Forum

Philip G. Hubbard, Developer of the Hot-Film Anemometer for Measuring Velocity of Turbulent Water Flow

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Introduction

Liquid water has comparatively small kinematic viscosity and therefore readily flows turbulently, with flow velocity fluctuating about a statistical mean at the point of velocity measurement (e.g., Prandtl and Tietjens 1934). This process commonly occurs in suitably swift-flowing water, especially when water flows along rough boundaries or shears with adjacent water. Fig. 1, for instance, illustrates turbulence in water flow along a river channel. But how were such fluctuations first reliably measured? And what role did Dr. Philip Gamaliel Hubbard (Fig. 2) play in developing the electronic instrumentation for making those measurements?

Flow velocity at a point in turbulent flow varies with time. Though turbulence typically is three-dimensional, its one-dimensional form is used here for simplicity. Accordingly, at a point the streamwise component of water velocity, $u(t)$, can be stated as

$$u(t) = \bar{u} + u'(t) \tag{1}$$

where $\bar{u}$ = mean velocity at the point; $u'(t)$ = fluctuating velocity component; and t = time. Formulations such as in Eq. (1) are often used to describe local turbulence fluctuations in flow velocity (e.g., Rodi 2017; Pope 2000; Hinze 1975; Reynolds 1976; McQuivey 1973; Taylor 1938; Reynolds 1895). Additionally, the relative intensity of turbulence is usually characterized in terms of I, where $I = \sqrt{u'^2}/\bar{u}$ (e.g., Schlicting 1979; McQuivey 1973; Macovsky 1948). Typically, $I < 0.01\%$ is considered very low and $I > 10\%$ is considered high (e.g., Nezu and Nakagawa 1993; Bradshaw 1976; Reynolds 1976). A large volume of literature exists on turbulent flows of water. Readers generally interested in turbulence are referred to a sampling of the literature (Rodi 2017; Pope 2000; Nezu and Nakagawa 1993; Bradshaw 1976; Hinze 1975; Reynolds 1976; White 1974).

Early Attempts at Measuring *u*(*t*)

The high spatial-temporal variability of turbulence in water flow imposes constraints on instrument sensors used for measuring $u(t)$. The sensor must be small enough to discern the smallest eddies of turbulence yet measure velocity fluctuations precisely and accurately. There were various early attempts at measuring $u(t)$ in turbulent water flows, but all attempts violated the requirements just mentioned.

The large size and response times of existing instruments for measuring water-flow velocity (Pitot tubes, cup or propellor meters) thwarted accurate resolution of turbulence length scales and frequencies. For instance, the typical dimensions of total-head and Pitot tubes generally were too large, limiting their response time. To a modest extent, some improvement was made by coupling total-head or Pitot tubes with pressure transducers (e.g., Howe 1950; Lowry 1951; Appel 1949). Other methods proved too awkward or messy, such as nozzles diffusing neutrally buoyant oil or dye in flows. There were some exceptions, usually when turbulence length scales were relatively large (i.e., several meters) and turbulence frequencies were less than about 10 Hz (such as wakes formed by bridge piers). For such flows, even miniature propellor meters yielded useful insights regarding turbulence (Nezu and Nakagawa 1993). There remained a substantial gap in instrumentation, however.

Often, early work examined if turbulence affected the values of $\bar{u}$ measured using instruments in common use, such as Pitot tubes and current meters formed of rotating cups or propellers. Studies typically found that, when turbulence was present, turbulence buffeting caused those instruments to give velocity values slightly higher than when turbulence was not present (e.g., McKeon et al. 2003; Thibodeaux 1994; Staubli 1988; Chaix 1966; Howe 1950; Rouse 1954; Addison 1946; Yarnell and Nagler 1931; Groat 1913).

Electronics for Hydraulics Engineers

The constraints mentioned above required that hydraulics engineers work closely with electronics engineers to develop the requisite instruments (e.g., Aberle et al. 2020; Tavoularis 2005; Eckelmann 1988; Sandborn 1972; Bradshaw 1971; Rouse 1954; Hubbard 1955; Wood 1949; Grinnell 1946; King 1914). Given that the fluctuations in water velocity $u(t)$ vary over a wide range of frequencies—typically less than 100 Hz but possibly up to 1,000 Hz for high-speed flows (Aberle et al. 2020; Hubbard 1955)—an instrument's sensor needed to be capable of sampling at minimally double the fastest turbulence frequency (Nyquist 1932). Also, a sensor had to be stable and yield measurement records long enough for meaningful statistical analyses to be done on $u(t)$ (Goldstein 1996). These constraints meant that sensors had to use electric currents because such currents could be designed to have frequencies well beyond the frequencies associated with turbulence in water (electric frequencies of 10^4 Hz are possible).

A further attractive feature of electrical currents is that electric resistance varies with the temperature of the conductor through which an electric-current passes: the cooler the conductor, the greater the conductor's resistance. Therefore, as flow velocity increases around a conductor, the conductor's temperature decreases, increasing the conductor's resistance and the voltage needed to drive the current through the conductor. The conductor's temperature relative to the fluid's far-field temperature is termed the resistance overheating ratio. Having a reasonable ratio is essential

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Fig. 1. Turbulent flow of water along a channel of the South Platte River, Colorado. (Image by author.)

