# ANALYSIS OF TURBULENT BOUNDARY LAYERS

TUNCER CEBECI / A. M. O. SMITH

INSTITUT 46/1484 FÜR METEOROLOGIE U. KLIMATOLOGIE DER TECHNISCHEN UNIVERSITÄT 3 HANNOVER · HERRENHÄUSER STR. 2

### )k: 551.5M.6

32

## ANALYSIS OF TURBULENT BOUNDARY LAYERS

Tuncer Cebeci and A. M. O. Smith

Douglas Aircraft Company McDonnell Douglas Corporation Long Beach, California



ACADEMIC PRESS New York San Francisco London 1974 A Subsidiary of Harcourt Brace Jovanovich, Publishers

### Contents

Preface	ix
Acknowledgments	xiii
Principal Notation	xv

#### Chapter 1 Introduction

1.1	Turbulence-Miscellaneous Remarks	2
1.2	The Ubiquity of Turbulence	7
1.3	The Continuum Hypothesis	8
1.4	Measures of Turbulence-Intensity	11
1.5	Measures of Turbulence-Scale	15
1.6	Measures of Turbulence—The Energy Spectrum	20
1.7	Measures of Turbulence-Intermittency	22
1.8	The Diffusive Nature of Turbulence	24
1.9	The Parameters of Primary Interest	28
1.10	Some Consequences of Turbulence	33
1.11	The Impossibility of Calculating Turbulent Flow from First Principles	41
1.12	Background Literature	45

#### Chapter 2 Conservation Equations for Compressible Turbulent Flows

2.1	Introduction	47
2.2	The Navier-Stokes Equations	48
2.3	Conventional Time-Averaging and Mass-Weighted-Averaging Procedures	49
2.4	Relation between Conventional Time-Averaged Quantities	
	and Mass-Weighted-Averaged Quantities	53
2.5	Continuity and Momentum Equations	54
2.6	Energy Equations	55
2.7	Mean-Kinetic-Energy Equation	56
2.8	Reynolds-Stress Transport Equations	57

#### **Chapter 3** The Boundary-Layer Equations

3.1	Introduction	62
3.2	Boundary-Layer Approximations for Compressible Flows	64
3.3	Continuity, Momentum, and Energy Equations	73
3.4	Mean-Kinetic-Energy Equation	81
3.5	Reynolds-Stress Transport Equations	82
3.6	Integral Equations of the Boundary Layer	87

#### Chapter 4 General Behavior of Turbulent Boundary Layers

4.1	Introduction	91
4.2	Composite Nature of a Turbulent Boundary Layer	91
4.3	Eddy-Viscosity and Mixing-Length Concepts	104
4.4	Mean-Velocity and Shear-Stress Distributions in Incompressible Flows	
	on Smooth Surfaces	113
4.5	Mean-Velocity Distributions in Incompressible Turbulent Flows on	
	Rough Surfaces with Zero Pressure Gradient	128
4.6	Mean-Velocity Distribution on Smooth Porous Surfaces with Zero Pres-	
	sure Gradient	135
4.7	The Crocco Integral for Turbulent Boundary Layers	140
4.8	Mean-Velocity and Temperature Distribution in Compressible Flows	
	with Zero Pressure Gradient	143
4.9	Effect of Pressure Gradient on Mean-Velocity Distributions in Incom-	
	pressible Flows	153

#### Chapter 5 Various Approaches to the Calculation of Turbulent Boundary Layers

5.1	Introduction	164
5.2	Integral Methods	165
5.3	Differential Methods	168
5.4	Short-Cut Methods	187

#### Chapter 6 Transport Coefficients in Turbulent Boundary Layers

6.1	Introduction	211
6.2	Coefficients of Momentum Transport	212
6.3	Coefficients of Heat Transport	239
6.4	Summary	255

vi

#### Contents

#### Chapter 7 The CS Method

258
258
260
264
265
266
269
280
281
289
293
295
296

#### Chapter 8 The CS Method for Laminar Boundary Layers

8.1	Introduction	298
8.2	Incompressible Laminar Flows	299
8.3	Compressible Laminar Flows	327

#### Chapter 9 The CS Method for Turbulent Boundary Layers

9.1	Introduction	. 329
9.2	Prediction of Transition	- 332
9.3	Two-Dimensional Incompressible Flows	335
9.4	Axisymmetric Incompressible Flows	355
9.5	Two-Dimensional Compressible Flows	359
9.6	Axisymmetric Compressible Flows	369
9.7	Some Applications of the CS Method	370
Ref	erences and Author Index	385
Subj	iect Index	401

vii