

FLOW MEASURING TECHNIQUES

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Summary

The measurement of hydraulic quantities is of vital importance in the planning, design and operation of water supply and water power systems. The accuracy of measurement required depends on the purpose for which the measurement is needed, be it the design of a hydraulic structure, an item of control equipment, or the earning of revenue for the delivery of pumped water, or water power. In all cases sophisticated measuring equipment and instrumentation, capable of accurately performing the measurement required, are needed. In this article, a resumé is given of the historical development of hydrometry/flow measurement, data collection, storage and retrieval. A measuring system consists of a chain of actions, ranging from the observation to the readout of the flow quantity by various equipment. Instruments such as sensors, transducers, recorders, analyzers, and presentation devices are involved. An important development is presented on the subject of error analysis, namely the reliability of data. Uncertainty in the measurement of flow quantities, if not restricted, would eventually lead to speculation, and possibly to making the wrong decisions in a life-support system, such as for water supply, flood control, or water power generation. Finally a review of the optimum design method for a hydraulic metering system is given.

1. Introduction

Hydraulic measurements support research and development in laboratories and in the field, and include data collection for water resources management. They can serve for the solution of an engineering problem, the physical understanding of a flow process, or contribute to the accumulation of a hydrological database (see *Water Data Collection Systems*).

1.1 Historical Background

Historically, the interest in hydraulic instrumentation developed in the seventeenth and eighteenth centuries, in parallel with the interest in a quantitative description of flow phenomena. The Pitot tube was invented around 1730 and provided an indirect local static measurement of flow velocity (see *Flow Measurement in Closed Conduits*). Dynamic point measurements became feasible after the advent of electronic equipment. Hot-wire anemometers, were invented in 1914, were the first instruments able to measure turbulent velocity fluctuations (see *Turbulent Flow Modeling*). A further major step was brought about by the advent of digital computers in the 1970s, which allowed fast analog-digital conversion of time-series information and the handling of large amounts of data. The development of electronic cameras led to methods of measuring entire velocity fields and to satellite-based remote sensing techniques (see *Hydraulic Methods and Modeling*).

1.2 Indirect Methods of Measurement

The fluid and flow quantities of interest, such as velocity, discharge, pressure, or salinity, cannot be measured directly (see *Fluid Mechanics*). Therefore, they have to be transformed by means of a transducer into a measurable quantity such as length, position, time, frequency, voltage or current. The result then has to be recorded, often after electronic amplification, analog-digital conversion, and digital storage of the data. This leads to a typical instrumentation chain as sketched in Figure 1.

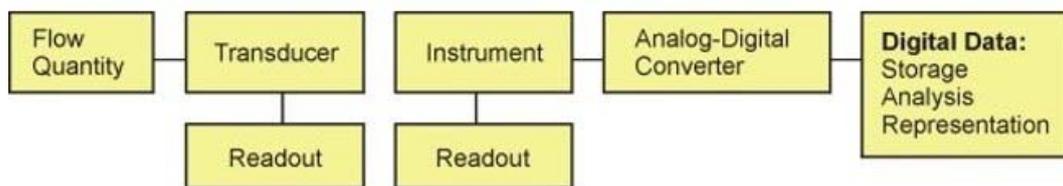


Figure 1. Elements of a typical flow measuring system

1.3 Scope and Purpose of Measurement and Choice of Measuring Techniques

To be successful, any measurement must be based on a clear specification of its scope and its purpose. The choice of a measuring technique and the design of instruments for a specific measurement is often an iterative process (see *Flow Measurement in Closed Conduits*). The matching of the experimental methods to the real process requires information which can only be gained with the help of the equipment under design (see *Flow Measurement in Free Surface Flow*). Measuring systems can normally not cope with the full complexity of the real flow, as their concepts are based on simplifying assumptions, and their effects on the results obtained have to be carefully evaluated (see *Experimental Methods and Physical Modeling*).

2. Elements of a Flow Measuring System

The elements of a flow measuring system are as defined in Figure 1. A transducer is a device by means of which a physical quantity, such as pressure, may be converted into

an electrical signal. Transducers provide the link between the fluid or flow quantity to be measured (measurand) with the actual measured value of that quantity, based on a “principle of measurement.” Length and time intervals can be measured directly with a ruler and a stopwatch or with mechanical devices, if these quantities are slowly varying with time. Other types of transducers, required for dynamic, more rapidly varying quantities, require electronic instruments (amplifiers, filters, etc.) for conditioning the signals before they are read by means of a voltmeter, or traced on a chart recorder, or are fed into an analog-digital conversion system. These digital signals are then transmitted to a computer for storage and/or analysis purposes.

Each measuring system is characterized by:

- Its resolution, i.e., the smallest increment of the measurand which can be detected.
- The dynamic range, i.e., the ratio of the maximal and the minimal value which can be measured.
- The deviation of the result from the ideal mathematical model of the measuring system, (e.g., its linearity).

2.1 Transducers

The concept of a transducer, explained above, as being the link between the quantity to be measured and its actual measured value, includes hydraulic devices such as manometers, orifice meters, Pitot tubes, etc., as well as highly sophisticated electromechanical innovations, namely Laser-Doppler Velocimeters, magnetic flow meters, etc. A grouping of the different flow quantities to be measured, the principle of measurement and the appropriate transducer used for the purpose of obtaining a measured quantity, is presented in Table 1 below. This is not a complete list, but covers the most common flow metering principles, and merely provides an overview of transducers for the measurement of basic fluid and flow quantities. In each case the principle of measurement, the transducer commonly employed and the actually measured quantity are listed.