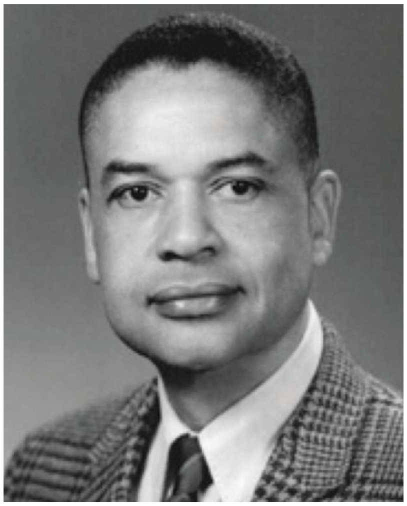


Fig. 2. Dr. Philip Gamaliel Hubbard, 1955. (Image courtesy of IIHR.)

for the conductor to be a practical sensor for measuring water-flow velocity. Tavoularis (2005) suggested values of 0.5–0.9 for hot wires and 0.1–0.2 for hot films operated in CTA mode (defined subsequently). A further attractive feature is that variations in conductor resistance could register a clearly discernible signal change caused by variations in temperature change. In this regard, the ratio of signal (S) to noise (N), S/N, is an important aspect of conductor responsiveness as a "sensor" of $u(t)$. The value of S/N is expressed normally in decibels (dB), a relative unit of measurement.

Hubbard's expertise in electronics and his willingness to learn fundamental aspects of hydraulic engineering positioned him to work with leading hydraulic engineers, who in turn recognized his talent.

Hubbard's Career Path

Philip G. Hubbard (1921–2002) was African American. His autobiographical book (Hubbard 1999), *My Iowa Journey: The Life Story of the University of Iowa's First African American Professor*, describes his personal life and much of his professional career. Hubbard was born in Macon, a small town in central Missouri. His parents (Rosa Belle and Philip Alexander Hubbard) named him after his father and gave him the middle name of US President Warren Gamaliel Harding, who was inaugurated on the same day Hubbard was born; Gamaliel is a biblical name. His mother was a teacher in Missouri's segregated school system, and his father was a railroad worker, who died of pneumonia fifteen days after Hubbard's birth (Philip A. Hubbard was the second of Rosa Belle's husbands; she had three sons with her first husband, Edward Wilbert Perkins, the principal of an African American high school.)

With the futures of her four sons in mind, Rosa Belle moved to Des Moines, Iowa, in 1925. Philip was four at the time. Rosa Belle's decision was motivated by the prospect that Iowa offered better life circumstances than were available in Missouri, which continued to permit segregated schools until 1954 when the Supreme Court decision in *Brown v. Board of Education* rendered segregated schools illegal throughout the US. Though Iowa's schools were integrated for its students, Rosa Belle (being African American) was not permitted to work as a teacher. She took a job as an elevator operator in a Des Moines department store. Later, she worked as a freelance dressmaker. She married once more, this time to William Washington Jones, a janitor employed by a Des Moines men's-clothing store.

Hubbard graduated from high school in 1939 and in August 1940 moved to Iowa City to attend the University of Iowa (Iowa). As Hubbard recalled, he chose Iowa due to the income he could earn from shining shoes at a stand in the Jefferson Hotel, conveniently located near the Iowa campus. The stand enabled Hubbard to earn money toward his education, and between shining shoes it was a useful place to study. Also, Hubbard "settled on engineering because it represented an intellectual challenge … could be completed in four years and was less affected by racial bias" (Hubbard 1999).

As Iowa's engineering dean (1936–1959), Dr. Francis (Frank) Murray Dawson took an active interest in Hubbard's progress as a student and, later, as a faculty member of Iowa's Department of Mechanics and Hydraulics. Besides being dean, Dawson was director (1936–1944) of the Iowa Institute of Hydraulic Research (IIHR) and therefore was closely involved in hydraulic engineering (e.g., Izzard 1940; Dawson and Kalinske 1939, 1937). Also, he had coauthored a leading textbook on hydraulic engineering (Schroder and Dawson 1927). During his three years studying chemical engineering and shining shoes, Hubbard worked part-time at IIHR, helping with various laboratory and field measurements. For instance, he assisted Professor Joseph Howe in measuring rainfall precipitation and runoff flow rates at the watershed scale.

Early in May 1943, Hubbard was conscripted into the US Army and did his basic training at Camp Dodge, Iowa. About a week before he reported for training, he had married Wynonna Griffin of West Des Moines. He served in several all-Black infantry units assigned to guard various facilities in the US. However, his engineering background soon led him to his assignment to the Army's Specialized Training Program, which prepared soldiers to gain expertise in areas the Army considered critically needed. A year later, Hubbard attained Army certification in electrical engineering. In late 1944, as the war in Europe was ending and the Army commenced demobilizing some units, Hubbard sought to be discharged so that he "… could make a contribution as a civilian" and not languish as a soldier (Hubbard 1999). "I wrote to Dean Dawson, and he quickly responded that my skills were needed in classified research at the university, but 'time was of the essence'" (Hubbard 1999).

