Frontispiece									
CONVENTIONS FOR REFERENCES		xxii							
I. INTRODUCTION. REAL AND IDEAL	FLUIDS								
By M. J. LIGHTHILL									
PART I. INTRODUCTORY ESSAY									
1. External aerodynamics before boundary-layer theory		1							
PART II. PHYSICAL BACKGROUND OF THE FLO STUDIED	WS TO BE								
2. Conditions under which density variation may be neglect	ed in external	l							
aerodynamics	• •	5							
2.1. Air in equilibrium	• •	5							
2.2. Air in motion	• •	7							
2.3. Temperature changes in external aerodynamics .	• •	7							
2.4. Pressure changes in external aerodynamics .	• •	9							
2.5. Solenoidality of the velocity field	• •	11							
2.6. Unsteady flow and sound waves	• •	12							
2.7. Summary of the conditions for solenoidality .	• •	13							
3. Other relevant physical properties of air		13							
3.1. Viscosity		13							
3.2. Conditions at a solid surface		16							
3.3. Heat transfer and evaporation		19							
3.4. Diffusivities		21							
4. Analogies with liquid motions	•	23							
4.1. Comparison between liquids and gases in equilibrium	m.,	23							
4.2. The liquid-vapour transition		24							
4.3. Surface tension		25							
4.4. Conditions for solenoidality of liquid flows .		26							
4.5. The viscosity of liquids		28							
4.6. Variation of viscosity with pressure and temperatur	re .	29							
4.7. Heat conduction and diffusion in liquids .		. 30							
4.8. The effect of a free surface		31							
PART III THE WATOD STRUCTEVING DEATING									
SUBJECT	OF THE								
5. Dynamical similarity and dimensional analysis		94							
5.1 Dynamical similarity and dimensional analysis	• •	9∕ •							
5.2 Force coefficients and pressure coefficients		95 95							
	•	. ƏU							

5.3. Numerical values of the Reynolds number .		36
5.4. Dynamical similarity in more general flows .		40
5.5. Use of non-dimensional parameters to determine	which physical	
properties may be neglected		42

II. INTRODUCTION. BOUNDARY LAYER THEORY

By M. J. LIGHTHILL

1.	Vorticity and the development of fluid flows .		•	46
	1.1. Introduction	•	•	46
	1.2. Vorticity	•	•	47
	1.3. Variation of vorticity in an inviscid fluid .	•	•	51
	1.4. Variation of vorticity in a viscous fluid	•	•	53
	1.5. Solid boundaries as sources of vorticity		•	54
	1.6. The vorticity distribution as fixing the flow field	•		55
	1.7. Flow development	•	•	57
2.	Boundary layers and separation			60
	2.1. The development of a laminar boundary layer .			60
	2.2. Boundary layers and wakes in steady flow .		•	61
	2.3. Two-dimensional flows; attachment and separation	•		63
	2.4. Two-dimensional boundary-layer theory .	•		67
	2.5. Two-dimensional thin-wake flows	•	•	70
	2.6. Attachment and separation in three-dimensional flows	•		72
	2.7. Topography of skin-friction lines and vortex lines	•	•	76
	2.8. Three-dimensional boundary-layer theory	•	•	82
	2.9. Pressure in boundary layers	•	•	86
3.	Instability and turbulence	•	•	88
	3.1. Hydrodynamic instability	•		88
	3.2. Transition to turbulence	•	•	94
	3.3. The turbulent boundary layer	•	•	96
4.	Variation of flow patterns with Reynolds number .	•		102
	4.1. Flow around bluff bodies	•		102
	4.2. Flow over streamlined bodies	•		109

III. THE NAVIER-STOKES EQUATIONS OF MOTION

By G. B. WHITHAM

PART I. GENERAL THEORY 1. Analysis of the motion of a fluid element • • . 114 • 2. Equation of continuity . . • • • . 115 3. Principal axes of rate of strain . . 116 • 4. Analysis of stress . . . 117 . • •

