplicity of sensing elements which can be applied directly to hydraulic measurements is now commercially available. For processing the signals from these elements, entire assemblies of electronic components which formerly had to be designed and refined in the laboratory can now be purchased directly from a choice of manufacturers in a highly reliable form. It is therefore possible for an engineer with imagination and skill in mechanical design to assemble satisfactory electronic

systems with little more than a "block-diagram" understanding of the electronic components. There are, of course, many problems whose solution demands a much deeper understanding of electronic principles, and obviously many more which to date have defied solution.

A cursory look at available statistics shows that the business of developing better sensing elements and simpler-to-operate electronic components is a highly-competitive field which has assumed giant proportions. From an annual volume of about one and one-half billion dollars in 1947, the instrumentation industry has grown until it now boasts a volume of more than four billion dollars [2] and has produced vigorous branches in computers and automation. Because of the increased use of automatic measuring and controlling devices, some even refer to present developments as the second industrial revolution. In 1946, an efficient instrumentalist had to keep abreast of the rapid release of a rich but unrefined storehouse of information which had developed in the confined atmosphere of wartime research. In 1955, an efficient instrumentalist must keep abreast of the rapidly increasing array of commercially available and highly refined instruments which are the product of the intervening years.

The author of a recent technical article surveys the range of available instruments and concludes that "the most important frontier of modern instrumentation is in application" [3]. This remark is highly significant and applies to a great many of the problems of hydraulics, especially in what may be considered the extremities of the field: the operation of model structures and the solution of hydrodynamic and other integro-differential equations.

As typical examples of techniques which are being applied to model operation, tidal fluctuations are now being produced automatically from a rectangular plot on paper of the desired stage relationships versus time, while different parts of a model are scheduled to reproduce desired conditions by means of feed-back loops in which the stage at one point, for example, controls the discharge at another [4]. At the measuring end, operations such as averaging, integrating or applying correction factors can be handled electronically with considerable savings in time and money. Final results can be recorded on charts, on magnetic tape, on oscilloscope tubes or, in keeping with latest trends, as digital data on punched cards, decade counters, or even automatically typed sheets.

For the analyst who has suffered the frustrating experience of managing to express the relationships between parameters in equation form only to find that useful solutions will require years

of work, analog and digital computers are now available which will quickly provide solutions. The ability of these computers to check their own operation and indicate faults automatically has improved so that they exhibit a freedom from error hundreds of times better than skilled workers. Since large general-purpose computers may cost more than a million dollars and produce answers at a fantastic rate, they are generally located at convenient centers of activity where they can serve many analysts on a rental basis. Special-purpose or "small" computers (in the trade, those which cost less than \$50,000) are often supplied complete with an intensive short course on their operation and presumably can be kept, like a slide rule, at the analyst's elbow.

SPECIFIC APPLICATIONS

In order to discuss some recent developments in more detail, it will be necessary to narrow the range of problems considerably. Because of the continually recurring need to measure velocity, pressure, and vertical displacement of a liquid surface or channel bed, these have been chosen as examples. The range will be further restricted by considering measurements made under research laboratory conditions as opposed to routine industrial measurements or field work under adverse conditions.

Electronic instruments are used in measuring fluid pressures in three categories: very low, rapidly varying, and where a record or remote indication is necessary. Several manufacturers supply instruments which will indicate the instantaneous values of pressures above about 1 psi with very fast time response and high accuracy. Extreme care has been taken to reduce the size of the sensitive portion and insure freedom from errors due to extraneous variables such as vibration and temperature variations. For measurements in this range, therefore, it is recommended that commercially available devices be considered before starting to design a sensing element. In Fig. 1, a typical pressure cell of this type is illustrated.