In late January 1945, Hubbard returned to Iowa and IIHR, where Dawson engaged him in research for the Navy and Army. The research included several critical wartime problems involving

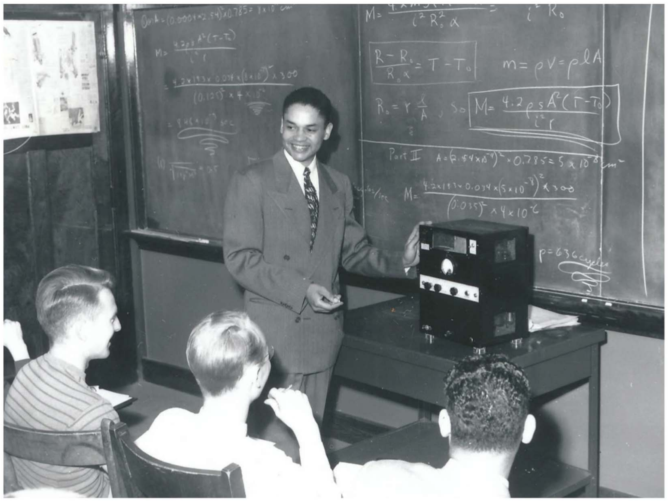


Fig. 3. Hubbard teaching the course *Electronics Instrumentation for Hydraulic Engineers*, October 1947; at left are graduate students Emmett Larson and Douglas Baines. (Image courtesy of IIHR.)

turbulent water flow: ship-hull movement; pressure distribution in and around various objects; and cavitation (erosion of surfaces caused by water-phase change). The Navy needed sensors that could measure turbulence in water to evaluate the hydrodynamic performances of ship hulls, torpedoes, and mines in water. Further, the Army needed sensors that could detect fluctuations in water velocity and pressure at various hydraulic structures, such as penstocks for hydroelectric facilities. In January 1946, Hubbard received his bachelor's degree in electrical engineering. He then became a graduate student at Iowa and an IIHR research associate, where his electronics expertise was needed to develop instrumentation for measuring velocities and pressures in hydraulics experiments.

When Hubbard joined IIHR, Dawson had decided that the demands of being both engineering dean and IIHR director were becoming too onerous. Therefore, in mid-1944 he had resigned as director and appointed Hunter Rouse in his place (1944–1966), with Prof. Emory Lane and Assoc. Prof. Anton Kalinske as IIHR's Associate Directors. Rouse and Kalinske had background in flow turbulence (e.g., Rouse 1937, 1938; Kalinske 1946, 1940; Dryden et al. 1941). Dawson had recruited Rouse (in 1939), who stood nationally at the forefront of advancing hydraulic engineering with well-formulated fluid-mechanics theory aided by experimental verification (Kennedy and Macagno 1987). Rouse saw the need for laboratory experiments to validate and, at times, guide the application of fluid-mechanics to hydraulic engineering (Rouse 1961, 1938). Dawson subscribed to this view and supported Rouse, who subsequently dedicated his book *Advanced Mechanics of Fluids* to Dawson (Rouse 1959). Sophisticated experiments, though, required instruments for measuring aspects of water flow.

Hubbard, who had earned a master's degree in 1949 and a doctorate degree in 1954, obtained additional electronics and hydraulics expertise in the development of hot-wire anemometers in air flow (M.S. thesis) and water flow (Ph.D. dissertation). Rouse was the advisor for both. When Hubbard received his M.S. degree, Dawson hired him as an assistant professor in the Department of Hydraulics and Mechanics and as an IIHR research engineer. Hubbard was already teaching (1947–1966) the graduate course *Electronic Instrumentation for Hydraulic Engineers*, as Fig. 3 shows.

As an assistant professor at Iowa, Hubbard directed his expertise in electronics toward developing the hot-film anemometer, essentially the first instrument to measure (with reasonable reliability) $u(t)$ in water flow (Ling and Hubbard 1956; Ling 1955; Hubbard 1954).Assisted by his student Sung-Ching Ling, he succeeded in developing this instrument after having spent many hours as a graduate student attempting to use it for measuring turbulent fluctuations in water-flow velocity. Many citations refer to the brief paper authored by Ling and Hubbard (1956) announcing the creation of the first hot-film anemometer—for example, Baily and Comte-Bellot (2015), Bruun (1996), Sheplak et al. (1996), NASA (1994), Kennedy and Macagno (1987), Seiner (1983), Rouse (1976), Comte-Bellot (1975), Hinze (1975), McQuivey (1973), Sandborn (1972), Gaster (1966), Robertson (1957, 1965), and Bankoff and Rosler (1962). Some refer only to Hubbard's collaborator, Ling, in the context of Ling's Ph.D. dissertation (Ling 1955), such as Fingenson and Freymuth (1996), Freymuth (1983), Richardson and McQuivey (1968), Humphrey (1969), McQuivey and Richardson (1969), Humphrey (1969), Kline (1960), and Miller (1960).

Hubbard went on to become a professor and collaborated extensively with Rouse and Louis Landweber, who in mid-1954 had come to IIHR from the Navy's David W. Taylor Model Basin. Landweber was an accomplished fluid mechanician who worked on problems concerning water flow around ship hulls and bodies

(a) (b) (c)

Fig. 4. Hubbard colleagues in the late 1940s: (a) Prof. Hunter Rouse, 1944; (b) Prof. Louis Landweber, 1954; and (c) Dean Francis Murray Dawson. (Images courtesy of IIHR.)

immersed in water. Figs. 4(a–c) show Rouse, Landweber, and Dawson.

However, Hubbard's career path veered away from engineering when, in January 1966, he became the "First Negro dean" at Iowa (Daily Iowan 1965). As dean of academic affairs (1966–1971), he was centrally involved in the quality of teaching and the career development of faculty. He said, "The assignment fit very well into my civil rights activities, and I anticipated with pleasure working with students, university employees, business and religious leaders, and general community representatives cooperating to change a paternalistic system that treated some members of the university community as second-class citizens" (1999), He had retired in 1990 as Iowa's vice-president for student services.

