FUNDAMENTALS OF HOT WIRE ANEMOMETRY

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To my wife, Arletta,
and our daughter, Kathy Mullen

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FUNDAMENTALS OF HOT WIRE ANEMOMETRY

This book provides a clear and comprehensive summary of the theory and practice of the hot wire anemometer, an instrument used to measure the speed of fluid flow. Many techniques and uses of this instrument, which until now have only appeared in technical journals, are discussed in detail. The author considers such topics as probe fouling, probe design, and circuit design, as well as the thermodynamics of heated wires and thin films. He also discusses measurements of turbulence, shear flows, vorticity, temperature, combined temperature and velocity, two-phase flows, and compressible flows, as well as measurements in air, water, mercury, blood, glycerine, oil, luminous gases, and polymer solutions. The book concludes with a section on the pulsed wire anemometer and other wake-sensing anemometers.

Fundamentals of Hot Wire Anemometry is written at the advanced undergraduate level and assumes a familiarity with basic fluid mechanics. However, mathematical descriptions occur near the end of each chapter, thus allowing those with a limited mathematical background access to the practical details at the beginning of each chapter. The volume will be useful to students, teachers, and researchers in fluid mechanics, and will serve as a handy reference to all users of the hot wire anemometer.

PREFACE

Over a number of years I observed that those who used the hot wire anemometer for velocity measurements in air were not aware of its many other applications. In addition, their knowledge was often limited to that obtained from instruction manuals and co-workers. This prompted me to write a book that would contain theoretical and practical information that otherwise could be acquired only by spending many hours researching the technical literature.

Readers will need an undergraduate engineering background, but the information will be accessible both to a research engineer designing a test program and to the technician who may do the testing.

The reader will find here the theoretical background for the measurements of velocity, turbulence, compressible flows, vorticity, temperature, concentration, and two-phase flows, as well as practical information about probe design and measurements in fluids, such as air, water, polymer solutions, mercury, blood, glycerine, oil, and luminous gases. To appeal to the enthusiast, novelties are included, such as a hot wire probe that costs almost nothing and is constructed in less than 1 minute by using one tool – a pair of pliers – and a low-velocity calibration technique in air using soap bubbles. Illustrations of handmade probes have been chosen to show the excellent results possible with simple tools and a little patience.

The manufacturers of hot wire anemometers were very helpful in contributing illustrations of commercially available probes. The following manufacturers graciously donated both time and information: Deltalab (France), Dantec Elektronik, formerly DISA (Denmark), Malvern Instruments (England), Prosser Scientific Instruments, Ltd. (England), and TSI, Inc. (United States).

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NOTATION

Symbols

a	overheat ratio
A	area
A	Wheatstone bridge ratio
b	yaw parameter
B	magnetic flux density
c	specific heat
C	fouling factor
d	diameter
e	fluctuating component of voltage
e_o	Wheatstone bridge off-balance voltage
E	voltage
f	frequency
fr	frequency response
g	acceleration of gravity
g	feedback amplifier transconductance
Gr	Grashof number
h	coefficient of convective heat transfer
h	distance
h	pitch factor
Ha	Hartmann number
i	fluctuating component of current
I	electrical current
k	thermal conductivity
k	yaw factor
K	constant
K	slope of the linearized calibration curve
Kn	Knudsen number
l	length
L	fixed length
L	inductance
M	Mach number
n	exponent used in King's law
n	molecular density
N	magnetic interaction parameter

Nu	Nusselt number
p	distance
P	pressure
Pe	Peclet number
Pr	Prandtl number
q	heat transfer rate
r	fluctuating component of electrical resistance
r	radius
R	electrical resistance
Ra	Rayleigh number
Re	Reynolds number
S	sensitivity
S	shear factor
Sn	Strouhal number
t	fluctuating component of temperature
t	time
T	temperature
T	time of flight
u	fluctuating component of velocity
U	X-component of velocity
v_*	friction velocity
x	characteristic length
x	horizontal distance
X	Sajben *X*-factor
y	vertical distance
z	lateral distance
α	temperature coefficient of resistivity
α	thermal diffusivity
α	angle of inclination of the velocity vector
β	volume coefficient of expansion
β	angle of inclination of the velocity vector
γ	angle of inclination of the velocity vector
γ	specific heat ratio
γ	fluctuating component of molal concentration
Δ	small change in value
ϵ	emissivity
ϵ	relative error
η	dimensionless length
θ	fluctuating component of temperature
θ	temperature difference
θ	yaw angle
λ	mean free path length
Γ	circulation
Γ	concentration
μ	absolute viscosity