If measurements in the range below 1 psi are to be attempted, two alternatives should be considered: to measure only the fluctuating component if possible, in which case commercially available hydrophones with sensitivities down to background noise can be obtained; or, if small changes in the mean level must also be known, to arrange components such as sensitive bellows or diaphragms so that they convert pressure differences to linear motion which can be detected with displacement detectors which, again, are available commercially in several forms. As an example only, a linear variable

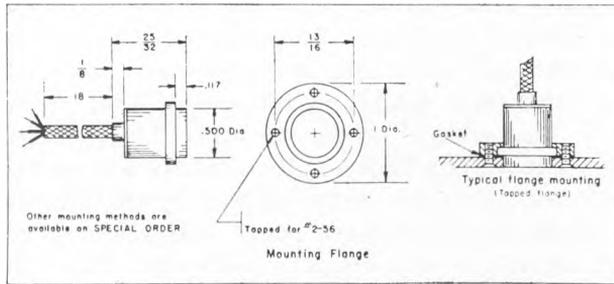


FIG. 1

differential transformer which reliably and accurately detects displacements of less than 10^{-4} inch is shown in Fig. 2. The problem of recording the results is simply a matter of selecting from a wealth of material. A recorder which happens to be available at the Institute is shown in Fig. 3.

Lest the conclusion be reached that all pressure measurements are now simply routine, a few words of caution concerning possible pitfalls should be noted. If the dimensions of the system under study are quite small and if fluctuations in pressure are rapid, considerable study and design are often necessary to assure freedom from inertial and viscous effects which can cause very large errors. A complete analysis of the factors which must be considered in this regard could well be the subject of a paper many times the length of this one, however, and will therefore not be even attempted now.

In the field of measuring liquid surface elevations in gage wells, manometers, or open channels (including waves), one recent de-

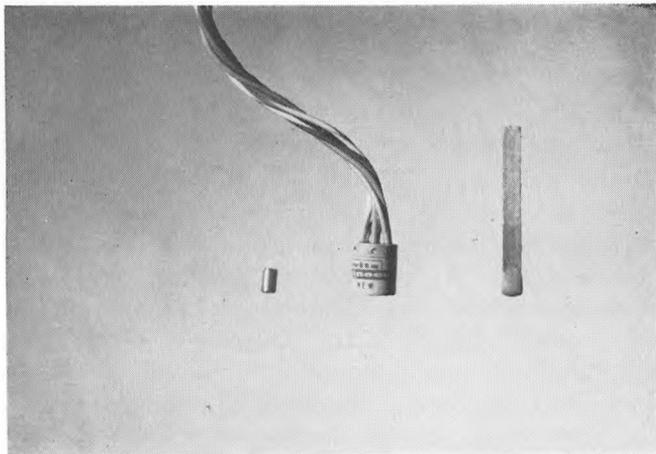


FIG. 2

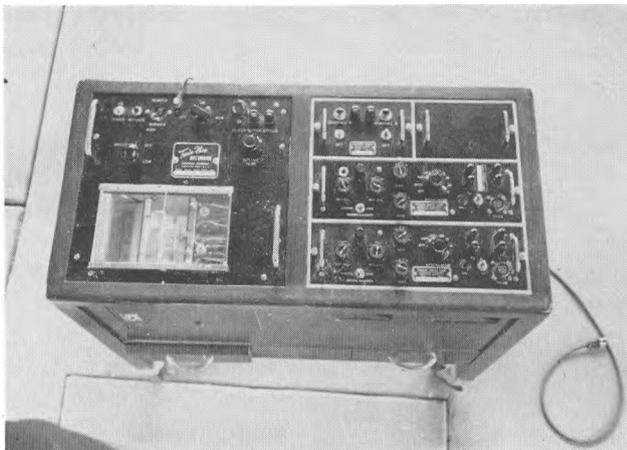


FIG. 3

velopment is the perfection of capacitive-type detectors consisting of very fine wires coated with a thin dielectric. When these wires are stretched between two points, one beneath and one above the surface, the capacitance from the wire to the liquid varies linearly with the immersed length. These fine wires usually do not create a noticeable disturbance in the system, respond as quickly as necessary, and the capacitance can be made nearly independent of the ambient temperature or conductivity of the fluid. Their chief virtue, of course, is simplicity.

Another liquid-level detector which has been highly developed recently is the vibrating-needle device which enjoys considerable popularity in Europe [5]. A related European development which to the writer's knowledge has not been employed in this country is the "wave-height analyser" of the Hydraulics Research Station in England [6]. The sensing element of this analyser is a series of vertical wires in graduated lengths which contact the moving water surface. When wires are immersed or exposed by the changing water surface, resistors connecting the wires are progressively shunted or vice versa. If a steady current is passed through the system thus formed, the voltage varies in a step pattern which is converted to pulses and finally to indications on a counter. It is expected that this novel device will enjoy considerable popularity because of its basic simplicity and high probable accuracy.