Hubbard's autobiography describes some of his career accomplishments in academia as well as the difficult racial experiences he encountered. Housing, for example, was a common difficulty. As a student, he had had to board with an African American family because, prior to 1946, Iowa did not permit African American students to use its dorms. As a new Ph.D., he declined an engineering faculty position at Northwestern University in Evanston, Illinois, largely because of "redlining" (a form of mortgage discrimination) by Chicago's banks. Subsequently, Iowa City's banks redlined him too. As a result, Dean Dawson financed Hubbard's first house in Iowa City.

Water Flows for Which Turbulence Can Be Neglected

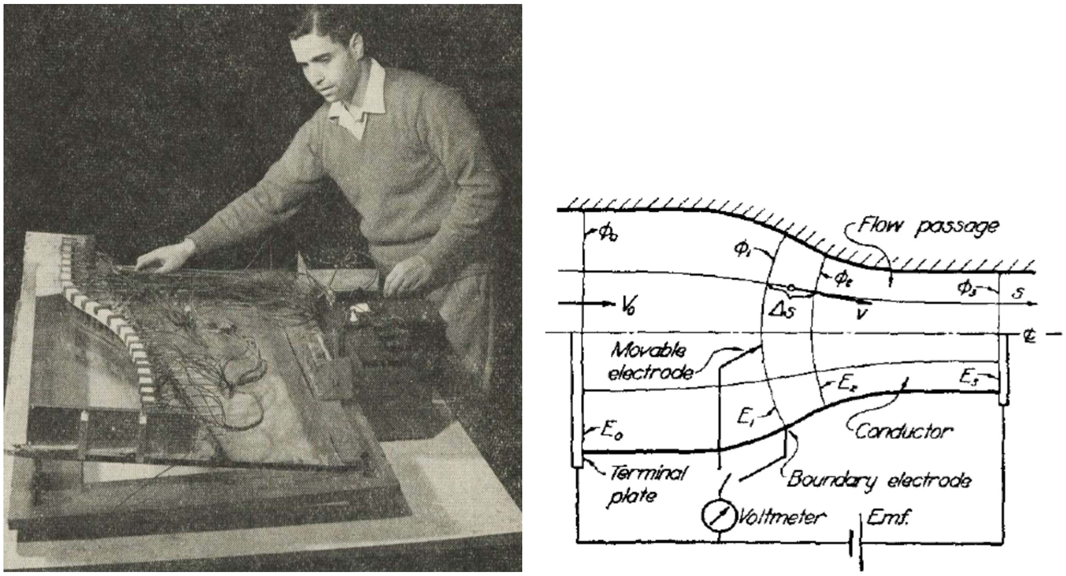
An initial task for Hubbard at IIHR involved improvement of the electric analogy, which offered a way to investigate flows for which turbulence can be neglected, $u'[t]<0.01\bar{u}$. The analogy was useful for flows in which $\bar{u}$ rapidly changed over a short distance, such as that in flared contractions or expansions. It used the idea that electric-current flow can be likened to water-flow velocity and that voltage can be equated to the flow's energy head (e.g., Lamb 1945). The analogy differed from hydraulic modeling and was suitable for flows that could be treated as potential or irrotational (effectively no viscosity) (Müller 1988; Aberle 2020; Tavoularis 2005). Although the electric analogy has since been relegated to the dustbin of technology, in the early to mid-1900s it enabled relatively quick determination of a potential-flow pattern and thereby good approximations of velocity and pressure distributions in practical flows.

Emory W. Lane had introduced the electric analogy in the US (Lane et al. 1934), though the method had already been in extensive use in Europe and Russia (e.g., Robertson 1965; Freeman 1929; Relf 1924; Pavlovsky 1922). Lane and his colleagues at the Bureau of Reclamation's Hydraulics Laboratory used the method to aid design estimation of the spacing of the water-intake towers used for Hoover Dam (then named Boulder Dam); the dam's two pairs of tall, intake towers (approx. 125 m high) did not readily lend themselves to hydraulic modeling at a length free of significant scale effects (Lane et al. 1934). Lane had been with IIHR during 1935–1944.

Though the analogy was already used at IIHR (e.g., Rouse and Hasan 1949), Hubbard quickly found that for three-dimensional (3D) systems of flow, the electrolyte-bath form of the analogy worked better than did the analogy limited to a planar slice of a flow field (Hubbard 1955, 1949a). Fig. 5 shows him using an electrolyte bath to determine distributions of flow velocity and pressure through a pipe convergence. In a 1949 article, he usefully explained the electric analogy and was occasionally cited (e.g., Valentine 1969). Later, with a graduate student, he used the electric analogy to investigate flow pressures low enough to cause incipient cavitation in flow fittings (Hubbard and Ling 1953; Ling 1955).

Water Flows for Which Turbulence Cannot Be Neglected

When turbulence cannot be neglected, $\overline{u'(t)} > 0.01\bar{u}$, $u(t)$ fluctuations need to be measured. In 1946, Hubbard had checked with several other hydraulics laboratories to learn the extent of the need



(a) (b)

Fig. 5. Hubbard in 1948 working with an electric analog of axisymmetric flow through a two-dimensional boundary contraction: (a) Hubbard; and (b) schematic of the analogy between irrotational flow and flow of an electric current. The analogy relates flow velocity V and velocity potential ϕ to electric field strength E and distance s. (Reproduced from Hubbard 1949a, with permission of API Publishing.)

for measuring $u(t)$ for turbulent flows of water. He quickly found that all laboratories needed this capability. Also, he was influenced by the US Navy's report (Macovsky 1948) that expressed high expectations that hot-wire anemometers would work in water. Hubbard suggested to Rouse that IIHR investigate the use of the hot-wire anemometer as an instrument for measuring $u(t)$ in water flow (Hubbard 1999). Rouse readily agreed. He admitted that "electrical gadgetry" was needed to measure turbulence, but stressed the primacy of sound fluid-mechanics theory. As mentioned previously, Rouse was the advisor for Hubbard's M.S. thesis (Hubbard 1949b) and Ph.D. (1954) dissertation regarding development of the hot-wire anemometer.

