

An Introduction to Turbulence and its Measurement

P Bradshaw

An Introduction to Turbulence and its Measurement

P. BRADSHAW

Aeronautics Department, Imperial College of Science and Technology



PERGAMON PRESS

Oxford · New York · Toronto Sydney · Paris · Braunschweig

Contents

Preface		X
Acknowledgements		xiii
GLOSSARY		xv
Chapter 1. The Physics of Turbulence		1
1.1. "Control-volume" Analysis for the E	quations of Motion	1
1.2. Newton's Second Law of Motion		4
1.3. The Newtonian Viscous Fluid	the second report of the	5
1.4. Possible Solutions of the Equations of1.5. The Reynolds Stresses	Motion	7 10
1.6. Vortex Stretching		12
1.7. Compressible Flow	100	17
1.8. Flow-visualization Experiments		18
CHAPTER 2. MEASURABLE QUANTITIES AND	THEIR PHYSICAL SIGNIFICANO	CE 21
2.1. Statistics of Random Processes		21
2.2. Turbulent Energy		24
2.3. Spatial Correlations		28
2.4. Time Correlations		29
2.5. Frequency Spectra 2.6. Wave Number Spectra		30 34
2.7. Space–Time Correlations		40
2.8. Cross-correlations and Cross-spectra		43
2.9. Higher-order Correlations and Spectra	a	43
2.10. Probability Distributions and Interm	ittency	44
CHAPTER 3. EXAMPLES OF TURBULENT FLOV	ws	47
3.1. Turbulence behind a Grid of Bars		47
3.2. "Infinite" Shear Flow		49
3.3. Couette Flow		50
3.4. Two-dimensional Boundary Layers3.5. Three-dimensional Boundary Layers		55 63
J.J. I III CC"UIII CIISIUII ai Duuliudi V Lavels		03

37111				
	17	1	1	1

CONTENTS

3.6. Duct Flows	64
3.7. Jets, Wakes and Plumes	68
3.8. Atmospheric and Oceanic Turbulence	72
3.9. Separated Flows	75
3.10. Heat and Mass Transfer	79
3.11. Turbulence in Non-Newtonian Fluids	82
Chapter 4. Measurement Techniques	85
4.1. Hot Wires, Films and Thermistors	86
4.2. Constant-current and Constant-temperature Operation	87
4.3. Doppler-shift Anemometers	92
4.4. Glow-discharge or Corona-discharge Anemometers	96
4.5. The Pulsed-wire Anemometer	97
4.6. Particle Visualization	98
4.7. Use of Steady-flow Techniques for Fluctuation Measurement	99
4.8. Measurement of Surface Pressure Fluctuations	102
4.9. Specialized Techniques of Turbulence Measurement	103
Chapter 5. The Hot-wire Anemometer	106
5.1. Heat Transfer	109
5.2. The Effect of Fluid Temperature	117
5.3. The Effect of Flow Direction	119
5.4. Contamination of Probes	123
5.5. Probe Design and Manufacture	126
5.6. Spatial Resolution	130
5.7. Frequency Response	131
Chapter 6. Analysis of Fluctuating Signals	134
6.1. Analogue Computing Elements	134
6.2. Input and Output Impedance, and Frequency Response	143
6.3. Noise and Hum	146
6.4. Averaging Time	148
6.5. Automatic Recording of Time-average Quantities	149
6.6. Digital Recording of Fluctuating Signals	150
CHAPTER 7. TEMPERATURE AND CONCENTRATION MEASUREMENTS	155
7.1. Separation of Velocity and Temperature Fluctuations	155
7.2. High-speed Flow	157
7.3. Probes for Supersonic Flow	159
7.4. Sensitivity of a Hot Wire to Velocity and Total-temperature Fluctuations	160
7.5. Small Temperature Differences	163
7.6. Measurements in the Presence of Concentration Differences	164

CONTENTS	ix
CHAPTER 8. SUMMARY OF PRACTICAL DETAILS	167
8.1. Choice of Anemometer	167
8.2. Choice of Probe	168
8.3. Calibration	170
8.4. Errors	175
8.5. Arrangements of Apparatus	181
8.6. Distortion of the Flow by the Presence of the Probe	184
APPENDIX 1. The Equations of Motion	186
Time and the second sec	
APPENDIX 2. Turbulence Research	194
Notation	201
References	204
Further Reading	208
ORTHER READING	200
INDEX	211
INITIEX	/