

# Hot-Wire Anemometry

## Principles and Signal Analysis

H. H. BRUUN

*Department of Mechanical and Manufacturing  
Engineering, University of Bradford*

OXFORD NEW YORK TOKYO  
OXFORD UNIVERSITY PRESS

1995

# CONTENTS

NOTATION	xvii
ABBREVIATIONS	xxiv
1 INTRODUCTION	1
1.1 Advantages of hot-wire/film anemometry	1
1.2 Significant <i>HWA</i> problems and proposed solutions	3
1.3 <i>HWA</i> restrictions/ <i>LDA</i> applications	4
1.4 The need for flow measurements	5
1.4.1 Time-mean governing equations	7
1.5 Mean velocity measurements	9
1.6 Some simple turbulence models	11
1.6.1 Turbulent viscosity, $\mu_t$ , models	11
1.6.1.1 Zero-equation (algebraic) models	12
1.6.1.2 One-equation models	13
1.6.1.3 Two-equation models	14
1.6.2 Advanced turbulence modelling	18
2 BASIC PRINCIPLES OF HOT-WIRE ANEMOMETRY	19
2.1 Heat transfer	19
2.1.1 Infinitely long wire elements	19
2.1.2 Finite length hot-wire sensors	21
2.1.2.1 Steady-state temperature distributions in sensor elements	23
2.1.2.2 The resistance of sensor elements	26
2.1.2.3 The heat-transfer relationship	28
2.1.2.4 Velocity and temperature sensitivities	30
2.2 <i>HWA</i> probes	32
2.2.1 Hot-wire probes	32
2.2.1.1 Applications of hot-wire probes	33
2.2.1.2 The overheat ratio	33
2.2.2 Hot-film probes	34
2.2.2.1 Applications of hot-film probes	36
2.3 Modes of <i>HWA</i> operation	36
2.3.1 Selection of anemometer types	36
2.3.1.1 The signal-to-noise ratio of hot-wire and hot-film sensors	37
2.3.2 The constant-current mode	38
2.3.2.1 The frequency response of a hot-wire sensor	39
2.3.2.2 The frequency response of a cylindrical hot-film sensor	42
2.3.2.3 The frequency response of a resistance-wire probe	44
2.3.3 The constant-temperature mode	45
2.3.3.1 The frequency response of a hot-wire probe operated in the <i>CT</i> mode	48

2.3.3.2	The frequency response of hot-film probes operated in the <i>CT</i> mode	53
2.3.3.3	The dynamic response of a <i>CT</i> hot-wire probe in a non-isothermal flow	55
2.4	Spatial-resolution errors	57
2.4.1	Non-uniform mean velocity distributions	58
2.4.2	Non-uniform turbulent velocity distributions	62
3	INTRODUCTION TO VELOCITY MEASUREMENTS	71
3.1	Specification of the measurements required	73
3.2	Selection of the anemometer type and the hot-wire probe	73
3.3	Selection of the hot-wire response equation	75
3.4	Calibration of a hot-wire probe	75
3.5	Digital measurement requirements	76
3.5.1	Digital measurement systems	78
3.6	Measurements with a hot-wire probe	79
3.7	Data analysis	80
3.7.1	Data conversion	80
3.7.2	Time-series analysis	82
3.8	Data presentation	82
3.9	Uncertainty analysis	84
3.10	Conclusion	84
4	ONE-COMPONENT VELOCITY MEASUREMENTS	85
4.1	Introduction	85
4.2	Single normal hot-wire probe types	85
4.2.1	Hot-wire-probe design and pitch-angle effects	87
4.2.2	Aerodynamic-disturbance effects	89
4.2.3	Probe-interference effects caused by vibration	91
4.3	Calibration of an <i>SN</i> hot-wire probe	92
4.3.1	<i>In situ</i> calibration versus the use of special calibration facilities	93
4.4	Hot-wire calibration equations	94
4.4.1	Power laws	95
4.4.2	Extended power laws	96
4.4.3	The universal-function principle	97
4.4.4	Spline-fits	97
4.4.5	Polynomial curve fits	98
4.5	The accuracy of hot-wire calibration equations	99
4.6	Hot-wire calibration equations for extended velocity ranges	101
4.7	Calibration at low velocities	103
4.8	Calibration at very low velocities (mixed-flow regime)	105
4.9	Dynamic calibration of an <i>SN</i> hot-wire probe	109
4.10	Single normal hot-film probes	112
4.10.1	Measurements in gas flows	112
4.10.2	Measurements in water flows	113
4.10.2.1	Calibration techniques	118
4.10.3	Measurements in other liquids	120
4.11	Measurements with an <i>SN</i> -probe	120