Hot-Wire Anemometers in Air (Hubbard 1949)

The key idea facilitating a hot-wire anemometer for measuring $u(t)$ is that the electrical resistance of the anemometer's heated hot wire (sensor) depends on the local velocity of flow around it. An increase in velocity increases heat loss from the sensor, reducing the its temperature. With due calibration, the sensor linked to circuitry and then to an electrical meter would directly give $u(t)$. Louis Vessot King, a Canadian assistant professor of physics, had proposed and formulated this idea (King 1914). He called his instrument a "hot-wire anemometer," a term stemming from the Greek word "anemos," meaning wind. The first reports of hot-wire anemometers used for measuring the velocity of turbulent air flow appeared in 1926 (Comte-Bellot 1975).

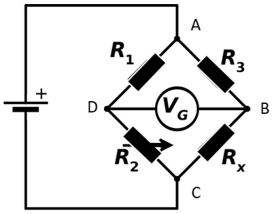


Fig. 6. Wheatstone-bridge circuit. The unknown resistance R_x is to be determined; resistances R_1, R_2, and R_3 are known, and where R_2 is adjustable and measured.

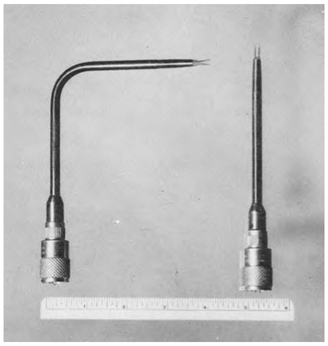
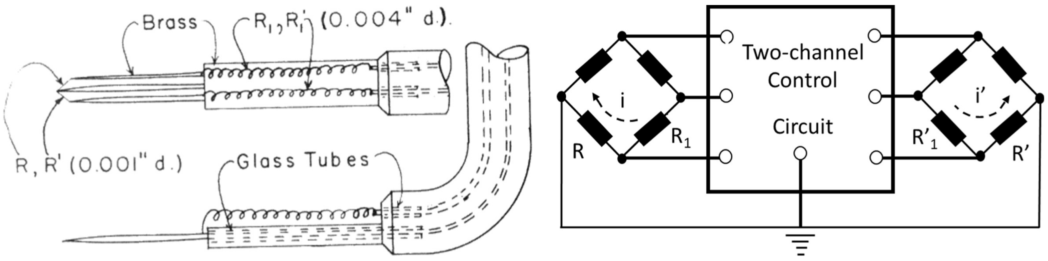


Fig. 7. Typical hot-wire anemometer (Hubbard 1957). (Image courtesy of IIHR.)

The hot wire forms a resistance arm of a Wheatstone-bridge circuit, as shown in Fig. 6, where R_x is the unknown resistance to be measured. The resistors R_1, R_2, and R_3 are known, though the resistance R_2 is adjusted and measured until the bridge is balanced, with no electric current flowing through the galvanometer V_g. At this point, the potential difference between the two midpoints (B and D) is zero. Therefore, the ratio of the two resistances in the known leg (R_2/R_1) is equal to the ratio of the two resistances in the unknown leg (R_x/R_3), so that $R_x = (R_2/R_1)R_3$. If the bridge is unbalanced, the direction of the current indicates whether R_2 is too high or too low. The heated wire creates R_x, and the resistance R_2 is recorded electronically to ensure that balance is achieved.

The Wheatstone bridge (Fig. 6) and facilitating circuitry suggest two modes to operate the sensor of a hot-wire anemometer: run a constant electric current through the hot-wire sensor, thus allowing the sensor to change in temperature; or keep the sensor at a constant temperature. The former mode was considered less demanding electronically and was chosen initially. However, as Hubbard soon found, the constant-current mode was difficult to implement and prone to problems. Unbeknownst to Hubbard, other researchers had also encountered this difficulty (e.g., Dryden and Kuethe 1929). Thermal lag of the heated hot wire was a problem, especially when flow velocities were relatively low (say less than 2 m/s). Initial attempts to reduce thermal lag entailed keeping the wire very thin compared to its length; the ratio of length/diameter >200 was used (e.g., Eckelmann 1988; Hasse and Dunkel 1980). Eventually, the thermal-lag problem was overcome by use of the constant-temperature-anemometer (CTA) mode, whereby the temperature of the hot-wire was kept constant by rapidly varying electric current. But because the existence of the constant-temperature form of hot-wire anemometer was little known at the time, Hubbard had to develop his own (Hubbard 1949), which involved circuitry challenges, though not as major as for the constant-current mode. Eckelmann (1988) and Sandborn (1972), for example, usefully (and accessibly) explained the electronics needed for both modes. Fig. 7 shows a typical hot-wire anemometer that Hubbard built.

Another issue was that a single hot wire did not indicate flow direction. This concern was overcome by adding a second hot wire oriented differently from the first (Hubbard 1949b). The direction normal to the hot-wire axis defines the direction of the measured velocity. Fig. 8 shows aspects of a hot-wire anemometer configured



(a) (b)

Fig. 8. Specially designed Type 3A hot-wire anemometer for use in air flow: (a) mechanical arrangement involving a two-wire sensor (1.0 in. = 25.4 mm); and (b) double Wheatstone-bridge electrical arrangement used with the two-wire sensor. (Images courtesy of IIHR.)