Flow Quantity	Principle of Measurement	Transducer	Measured Quantity
Pressure	Balance with Hydrostatic pressure	U-Manometer	Length
	Force on Membrane	Manometer	Length, voltage
Velocity	Stagnation Pressure	Pitot Tube	Length, voltage
	Cooling of a Hotwire	Hotwire, Hotfilm	Voltage
	Doppler shift of scattered Laser light	Laser-Doppler Anemometer	Frequency (Doppler shift)
	Doppler shift of acoustic wave	Acoustic-Doppler Velocimeter	Frequency shift
Velocity field	Displacement of particles in a given time interval	Particle Tracking/, Particle Image Velocimetry	Length

Discharge	Critical depth	Weirs, Venturi	Level
	Dynamic head	Orifice meter Venturi meter	Pressure
	Lorentz Force	Magnetic Flow meter	Voltage
	Vortex shedding	Vortex-shedding flow Meters	Frequency
	Speed of sound in flows	Acoustic Discharge meter	Time interval
Mass Flux	Coriolis force	Mass Flow meter	Torque
Temperature	Expansion	Thermometer	Length
	Electrical Resistance (T)	PT 100, Thermistor	Voltage
Density	Buoyancy	Aerometer	Position
	Conductivity	Conductivity cell	Voltage (Resistance)
Viscosity	Stress-Strain-Relation	Rotating Viscometer	Torque
	Hagen-Poiseuille-Flow	Capillary tube	Discharge
	Stokes Resistance	Velocity of falling Sphere	Time interval, Diameter of sphere

Table 1. Overview of transducers available for the measurement of basic fluid and flow quantities

2.2 Instruments

Electronic instruments allow the conditioning of time-dependent signals, i.e., the transformation of analog signals of the measurand, such as pressure, into electrical signals capable of being amplified, read, transmitted, and recorded. They are characterized by a frequency response curve, which describes the amplification and the phase shift at each frequency in the spectrum, and an electrical input and output resistance. The frequency response must provide the necessary amplification and spectral bandwidth for the signal. The input resistance must be high, so that the output circuit of the transducer is not improperly loaded, and the output resistance must be low, so that the next element in the chain of instruments can draw sufficient current. The feedback must be small enough to avoid any resonance (see *Applied Hydraulics and Hydraulics Instrumentation*).

2.3 Recording

The traditional digital recording of data in tables on paper is a method which is easy to use and easy to control. In a similar way, the analog recording on a strip-chart recorder can be readily evaluated. However, these methods allow only the handling of limited volumes of data, and the evaluation is work intensive (see *Water Data Collection Systems for Surface Water*).

An analog-digital converter is a device which samples the analog signal at a certain frequency and puts a digital number, proportional to the analog voltage, into a register of the host computer. The digital data is then stored locally, or can be transmitted to a central database. From there the data can later be recovered for analysis and the presentation of results (see *Water Data Acquisition Systems*).

Digital data analysis systems have the capability of handling complex data structures and large volumes of information. They can provide on-line analysis, real-time control, and have forecasting capabilities. However, acquiring and operating the necessary hardware and software involved requires specialists with intensive training, in order to maintain supervision over these very complex and expensive systems (see *Hydroinformatics*).

3. Uncertainty Analysis

The reliability of data depends on the quality of the measuring techniques and the characteristics of the measuring system. It is, therefore, good engineering practice, to analyze carefully the errors and uncertainties of every measurement, and their implications.

The error of a method is the difference between the result of the measurement and the true value of the measurand. Random errors can be reduced by increasing the number of measurements. Systematic errors can be evaluated by calibration with a method which is more accurate. The uncertainty is an estimate characterizing the range of values within which the true value of a measurand lies. According to the definition of the ISO (International Standards Organization) an error can be corrected, but not an uncertainty.

3.1 Definitions of Errors: Random Error, Bias Error

For the analysis of errors and uncertainties a conceptual relation between the measurement, $\hat{\Phi}$, and the unknown measurand, Φ , (the quantity to be measured) has to be constructed (Figure 2). If the measurement is repeated many times, the individual estimates, $\hat{\Phi}_i$, will be distributed around a mean value, $E(\hat{\Phi})$. It is normally assumed that the corresponding probability density distribution is Gaussian, characterized by its variance, σ . The true value, Φ , of the measurand can differ by a systematic error or bias, b , from the mean value $E(\hat{\Phi})$.

In mathematical terms these relationships can be expressed by equating the average,

$$E\left[(\hat{\Phi} - \Phi)^2\right],$$

which, by definition, is the square of the uncertainty, or the expected value of the square of the difference between the measurement, $\hat{\Phi}$, and the measurand, Φ .

It is equal to the sum of the square of the variance, σ^2 , and of the bias, b^2 , since the factor,

$$E\left[\left(\hat{\Phi} - E\left[\hat{\Phi}\right]\right)\right],$$

in equation (1) is zero:

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Biographical Sketch

Dr. Andreas Müller is a research scientist at the Swiss Federal Institute of Technology (ETHZ) in Zurich, Switzerland. He performed his undergraduate work in physics and joined the Institute of

Hydromechanics and Water Resources Management for his Ph.D. studies, where he was one of the pioneers in developing Laser-Doppler Anemometry. He was offered a post-doctoral position at the Iowa Institute of Hydraulic Research, where he was responsible for teaching experimental methods and was also involved in ice research. Returning to Zurich, he became active in research on experimental fluid mechanics, especially in turbulence, sediment transport and density-driven flows. Dr. Müller was chairman of the Section on Instrumentation of the International Association of Hydraulic Engineering and Research (IAHR) and was selected to be the first IAHR lecturer for teaching a course in Flow Measurement Techniques in Roorkee, India. He edited the report “IAHR looking into Sustainable Development,” the Research Agenda of IAHR. At present he is one of the Vice-Presidents of IAHR.

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