ν	kinematic viscosity
ρ	density
ρ_r	resistivity
σ	Stefan–Boltzmann constant
σ	electrical conductivity
τ	time constant
τ	shear stress
ϕ	phase angle
ϕ	pitch angle
ψ	normalized voltage
ψ	roll angle
ω	circular frequency
ω	rolloff frequency
ω	vorticity

Subscripts

adj	adjustable
a	apparent
a	air
b	bridge
c	cable
c	corrected
c	critical
cca	constant current anemometer
cta	constant temperature anemometer
cl	centerline
conc	concentration
e	equilibrium
eff	effective
eq	equivalent
f	fluid
g	gas
i	impurities
m	mean
m	measured
m	mixture
max	maximum
min	minimum
n	arbitrary orthogonal coordinate
o	reference or stagnation conditions
off	offset
oven	oven
p	probe
P	constant pressure
q	quartz

s	sensor
s	solvent
s	streamwise
sub	substrate
sur	surroundings
t	arbitrary orthogonal coordinate
T	temperature
temp	temperature
vel	velocity
w	wall
1	conditions upstream of a normal shock wave
2	conditions downstream from a normal shock wave
∞	free stream conditions

CONTENTS

1 INTRODUCTION

Hot wire anemometers have been used since the late 1800s, when experimentalists in fluid mechanics built their own rudimentary constant current anemometers. Because no commercial equipment was available, all improvements were made by the scientists themselves. Eventually, electronic amplification and shaping networks were added, and the constant current anemometer became a sophisticated, high-frequency-response research instrument. The appearance of commercial constant current anemometers, and later of commercial constant temperature anemometers, coincided with a major growth in popularity of these instruments. Today the hot wire anemometer is used in research laboratories throughout the world.

Besides the use of the hot wire anemometer in air, measurements can be made in other fluids, such as fresh water, salt water, polymer solutions, blood, mercury, glycerine, oil, freon, and luminous gases. In addition, the hot wire anemometer can be used to determine the direction and speed of a fluid, to make turbulence measurements, to make measurements in compressible flows, and to measure fluid temperature. Special techniques allow the hot wire anemometer to measure gas mixture concentrations and to make two-phase flow measurements as well.

The hot wire anemometer also has excellent frequency response; an upper frequency limit of 400 kHz is common for commercially available instruments. Only the laser Doppler velocimeter, which at this writing is four to five times more expensive for an equivalent system, can compete in this respect. In addition, the hot wire anemometer has excellent sensitivity at low velocity, good spatial resolution, and an output signal in the form of a voltage difference for convenient data analysis. All in all, the hot wire anemometer is one of the most flexible instruments available for research in fluid mechanics.

The name *hot wire anemometer* implies using a heated wire to make velocity measurements in air only. The word *anemometer* is inaccurate because the instrument is used in a variety of fluids, and the term *hot wire* is misleading because probes using a heated metal film are popular. This nomenclature was adopted in the early 1900s, when hot wire probes were used in air measurements only. Times have changed, but the name remains.

Every hot wire anemometer, regardless of type, contains the same basic parts: a probe with its cable, and an electronics package. A typical hot wire probe is illustrated in Figure 1.1.

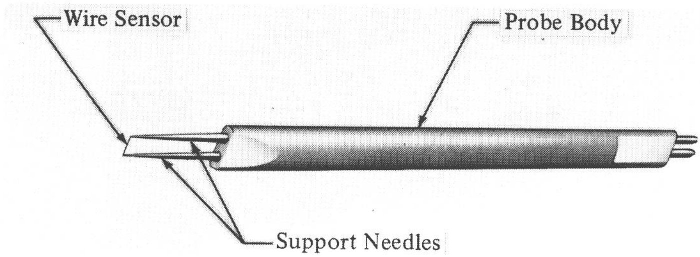

Figure 1.1. A typical hot wire probe. This is the most common and least expensive type; it has a single-wire sensor attached to the tips of two support needles and a connector at the other end to allow quick detachment for cleaning, recalibration, or replacement. Reprinted with permission from Dantec Elektronik.