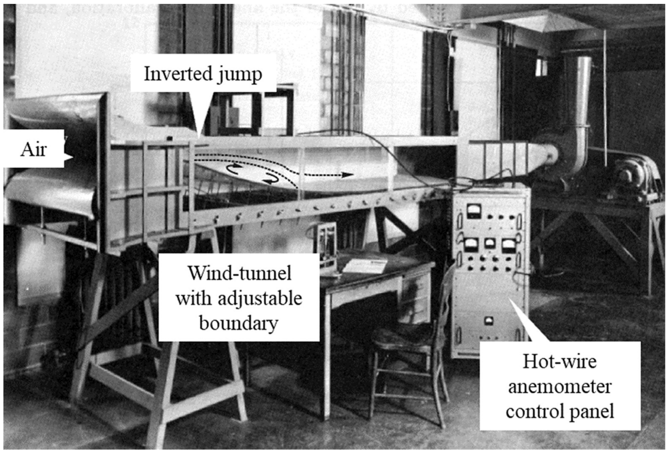


Fig. 9. Hot-wire anemometer for measuring air-flow velocities in the (inverted) air-flow simulation of a hydraulic jump. Also shown is the anemometer control panel. (Adapted from image courtesy of IIHR.)

Fig. 10. Hubbard in 1951 working on electronic circuitry for the hot-wire anemometer used in water flow. (Image courtesy of IIHR.)

with two hot wires (and corresponding double Wheatstone bridge) to determine flow direction.

To increase the frequency of measurement while keeping the sensor small and easily portable, the electric current had to pass through an extremely fine wire (with a diameter of about 8×10^{-3} mm and length of about 5 mm) placed in a cross flow. For this wire, platinum was selected as it is a metal of remarkably low electrical resistance and is not prone to corrosion (as is tungsten), though it is weaker than tungsten. The resulting hot-wire sensor offered several advantages: small sensor, high-frequency response, suitable S/N, and no inertia effect from moving parts (other than possible vibration of the wire at high velocities). Hubbard and Rouse knew that a hot-wire anemometer had been applied with fair success in air flow (e.g., Dryden and Kuethe 1929), and they knew that initial laboratory results in water flow looked promising (Macovsky 1948; Piret et al. 1947; Addison 1946).

Hubbard successfully developed IIHR's hot-wire anemometer for use in air flows (Hubbard 1948, 1949b) that Rouse employed when air flow could be used to simulate water flow (Rouse et al. 1959; Rouse 1954, 1953, 1950; Albertson et al. 1948; Rouse et al. 1950). As Knapp et al. (1970) depicted, Rouse with Hubbard's help made some of the most extensive early studies on cavitation caused by submerged jets, as occur when flow separates around fixed bodies or propellers create jets of water (Rouse et al. 1950). Iamandi and Rouse (1969) used the hot-wire anemometer to extend Rouse's earlier experiments on submerged jets. Also, Hubbard's hot-wire anemometer enabled Rouse et al. (1959)—in their ASCE Hilgard Prize paper—to measure turbulence in an air-flow simulation of a hydraulic jump in water flow. The air-flow model essentially comprised an upside-down expansion of air flow, as shown in Fig. 9. The anemometer augmented the use of a purpose-built, double-headed Pitot tube (one tube pointing upstream and the other pointing downstream) to get mean flow velocities in the modeled jump, and a total-head tube in contact with simulated channel bed to measure shear stress along the bed.

Hot-Wire Anemometers in Water (Hubbard 1954)

Despite advances, Hubbard found several problems with hot-wire anemometers placed in water flow. Other researchers had experienced these problems too (e.g., Grossman et al. 1957). The hot-wire readily corroded, and electrolysis at the hot-wire led to bubble formation (usually oxygen and hydrogen) that accelerated corrosion. Further, the wire tended to become fouled with dirt or filaments in the flow (Hubbard 1954). These difficulties caused an anemometer's calibration to drift. Furthermore, as water is denser than air, the hydrodynamic forces were larger, creating the need for a thicker wire, which accordingly was less responsive in water than in air (Hubbard 1954). Hubbard could get the hot-wire probe to work in water flow (or to be towed through stationary water) by increasing the current through the sensor, but the hot-wire anemometer proved unreliable. Fig. 10 depicts Hubbard at work on circuitry for the anemometer. Rouse saw the problems Hubbard had with the hot-wire anemometer in water flow, and kept a skeptical eye on data from instruments that did not measure reliably (Rouse 1953).

The dubious success with hot-wire anemometers in water compelled further investigation of adapting Pitot tubes to measure turbulence in water flow. For instance, Ippen and Raichlen (1957) found a modicum of success by combing a total-head tube with a pressure transducer, but their probe responded to both pressure and velocity fluctuations, complicating decipherment of their intertwined signals. Grossman et al. (1957) devised an electromagnetic-induction method whereby a probe traversed an electromagnetic field created at a cross section of a 50-mm-diameter pipe. The method yielded results but was cumbersome, not easily portable, and plagued by persistent problems that compromised reliability, according to Richardson in a handwritten note accompanying an article by Grossman et al. (1957).

Hot-Film Anemometers

Problems with hot-wire anemometers in water led Hubbard to develop a new heat-transfer sensor for water flow: the hot-film anemometer (Ling 1960; Hubbard 1957; Ling and Hubbard 1956; Ling 1955; Hubbard 1955, 1954). This sensor's operating principles entailed essentially the same CTA mode as used for hot-wire anemometers but overcame several of the problems attending hot-wire anemometers in water.