When the surface elevation to be measured is not the liquid-air interface but the interface between water-saturated earth and the water, the problems of accurate and dependable measurement are much farther from satisfactory solution. First, because of the

heterogeneous nature of the bed material and the possibility of partial suspension in flowing water, simply specifying the location of the bed becomes a matter of statistical definition before any measurements are attempted. Secondly, practically none of the physical characteristics of the surrounding media go through a sharply defined change as the point of measurement crosses the interface. In the face of these facts, it is not surprising that the best available measurements of bed level are only 1/10 to 1/100 as precise as corresponding measurements of the liquid surface; nevertheless, there is recent progress to report in this field. At the Institute, for example, the bed level at a fixed object such as a bridge pier or abutment is being measured by means of a series of small electrodes embedded in the surface on a vertical line [7]. If the electrical impedance from each of these electrodes to a large electrode fixed in the water is measured, a definite difference is evident as the interface is crossed. In keeping with earlier remarks, this change is not abrupt, but becomes increasingly sharp as the particle size in the bed and the vertical dimension of the electrode decrease. When the water is moving, however, the gradually varying concentration of suspended material complicates the problem of defining the bed level.

For another recent development in electronic bed-level detection, attention can again be directed to work being done abroad. In both England and France, investigators have independently developed instruments operating on the change in electrical impedance between two immersed electrodes as they approach the bed [8]. An associated pair of electrodes compensates for changes in the conductivity of the water and, under favorable conditions, a reproducibility of indication less than 1 mm is reported. No mention was made of adapting the device to automatic recording, but this should be a relatively simple step using modern servo devices.

Of all problems of hydraulic measurement probably none has received more attention during the past decade than the measurement of velocity, and probably none is farther from satisfactory solution throughout the range of normally-encountered conditions. With one or two possible exceptions, none of the techniques being used is based on an entirely new principle, but several variations and improvements on old methods are worthy of notice.

One of the oldest and most direct methods of velocity determination is to inject a neutrally buoyant but optically distinct material into the stream and to observe its subsequent motion. At least two new methods of introducing the tracer electrically have come to the writer's attention, and are especially useful in observations of the

boundary layer. Wortmann, in Germany reports on the use of a very fine tellurium wire stretched across the stream at a point where it can be observed optically [9]. With this wire as the cathode and any convenient metal as the anode, a pulse of current lasting a few milliseconds is passed through the water. This pulse dislodges ionized particles of tellurium which are transformed into elementary tellurium by a secondary reaction and proceed with the flow in what appears to be a dense black line. The distortion of this line with passage of time is related to the velocity, of course, and can be observed photographically for quantitative results. By using due care, the particles produced have fall velocities of less than 0.1 mm/second and diffusion velocities of less than 10^{-3} mm/second.

A superficially similar method utilizing an entirely different principle to produce similar results has been reported in a thesis by Geller at Mississippi State College [10]. As in the Wortmann method, a fine wire is stretched across the flow and used as the cathode to pass a pulse of current through the water. The wire was made of platinum, however, and operated by producing a fine line of very small bubbles of gas through electrolysis, instead of ionized particles. The actuating pulse was provided by discharging a condenser through the water, and better results were obtained by adding salt or acid to the water to increase its conductivity; errors due to bubble buoyancy were eliminated by using vertical flow past the measuring point. Besides the novel method of introducing the line of bubbles, the thesis also described an improved method of establishing a time base by repeating the pulses at controlled short intervals of time so that a single film exposure included several lines of bubbles. Furthermore, by combining the repetitive-pulse technique with motion pictures, unsteady flow patterns were successfully measured.