4.11.1	Identification of the mean-flow direction	121
4.11.2	Data acquisition and storage	121
4.12	Data analysis for an $SN$ -probe	122
4.12.1	Voltage-signal analysis	123
4.12.2	Velocity-analysis method	124
4.12.2.1	Data conversion	124
4.12.2.2	Look-up-table method	124
4.12.2.3	Analysis of $V_c(m)$ records	126
4.13	Uncertainty analysis, $SN$ -probes	127
4.13.1	$V_c(t)$ - and $E(t)$ -methods	127
4.13.2	The $V_e^2$ -method	130
5	TWO-COMPONENT VELOCITY MEASUREMENTS	132
5.1	Hot-wire probe types	132
5.2	Hot-wire probe design and interference effects	133
5.2.1	Single yawed hot-wire probes	133
5.2.2	X-hot-wire probes	133
5.2.2.1	Thermal-wake interference	133
5.2.2.2	Prong-wake problems	134
5.2.2.3	Aerodynamic-disturbance effects of X-probes	134
5.3	Single inclined hot-wire probes	135
5.3.1	The calibration of $SN$ and $SY$ probes	137
5.3.1.1	The calibration of inclined $SN$ -probes	137
5.3.1.2	The calibration of an $SY$ -probe	139
5.3.1.3	The combined velocity and yaw calibration of an $SY$ -probe	141
5.3.1.4	The dynamic calibration of an $SY$ or X-probe	141
5.3.2	Measurements with an inclined $SN$ or $SY$ probe	143
5.3.2.1	Data acquisition and storage	143
5.3.3	Data analysis for inclined $SN$ or $SY$ probes	144
5.3.3.1	Voltage-signal analysis	144
5.3.3.2	Velocity-analysis method	145
5.4	X-hot-wire probes	147
5.4.1	The calibration of an X-probe	149
5.4.1.1	$V_c$ -calibration methods	151
5.4.1.2	Multi-angle calibration methods	152
5.4.2	Measurements with X-probes	152
5.4.2.1	Data acquisition	153
5.4.3	Signal analysis for X-probes	153
5.4.3.1	The $V_c$ -analysis method (sum and difference)	153
5.4.3.2	The $(\bar{V}, \theta)$ analysis method	156
5.4.3.3	Look-up matrix methods	156
5.5	Other hot-wire probe types	158
5.5.1	Hot-wake-sensor probes	158
5.5.2	V-shaped hot-wire probes	161
5.6	Inclined hot-film probes	162
5.6.1	Calibration	162
5.6.2	Measurements with inclined hot-film probes	164
5.7	Split-film probes	164

5.7.1	Practical split-film anemometry	166
5.8	Uncertainty analysis, <i>SY</i> probes	169
5.8.1	$V_e$ -method	169
5.8.2	$\overline{V_e^2}$ -method	170
5.9	Uncertainty analysis, <i>X</i> -probes	171
5.9.1	Sum-and-difference method	171
5.9.2	Look-up matrix method	175
6	THREE-COMPONENT VELOCITY MEASUREMENTS	176
6.1	Multiposition single-sensor techniques	176
6.1.1	General response equations for a single-sensor probe	177
6.1.2	$V_e$ -solution procedures	180
6.1.2.1	One-component mean velocity	180
6.1.2.2	Two-component mean velocity	182
6.1.2.3	Three-component mean velocity	184
6.1.3	$V_e^2$ -analysis methods	185
6.1.3.1	One-component mean velocity	186
6.1.3.2	Two-component mean velocity	187
6.1.4	$V_e^2$ -analysis method	187
6.2	Multiposition <i>X</i> -probe techniques	188
6.3	Triple-sensor ( <i>3W</i> ) probes	189
6.3.1	Calibration of a <i>3W</i> -probe	189
6.3.2	Data-acquisition criteria and procedures for a <i>3W</i> -probe	191
6.3.3	Signal-analysis methods for <i>3W</i> -probes	191
6.3.3.1	The TSI triple-hot-film probe 1299-20-18	192
6.3.3.2	The Dantec 55P91 triple-wire probe	194
6.3.4	Other <i>3W</i> -probe types and signal-analysis procedures	199
6.4	Four-wire probes	201
6.5	Uncertainty analysis, three-velocity-component evaluations	205
7	TEMPERATURE EFFECTS: correction methods for drift in the fluid temperature; measurements of fluid temperature fluctuations	208
7.1	Introduction	208
7.2	The velocity and temperature dependence of <i>CT</i> anemometer signals	208
7.2.1	Direct velocity and temperature calibration of a <i>CT</i> hot-wire probe	209
7.2.2	Nondimensional heat-transfer relationships	212
7.2.3	The recommended heat-transfer relationship for <i>CT</i> hot-wire probes	214
7.3	Correction methods for ambient fluid temperature drift	215
7.3.1	Automatic compensation	217
7.3.2	Manual adjustment of the hot resistance	218
7.3.3	Analytical-compensation techniques	218
7.3.4	Temperature effects for hot-film probes in water	219
7.4	Measurements of the fluctuating fluid temperature	219
7.4.1	The multiple overheat ratio method	219
7.4.2	Dual <i>CT</i> hot-wire probes	220