The sensor of the typical hot wire probe is a wire, usually made of tungsten or platinum, about 1 mm long and 5 μm in diameter. It may have a thin plating of a different metal. The diameter of the wire is much less than that of a human hair, which has a diameter of about 85 μm. This means that the sensor cannot be easily seen with the unaided eye of the inexperienced user. The sensor is attached between the tips of two support needles by arc welding or soldering, and is electrically heated. It is convection cooled by the fluid passing over it, and this cooling effect is a measure of the fluid velocity. The probe body is usually made of epoxy or ceramic material or fabricated from a metal tube potted with epoxy. An electrical connector is often located at the other end of the probe body to allow easy removal and replacement of the probe. The contacts of the connector are sometimes plated with gold to reduce resistance, and the connector is usually designed to be watertight.

The sensor of a hot film probe is usually made of nickel or platinum deposited in a thin layer onto a backing material, such as quartz, and connected to the electronics package by leads attached to the ends of the film. A thin protective coating of quartz or other material is usually deposited over the film to prevent damage by abrasion or chemical reaction. The wedge hot film probe illustrated in Figure 1.2 is quite popular. This probe is made from a quartz rod ground to a wedge at one end, and the metal film is deposited in a strip along the knife edge of the wedge.

Three types of electronics packages are used, each controlling the sensor heating current in a different way. The most common is the constant temperature anemometer, which supplies a sensor heating current that varies with the fluid velocity to maintain constant sensor resistance and, thus, constant sensor temperature. Less often used is the constant current anemometer, which supplies a constant heating current to the sensor. A third type, the pulsed wire anemometer, measures velocity by momentarily heating a wire to heat the fluid around it. This spot of heated fluid is convected downstream to a second wire that acts as a temperature sensor. The time of flight of the hot spot is inversely proportional to the fluid velocity.

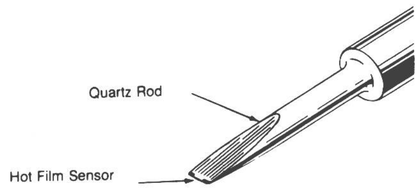

Figure 1.2. A wedge hot film probe. This probe is the hot film analog of the standard single-sensor hot wire probe shown in Figure 1.1. A quartz rod having a "chisel" shape is plated with a thin film of metal on the leading edge. Reprinted with permission from TSI, Inc.

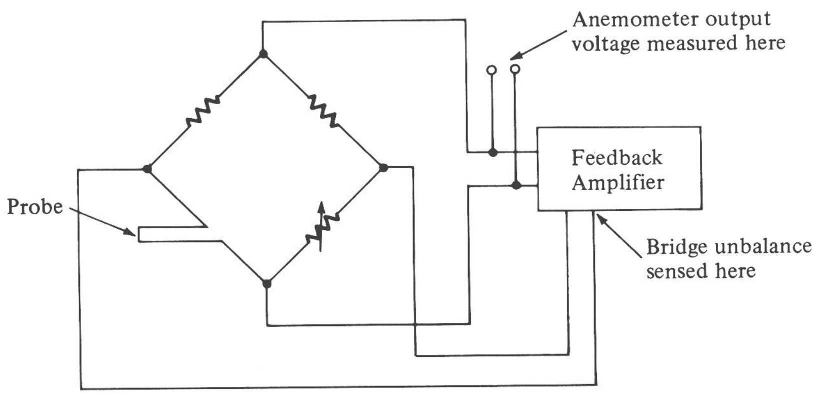

Figure 1.3. The block diagram of a constant temperature anemometer. A hot wire probe acts as one resistor in the Wheatstone bridge, and the feedback amplifier automatically adjusts the current to maintain bridge balance.

The electronics package of the constant temperature anemometer contains a Wheatstone bridge circuit with the sensor as one arm of the bridge, as shown in Figure 1.3; two fixed resistors and one adjustable resistor complete the circuit.