 $\mathbf{x}\mathbf{i}\mathbf{v}$

5.	Relations between the stress a	nd rate	-of-strai	n compo	onents	•	•	118
6.	The momentum equations .			•	•	•	•	120
7.	Equations for the vorticity. The	ne rate	of chang	ge of cir	culation	•	•	121
8.	The energy equation		•	•	•	•	•	124
9.	Dynamical similarity .		•	•	•	•	•	127
10.	The stream function .		•	•	•	•	•	128
11.	General orthogonal coordinates	s	•	•	•	•	•	129
12.	Cylindrical polar coordinates		•	•	•	•	•	132
13.	Spherical polar coordinates .		•	•	•	•	•	133
PA	RT II. SOME EXACT SOI	UTIO	NS					
14.	Solutions for which the conve	ction te	rms van	ish	•	•	•	134
15.	Examples of flows with suction	n	•		•	•	•	141
16.	Similarity solutions		•	•	•	•	•	142
17.	Two-dimensional flow between	ı non-p	arallel p	lane wa	lls	•	•	144
18.	Round jets		•	•		•	•	150
19.	Stagnation point flows .		•	•	•	•	•	155
20.	Flow due to rotating disks .		•	•		•	•	157

IV. FLOW AT SMALL REYNOLDS NUMBER

By C. R. ILLINGWORTH

1.	Introduction			•	•	•	•	163
2.	The Stokes and Oseen variables			•	•	•	•	167
3.	Stokes flow			•	•	•	•	169
	3.1. Flow past a sphere .		•	•	•	•	•	170
	3.2. Flow past a circular cylind	er	•		•	•	•	171
4.	Swimming of microscopic organ	isms	•	•			•	172
5.	Oseen flow		•	•	•	•	•	175
	5.1. Flow past a sphere .				•	•	•	176
	5.2. Flow past a circular cylind	er	•	•	•			179
	5.3. Flow past a flat plate .		•		•		•	180
	5.4. Oseen's fundamental soluti	ions	•	•	•	•	•	181
	5.5. Imai's method for plane flo	w	•	•	•	•	•	184
6.	An improved theory of flow at	small	Reynold	ls numb	\mathbf{er}		•	186
	6.1. Flow past a sphere .		•	•	•	•	•	188
	6.2. Flow past a circular cylind	\mathbf{er}	•		•		•	190
7.	Heat transfer		•		•	•		192
	7.1. Circular cylinder				•			193
	7.2. Sphere		•		•	•	•	194
8.	The flow at large distances from	n an o	bstacle		•	•	•	194
ŧ	5713.2	b						

xv

V. TWO-DIMENSIONAL BOUNDARY LAYERS

By c. w. jones and e. j. watson

PART I. EQUATIONS OF MOTION

1.	Derivation of the boundary-layer equations for flow along a flat surface	198
2.	Boundary-layer equations for flow along a curved surface	201
3.	Boundary conditions for steady flow	203
4.	Vorticity, stress, and energy dissipation in boundary layers	204
PA:	RT II. PROPERTIES OF THE EQUATIONS AND THEIR COLUTIONS	
5.	Boundary-layer thicknesses, skin friction, and energy dissipation	205
6.	Momentum and energy equations	206
7.	Behaviour of the solutions of the boundary-layer equations and condi- tions for separation	209
8.	The transposition theorem of Prandtl	211
9. 9	Transformations of the equations of steady motion	212
10.	The analogy with heat conduction for the steady boundary layer	214
11.	Algebraic singularities in boundary-layer solutions: conditions at a	
	point of separation	217
PA	RT III. SPECIAL EXACT SOLUTIONS	
12.	Flow along a flat plate at zero incidence in a uniform stream	222
13.	Limitations of the boundary-layer solution for a flat plate; better approximations near the leading edge	226
14.	Steady flow in the boundary layer along a cylinder near the forward	Į
	stagnation point	231
15.	Weyl's theory of the simpler boundary-layer equations .	233
16.	Steady flow in the boundary layer along a wedge; the solution of Falkne and Skan	r 234
17	Flow in a converging channel between intersecting planes	236
18	The role of coordinate systems in boundary-layer theory	238
19.	The asymptotic suction profile	241
20.	Solutions for boundary-layer flow with suction derived from those)
	without suction: flat-plate and stagnation-point flows	. 242
21.	Solutions with similar velocity profiles	. 243
22.	The boundary layer between parallel streams	. 252
23.	The two-dimensional jet	. 254
Ар	PENDIX: Parabolic cylinder functions	. 256
	VI. APPROXIMATE METHODS OF SOLUTION	
	By G. E. GADD C. W. JONES, and E. J. WATSON	