Hubbard's hot-film anemometer comprised an extremely thin ($5\text{–}10 \times 10^{-6}$ mm) platinum film as sensor fused (spluttered) on the surface of a wedge-shaped glass or ceramic support body. Fig. 11 gives its dimensions. The sensor's wedge form greatly reduced problems caused by dirt or filament accumulation. Although the sectional width of the hot-film sensor was approximately 50 times the diameter of a typical hot-wire sensor, the dynamic response was acceptably good. The decibel response was superior

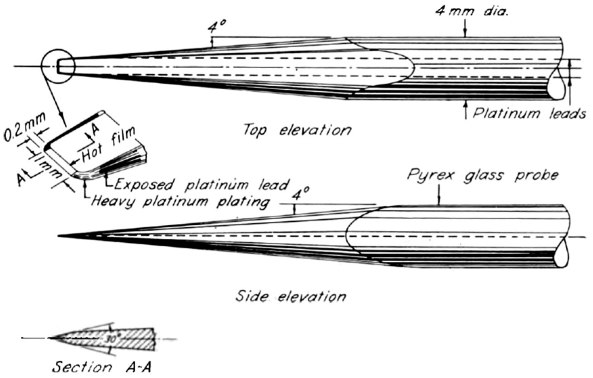


Fig. 11. A wedge-form, hot-film anemometer for measuring velocity fluctuations in water flow (Ling and Hubbard 1956; Hubbard 1957). Oddly, no photographs of the anemometer remain. (Image courtesy of IIHR.)

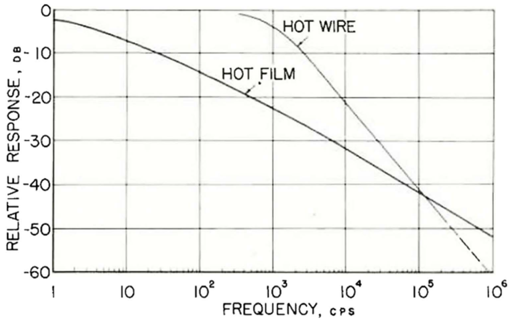


Fig. 12. Comparison of the frequency response of hot-film and hot-wire anemometers (Ling and Hubbard 1956). The lesser response of the hot-film anemometer is offset by the its larger S/N. (Image courtesy of IIHR.)

at high frequencies, but at low frequencies the hot-wire anemometer gave a greater relative response, as Fig. 12 indicates. The low-frequency deficiency of the hot film was more than compensated by the probe's higher S/N value. Another factor was the improved mechanical arrangement of the film fully supported by a glass or ceramic base. These changes eliminated extraneous electrical signals due to thermal stress and local vibration experienced with a hot wire.

Development of a hot-film anemometer required analysis of heat transfer in water boundary layers interacting with several forms of constant-temperature sensors. As the analysis entailed complexities in fluid mechanics, Rouse recommended that Chia-Shuen (Gus) Yih be the formal adviser for Ling's Ph.D. dissertation (Ling 1955), with Hubbard advising on electronic aspects. Yih's own dissertation, advised by Rouse, had dealt with heat transfer in a flow (Yih 1948).

The hot-film anemometer immensely improved reliability of turbulence measurement but was expensive and quite complicated to produce. Moreover, it was still prone to bubble formation on the film and could deteriorate with frequent use. Tavoularis (2005), Bruun (1996), and Nezu and Nakagawa (1993) briefly elaborated the difficulties. Rouse, it must be said, found Hubbard's hot-film anemometer much more expensive than the hot-wire anemometer, which he already thought too costly for use by undergraduates (Rouse 1961).

Hubbard, however, demonstrated the utility of the hot-film anemometer by using it to obtain the first measurements of turbulence in hydraulic jumps formed by water flow. His measurements compared very well with those obtained using a hot-wire anemometer for a hydraulic jump replicated by air flow, as Rouse et al. (1959) showed in their ASCE award–winning paper on hydraulic jumps. Furthermore, the measurements revealed additional aspects of turbulent flow in hydraulic jumps (Hubbard 1959). Subsequent investigations of hydraulic jumps were carried out using water flow and a hot-film anemometer.

Fig. 13. Hubbard with the control box for the hot-film anemometer used in IIHR's towing tank, 1956. (Image courtesy of IIHR.)

Most of Hubbard's work with his hot-film anemometer occurred in IIHR's towing tank (Fig. 13), where Hubbard worked in collaboration with Landweber and graduate students on Navy-funded work to measure turbulent water movement around ship hulls and various submerged bodies. Calibration of the hot-wire sensor was done by towing it through still water (of ambient temperature) at a known velocity and recording the wire's resistance. The anemometer measured velocity fluctuations in a single direction. Hubbard advised graduate theses on this topic (e.g., Chevray 1967; Gear 1965; Hung 1966; Aaron 1960; Macagno et al. 1971).

Also, Hubbard continued to address difficulties associated with the use of hot-wire anemometers in water flow (e.g., Hung 1966; Chen 1964; Kuo 1965), as well as in air flow (e.g., Hsu 1966; Glover 1965, 1961). With John (Jack) R. Glover, for example, he investigated the effects of several adjustments (e.g., by coating the hot wire in polyurethane) to improve reliability in water, but he never achieved continuous success (Glover 1965).