A differential feedback amplifier senses the bridge unbalance and adds current to hold the sensor temperature constant. Before the system is placed in operation, the adjustable resistor is set to a value larger than would be required to balance the bridge. When power is applied, the feedback amplifier increases the sensor heating current, causing the sensor temperature to rise and increase the sensor resistance until the bridge becomes balanced. An increase in velocity cools the sensor and unbalances the bridge. This causes the feedback amplifier to increase the sensor heating current and to bring the bridge back into balance. Since the feedback amplifier responds rapidly, the sensor temperature remains virtually constant as the velocity changes. The voltage difference across the bridge is proportional to the fluid velocity.

The constant current anemometer may contain both a Wheatstone bridge

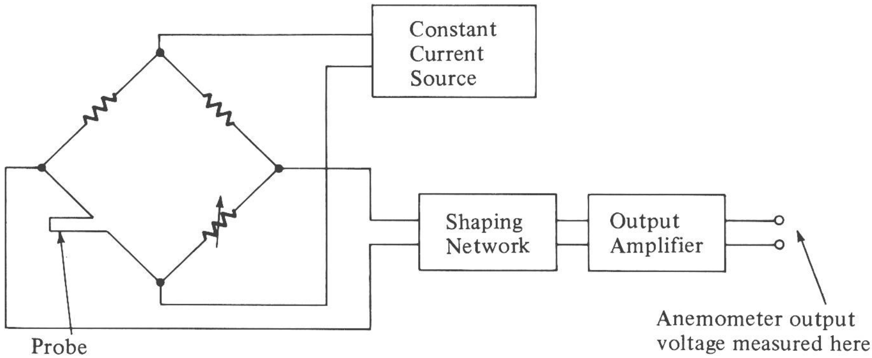

Figure 1.4. The block diagram of a constant current anemometer. A hot wire probe acts as one resistor in the Wheatstone bridge, which is powered by a constant current source. The bridge unbalance voltage is shaped and amplified before reaching the recording device.

circuit and an amplifer, but the feedback technique is not used. Instead, the bridge current is provided by a constant current power supply, as shown in Figure 1.4.

The Wheatstone bridge is balanced only at one velocity and becomes unbalanced as the velocity changes. As with the constant temperature anemometer, the voltage difference across the Wheatstone bridge is proportional to the velocity. This voltage is sometimes modified by a shaping network and amplifier to improve the frequency response.

We now give some definitions that are basic to hot wire anemometry. The first, the sensitivity of the hot wire anemometer to changes in fluid speed, temperature, or direction of the mean velocity vector, is defined as a derivative of the anemometer output voltage with respect to the fluid property under consideration. For example, the velocity and temperature sensitivities, S_{vel} and S_{temp}, can be expressed as

$$S_{vel} = \frac{\partial E}{\partial U}$$

and

$$S_{temp} = \frac{\partial E}{\partial T}$$

where E is the anemometer output voltage, U is the velocity, and T is the fluid temperature. Because the output voltage is a function of both fluid velocity and temperature, the chain rule gives

$$dE = \frac{\partial E}{\partial U} dU + \frac{\partial E}{\partial T} dT \tag{1.1}$$

where the sensitivities appear as factors in this equation.

The concept of sensor operating temperature is important because it influences both the life of the probe and its sensitivity to velocity and ambient temperature changes. The sensor temperature is usually expressed as a ratio, called the *overheat ratio, a*, and defined as either a resistance ratio

$$a_1 = \frac{R_s}{R_f}$$

or a resistance difference ratio

$$a_2 = \frac{R_s - R_f}{R_f}$$

where R_s is the resistance of the heated sensor at its operating temperature, and R_f is the resistance of the sensor at the temperature of the ambient fluid. The first definition is used in this book.

A different definition for sensor operating temperature is sometimes used by those who make blood flow measurements. Because blood can only be heated a few degrees centigrade above body temperature without damage, the overheat concept is sometimes expressed as an ''overheat temperature'' of, for example, 5°C. This means the adjustable resistor in the Wheatstone bridge is set to a value that allows the sensor temperature to be held at 5°C above ambient blood temperature.