PA	RT I. ACCURATE SOLUTIONS AN	D APE	PROXIMA	ТE		
I	METHODS BASED ON THEM					
2.	Solutions in series: method of Blasius and	d Howa	rth .		•	260
3.	Solutions in series: Howarth's method for	r an adv	verse veloc	ity grad	lient	264
4.	Solutions in series: Falkner's transformat	ion .	•	•	•	266
5.	Falkner's approximate methods .	•	•	•	•	267
6.	Solutions in series: Görtler's expansion	•	•	•	•	270
7.	Methods of iteration: the method of Pi	ercy an	d Preston	and its	s ex-	
	tensions	•	•	•	•	272
8.	The method of Piercy, Whitehead, and Ty	ler .	•	•	•	275
9.	Methods of continuation: Goldstein's exwake behind a flat plate	pansion	. at a sing •	ularity	\cdot the \cdot	278
10.	Numerical step-by-step methods .		•	•	•	281
11.	Methods of expansion near the wall $\$.	•	•	•	•	286
12.	The work of Meksyn	•	•	•	٠	288
ЪA	ρη ΤΓ ΑΡΡΡΟΥΤΜΑΤΈ ΜΈΤΗΟΒΟΙ	BASED	ON INT	EGRA	TED	
1 4	TORMS OF THE BOUNDARY-LAVE	ER EO	ILATION:	S	1 11 12	
12	Methods based on the momentum equati	on · Pol	lhaucon'e	o method	1	299
10.	Methods based on the momentum equal	$\frac{1}{1000}$	ltornativo	nolync	mial	202
14.	forms	••••••		·	•	297
15.	Methods based on the momentum equatio	n:Timr	nan's fami	ly of pro	ofiles	298
16.	Methods based on the momentum equation	on: a n	nethod of '	Fhwait e	s.	300
17.	Methods based on the momentum equa profiles	ation: t	he family ·	of 'sin	nilar'	301
18.	Approximate integration of the momen posed by Thwaites	tum eq	uation: re	lations	pro-	303
19.	Application of the energy equation .		•			308
20.	Wieghardt's two-parameter method .					311
21.	Simplifications of Wieghardt's method				•	312
22.	Methods of Loitsianskii and Whitehead				•	317
PA	RT III. APPROXIMATE METHODS	BASE	D ON O Ι	JTER .	AND	
]	INNER SOLUTIONS					
23.	Method of Kármán and Millikan .		•	•		318
24.	Doenhoff's method for the separation po	int .				322
25.	Stratford's method					324
PA	RT IV. COMPARISON OF APPROX	XIMAT	E SOLU	TIONS	OF	
,	THE BOUNDARY-LAYER EQUATION	ONS				
26.	The accuracy and relative merits of diffe	rent me	thods of s	olution	•	329
PA	RT V. BOUNDARY LAYERS ON PO	ROUS	SURFAC	CES W	ітн	
5	SUCTION OR BLOWING					
27.	Boundary-layer problems involving sucti	on or b	lowing			332
28.	Solutions in series: potential flow past a	circular	cvlinder			333
	Potonition non publica			-		

xvii

29. Methods based on the momentum and energy equations	•	335
30. The prevention of separation by means of suction .	•	339
31. Uniform flow over a flat plate with constant suction .		341
32. Boundary-layer flow with strong suction and blowing		345