7.4.3	The resistance-wire method	223
7.4.3.1	The temperature dissipation rate, $\epsilon_\theta$ , and the microscale, $\lambda_\theta$	229
7.5	Simultaneous velocity and temperature measurements	231
7.5.1	Dual-sensor probes	231
7.5.2	Multi-sensor probes	232
8	<b><i>HWA</i> TECHNIQUES FOR REVERSING FLOW AND FOR THE NEAR-WALL REGION</b>	234
8.1	The forward–reverse ambiguity	234
8.2	Shielded single-sensor probes	234
8.3	Cylinder-wake probes	234
8.4	Continuously heated hot-wake probes	236
8.5	The pulsed-wire anemometer	239
8.5.1	The ideal <i>PWA</i> probe response	240
8.5.2	The response of a <i>PWA</i> probe to a heating pulse	241
8.5.3	Velocity calibration of a <i>PWA</i> probe	245
8.5.4	Probe geometry and operational considerations	247
8.5.5	Turbulence measurements with a <i>PWA</i> probe	249
8.5.6	Near-wall <i>PWA</i> measurements	250
8.6	The flying hot-wire-anemometer technique	253
8.6.1	The basic principle of the <i>FHA</i> system	253
8.6.2	Implementation of an <i>FHA</i> system	254
8.6.3	Probe position and probe velocity	255
8.6.4	Measurement of the relative velocity	258
8.6.5	Evaluation of the flow velocity	260
8.6.6	Operational procedure for the Bradford <i>FHA</i> system	260
8.7	Split-film probes	262
8.7.1	Forward flow-fraction measurements using a split-film sensor	262
8.7.2	Triple-split probes	262
8.7.3	The TSI total-velocity vector system	264
8.8	Near-wall and skin-friction measurements	264
8.8.1	Near-wall measurements	265
8.8.2	Skin-friction (mean wall shear stress) measurements	272
8.8.3	Time-dependent surface-shear-stress measurements	283
9	<b>TWO-PHASE FLOWS, GAS MIXTURES, AND COMPRESSIBLE FLOWS</b>	287
9.1	Two-phase flows	287
9.1.1	The probe response to the passing of a bubble	287
9.1.2	Signal analysis in two-phase flows	292
9.1.2.1	Void-fraction evaluation	293
9.1.2.2	Continuous-phase velocity evaluations	294
9.1.3	Liquid droplets in a gas flow	297
9.2	Concentration measurements in gas mixtures	298
9.2.1	Single-sensor response	298
9.2.2	The interfering-sensor method	300
9.2.3	Aspirating probes	302

9.3	Compressible flows	304
9.3.1	Transonic flows	306
9.3.2	Supersonic flows	307
9.3.2.1	Probe design	315
10	VORTICITY MEASUREMENTS	317
10.1	The streamwise vorticity component	318
10.2	Cross-stream vorticity components	326
10.2.1	Velocity-gradient measurements with closely spaced X-arrays	333
10.3	The three components of the vorticity measured simultaneously	335
11	CONDITIONAL SAMPLING TECHNIQUES	343
11.1	Phase-locked-averaging techniques	343
11.1.1	Rotating-wake phenomena	343
11.1.2	Internal-combustion engines	351
11.2	The identification of turbulent flow phenomena	365
11.2.1	Turbulent boundary layers	366
11.2.1.1	Outer flow region	367
11.2.1.2	The near-wall region	382
11.2.2	Free shear layers	398
12	TIME-SERIES ANALYSIS	405
12.1	The classification of physical data	405
12.1.1	Stationary random processes	406
12.1.2	Ergodic random process	407
12.2	Uncertainty specification for measured statistical quantities	409
12.3	Amplitude-domain analysis	411
12.3.1	Single time-history record statistics	411
12.3.1.1	Mean value	411
12.3.1.2	The mean-square value and higher-order moments	418
12.3.1.3	The probability density function	423
12.3.2	The joint statistics of two sample records	425
12.3.2.1	The mean value, the spatial correlation, and higher moments	425
12.3.2.2	Joint-probability density function	426
12.4	Time-domain analysis	428
12.4.1	The autocorrelation function	428
12.4.2	The cross-correlation function	431
12.5	Spectral density functions	433
12.5.1	Spectra by the narrow-band filtering method	433
12.5.2	Spectra via correlation functions	436
12.5.3	Spectra via finite Fourier transforms	437
12.5.4	Digital spectral analysis	442
	REFERENCES	446
	INDEX	503