The method which is intrinsically most nearly perfect for measuring velocities is that of electromagnetic induction. It is capable of indicating over an extremely wide range, has zero lag, is practically independent of conductivity, temperature, pressure, and gaseous or solid impurities, and indicates the true vector component of velocity. During the many decades that the principle has been understood, however, much work by many different investigators has failed to produce a practical instrument for any but very limited conditions. Work on the method has been continued, however, and several papers describing the results are to be found in the literature of the last decade. Two of these are of particular interest to hydraulic engineers: One describing a probe-type in-

strument for use in pipes at the University of California [11], and one describing several forms of instruments used by Electricite de France [12]. Their work was significant and produced useful results, but many problems still must be solved before the method can find widespread application in hydraulic measurements. The principle has been mentioned in the present paper primarily because of its tremendous potential.

Proceeding to a method which is less direct than either of the preceding ones, the well-known stagnation tube has come in for its share of development through electronic auxiliaries, and has actually been used to measure turbulence in several laboratories. At the Massachusetts Institute of Technology, for example, a small stagnation tube has been connected to a variable-capacitance sensing element and used to measure turbulence in high-velocity flow at shallow depths [13]. At the Iowa Institute, several forms of modified pitot-static tubes have been developed, some of which indicate fluctuations in the direction as well as the magnitude of the velocity [14]. They have limited application in the laboratory primarily because of the relatively low sensitivity of the fast-response types and the difficulty of producing them in sufficiently small sizes.

No discussion of electronic instruments for measuring velocity would be complete, of course, without including the hot-wire anemometer and its close relative, the hot-film anemometer, which is particularly well adapted to measurements in water [15], [16]. Although these instruments are less direct indicators of velocity than any of those already discussed, they have produced excellent results and are considered most likely to be used soon in general laboratory investigations of turbulent flow. Operating techniques which minimize the influence of secondary variables have been developed, and long-time stability has been achieved. The size and response time are adequate for practically all conditions which will be encountered in laboratory work, although their use in field studies is limited by the fragility of the sensing element.

PROSPECTS FOR THE FUTURE

A discussion of recent developments naturally leads to the consideration of future developments either expected or hoped for, a task which is pleasant but somewhat hazardous. Firstly, what are the major unsolved problems of measurement confronting hydraulic engineers? The following list is almost certainly incomplete, but represents the writer's assessment of the problem, with no particular significance applied to the order of presentation.

1. An in-place sediment-concentration analyzer.
2. A size-frequency sediment analyzer for use in large-scale studies.
3. Improved velocity meters for field use, especially for very low velocities and very rapid or very intense fluctuations.
4. A better stage recorder for the field.
5. Instruments to measure pressure and pressure-velocity correlation in turbulent flow.

Finally, what current developments in instrumentation are likely to have the most influence on future developments in hydraulic measurements? The comments made above apply equally well to the following list.

1. Increased use of digital-type indicators with a resultant decrease in operator-judgment factors.
2. Increased use of automatic computing, compensating, and recording techniques.
3. Transistorized circuitry for light-weight, long-life field instruments.
4. Speed-changing recording techniques to make better use of standard analyzing equipment.
5. Greatly expanded use of servo-type instruments for control and measurement in hydraulic models.

DISCUSSION

Mr. Baines remarked that all of the examples cited rely primarily on electrical techniques, and that some electrical modifications of standard techniques have also been produced. For example, much work has been done on the midget current meter in an effort to reduce friction and record the revolutions remotely. Two organizations have developed propeller-type meters, one metal, one plastic, and have independently perfected nearly identical electrical circuits to detect the speed. A carrier current is passed through a wire near the blades, and passage of each blade produces a blip in the carrier. This is converted to a pulse which actuates a standard counter. The counters operate for periods up to 100 seconds and display the total number of pulses during the period.

Mr. Baines then asked about the present status of the hot-film anemometer, its frequency response, and temperature-velocity correlations. The speaker replied that any desired frequency response could be obtained up to at least 50 kilocycles, but that 1 kilocycle was usually adequate for the conditions encountered in water. He then referred the questioner to the recent Ph.D. dissertation by S. C. Ling for additional information on frequency response and the various correlations which could be measured.

Mr. Harbeck asked if the speaker cared to evaluate the vibrating-string type of instrument for measuring pressures, and the speaker emphasized the advantages of using commercially available devices wherever possible. These are available in many forms, but he knew of none using the vibrating-string principle. Although this principle and many others are well understood and probably reliable, most development work involves a great deal of time eliminating the effects of extraneous variables.