Hubbard's work with anemometers underpinned much of IIHR's research in the 1950s. In 1951 Hubbard founded the Hubbard Instrument Company, which specialized in instrumentation for measuring and recording velocity and pressure in turbulent flows. From the mid- through the late 1950s, the demand for his expertise in developing the hot-film anemometer and electronic probes for measuring and recording other aspects of turbulence in water flow grew swiftly. Various organizations and laboratories (e.g., Navy, Army, USGS) needed Hubbard's expertise in electronics applied to water flow. Hubbard built his electronic instruments at IIHR, assisted by his electrical-engineering Ph.D. student Jack Glover and an electronics technician. IIHR received part of the income generated by Hubbard's company.

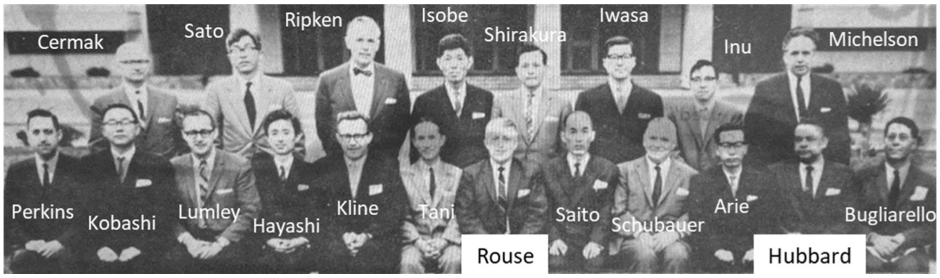


Fig. 14. Attendees at a US-Japanese seminar on fluid-flow instrumentation in Sendai, Japan, 1965. (Image courtesy of IIHR.)

Hubbard wrote a manual documenting the designs of IIHR's hot-wire and hot-film anemometers and guiding users on how to apply such anemometers (Hubbard 1957). Also, he co-chaired the Sixth Hydraulics Conference, whose theme was measurement of water flow (Landweber and Hubbard 1955). The conference had about 220 participants discussing many aspects of measurements in hydraulic engineering. Most measurement methods involved electronics. Hubbard traveled extensively throughout the US, Canada, Europe, South America, and Asia giving seminars about measurement of water-flow turbulence (Macagno and Hubbard 1962; Hubbard 1961). For example, in October 1965 he traveled with Rouse and other turbulence luminaries to a US-Japanese seminar on fluid-flow instrumentation (Fig. 14).

Commercial Manufacturing of Instruments

The remarkable growth in the commercial manufacturing of instruments for measuring aspects of fluid flow (Wood 1949; Hubbard 1955) quickly overtook Hubbard, who closed his company in the early 1960s, about a decade after starting it. By the late 1950s, anemometers were available commercially from manufacturers like Dansk Industri Syndicate (DISA), which marketed its first CTA hot-wire anemometer in 1958 (Dantec 2023); in the late 1960s, Thermo Systems Inc. developed its hot-film anemometer (TSI 2023). In the five years following Hubbard's M.S. thesis, measurement-instrument manufacturing had created a $4.5 billion industry (*Instrument and Apparatus News* 1954). Hydraulics researchers and practitioners could order commercially manufactured instruments from catalogs. An editorial at the time remarked: "… the most important frontier in modern instrumentation is in application" (*Instrument and Apparatus News* 1953). Access to commercially manufactured instrumentation was a significant factor contributing to the advance of hydraulic engineering. Rouse (1976) used the term "golden era" to characterize this advance, which he took to extend from the late 1940s.

Manufacturers improved the designs of hot-film anemometers and support electronics. For example, conical hot-film sensors eliminated debris accumulation by films (e.g., Resch 1969). Also, varying sensor arrangements measured the components of water flow (e.g., Eckelmann 1988). Hot-film anemometers were used extensively to measure water-flow turbulence (e.g., Aberle et al. 2020; Bruun 1996; Lief and Saetran 1983; Melville and Raudkivi 1977; Rajaratnam 1965).

Concluding Comments

The application of electronics to hydraulics measurements created and continues to create opportunities for hydraulics engineers to measure water velocities and pressure in water flows, and thereby carry out laboratory experiments and fieldwork. Philip G. Hubbard was an engineer knowledgeable in both electronics and hydraulic engineering who developed the first hot-film anemometer, which enabled hydraulic engineers to measure and record velocities in turbulent water flows reliably, though time has shown that no instrument is fully reliable. Hot-film anemometers are still used, but now measurements commonly utilize other principles. For example, acoustic and optic velocimetry makes use of the Doppler shift, and several image-based methods have been developed (e.g., Aberle et al. 2020; Tavoularis 2005). Each method, however, illustrates hydraulic engineering's continued dependency on developments in fields besides fluid mechanics.

Hubbard's work also involved measuring and recording pressure fluctuations in turbulent water flows. Pressure fluctuations often posed concerns for various parts of hydraulics structures: water cavitation and flow-induced vibration. Additionally, his work involved measuring and recording changes in water depth associated with hydrographs or scour. This work created additional opportunities for him to apply his electronic expertise (e.g., Rouse and Jezdinsky 1966; Locher 1965; Hubbard 1962, 1955).

Hubbard's contributions were made with the assistance of many people and endured for about a decade, from the mid-1950s to mid-1960s. Eventually, commercially manufactured measurement instrumentation took over. Philip G. Hubbard's career in electronics and hydraulic engineering ended in January 1966, when he became Iowa's dean of academic affairs, though he retained his interest in the university's College of Engineering and IIHR. In his work at IIHR and Iowa, Hubbard overcame difficult obstacles to make important contributions to turbulence measurements, hydraulics, and post-secondary education. He was a pioneer in both hydraulic engineering and academics (Hubbard 1996).

Data Availability Statement

No data, models, or code were generated or used during the study.

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