Mr. Folsom corrected the speaker's error in displacing Messrs. Grossman and Charwat from their true home at the University of California in Berkeley. He was also gratified by the favorable reference to the electromagnetic induction method and agreed that it should be exploited more thoroughly. With regard to the speaker's prediction concerning a shift to digital recording, he has already put all of his laboratory manometers on Veeder-Root counters. Random errors in the experimental results disappeared as if by magic.

Mr. Gent asked if the cloud of bubbles produced by the platinum wire could be produced by discharging current directly through the water. The speaker said that this was an unlikely possibility, but that production of cavitation bubbles by producing intense standing waves in the water was a possible means of eliminating the troublesome wire in the fluid. When intense standing waves are produced by a crystal or magnetostriction transducer, the fluid actually vaporizes in the pressure loops.

Mr. Shoumatoff was interested in the probable behavior of a hot-wire or hot-film anemometer in a fluid containing cellulose fibers, and in the precision of the vibrating-needle technique for measuring viscosity. The speaker recommended a hot-film anemometer with a conical tip to minimize the tendency to collect fibrous material, but was not familiar with the vibrating-needle method of measuring viscosity. Mr. Shoumatoff said that their attempts to obtain an instantaneous measure of viscosity with the vibrating needle had been unsuccessful.

Mr. DeHaven reported that their experience with the Fiscotron at Phillips Petroleum had also been unsatisfactory.

REFERENCES

1. Grinnell, S. W., "The Application of Electronics to Hydraulic Research," *Proc. Third Hydr. Conf.*, 1946.
2. Editorial, *Instrument and Apparatus News*, Vol. 2, No. 1, 1954.
3. Editorial, *Instrument and Apparatus News*, Vol. 1, No. 5, 1953.
4. Wilkie, M. J., "Some Automatic Devices for Use on Tidal Models," *Jour. Sci. Instr.*, Vol. 30, Aug., 1953.
5. Gridel, H., "The Accurate Measuring and Recording of Stable or Fluctuating Water Levels by Means of Continually Vibrating Limnimetric Points," *La Houille Blanche*, Special B/1950, p. 709.
6. Wilkie, M. J., and King, R.F.J., "A Wave-Height Analyzer," *Jour. Sci. Instr.*, Vol. 30, 1953.
7. Hubbard, P. G., "Field Measurement of Bridge-Pier Scour," *Proc. Hwy. Res. Board*, Vol. 34, 1955.
8. Wilkie, M. J., and King R.F.J., "A Bed Level Indicator for Detecting the Boundary of a Body of Water," *Jour. Sci. Instr.*, Vol. 31, 1954.
9. Wortmann, F. X., "Eine Methode zur Beobachtung und Messungen mit Tellur," *Zeit. f. Ang. Phy.* 5 Band, 6 Heft, 1953.
10. Geller, E. W., "An Electrochemical Method of Visualizing the Boundary Layer," Mississippi State College M.S. Thesis, August, 1954.
11. Grossman, L. M., and Charwat, A. F., "The Measurement of Turbulent Velocity Fluctuations by the Method of Electromagnetic Induction," *Rev. Sci. Instr.*, Vol. 23, 1952.
12. Remenieras, G., and Hermant, C., "Mesure Electromagnetique des Vitesses dans les Liquides," *La Houille Blanche*, No. Special B/1954.
13. Ippen, A. T., Tankin, R. S., and Raichlen, S., "Turbulence Measurements in Free Surface Flow with an Impact Tube-Pressure Transducer Combination," *M.I.T. Tech. Rpt.* No. 20, July, 1955.
14. Hubbard, P. G., Appel, D. W., and Ling, S. C., "Instruments for Measuring Large-Scale Turbulence in Water," *Iowa Inst. of Hydr. Res. Rpt.* Oct. 1952.
15. Hubbard, P. G., "Constant-Temperature Hot-Wire Anemometry with Application to Measurements in Water," S.U.I. Ph. D. Dissertation, 1954.
16. Ling, S. C., "Measurement of Flow Characteristics by the Hot-Film Technique," S.U.I. Ph. D. Dissertation, 1955.