VII. UNSTEADY BOUNDARY LAYERS

By J. T. STUART

1.	General introduction		349
2.	Classes of solutions of the unsteady Navier–Stokes equations.	•	356
PA	RT I. BOUNDARY-LAYER MOTION FROM REST		
3.	Some exact solutions of the unsteady Navier-Stokes equations and o	of	
	the unsteady boundary-layer equations	•	358
4.	Impulsive motion of a semi-infinite flat plate normal to its edge	•	360
5.	Impulsive motion of fluid along corners and edges of infinite length	•	362
6.	Impulsive motion of an infinite cylinder parallel to its axis .	•	365
7.	Unsteady motion of an infinite cylinder normal to its axis .		368
8.	Three-dimensional unsteady motion	•	376
РА	RT II. PERIODIC BOUNDARY LAYERS		
9.	The flow due to an oscillating infinite plane		381
10.	The theory of periodic boundary layers in the absence of a mean flow		382
11.	Flow in a pipe due to a periodic pressure gradient .		388
12.	The forces on vibrating bodies		390
13.	The theory of the response of skin friction to fluctuations in the strea	m	
	velocity		393
14.	Fluctuating flow past an infinite porous flat plate .		397
15.	Applications of Lighthill's theory to the stagnation-point and Blasi	us	
	boundary layers		401
16.	The flow near an oscillating stagnation point		402
17.	Heat transfer and temperature fluctuations in unsteady flow .		406
	VIII MIDDE DIMENSIONAL DOUNDADY LAVED	4	
	VIII. IHREE-DIMENSIONAL BOUNDARY LATER	a	
	By L. F. CRABTREE, D. KÜCHEMANN, and L. SOWERBY		
PA	ART I. FUNDAMENTAL EQUATIONS		
1	Introduction		409
2	. The boundary-layer equations		411
3	. The momentum equations		416
	•		
$\mathbf{P}A$	ART II. THE ROTATIONALLY SYMMETRICAL CASE		
	The goodinate system and the boundary layor coustions for form as	at	

4.	The coordinate system	and the	boundary	7-layer e	quations i	for flow	past	
	a body of revolution	•	•	•	•	•	•	417

xviii

2	Stordy flow in the boundary layor alo	nor o cum	food of m	avalutio	n noon th		
э.	forward stagnation point .	•		•	. near u	•	419
6.	Steady flow without swirl; expansion	ı in serie	es	•			420
7.	The flow past a sphere .						423
8.	The transformation to the two-dimen	nsional o	ease				426
9.	Efflux through a small hole .			•			427
10.	Flow past a cone					•	428
11.	The momentum equations .		•				43 0
12.	Steady axisymmetric flow; approxim	nate solu	tion wit	h no suo	etion		431
13.	Steady flow with swirl .		•				432
14.	The boundary layer on a rotating sp	here					436
15.	Entry flow in a circular pipe .						439
16.	Flow along the outside of a long thir	ı circula	r cylinde	ər			446
17.	The rotationally symmetrical jet; de	cay of s	wirl				452
18.	The axially symmetrical wake	•		•			455
$\mathbf{P}A$	RT III. THE GENERAL THRE	E-DIM	ENSIO	NAL C.	ASE		
19.	Secondary flow in a boundary layer						456
20	Parabolic flow over a flat plate						457
21.	Flow near a stagnation point on a ge	eneral cu	urved sur	rface			461
22	Flow over sheared wings and yawed	cylinder	rs				467
23	. Swept wings .						474
24	Rotating blades						480
25	Flow along corners and edges						483
26	Flow separation in three dimensions			•			488
	-					-	

IX. HYDRODYNAMIC STABILITY

By J. T. STUART

1.	Introduction .			•		•		492
2.	Centrifugal instability	•						494
	2.1. The instability of i	flow betwee	n rotati	ng cylin	ders			495
	2.2. The instability of	the bounda	ry layer	on a co	ncave su	urface		502
	2.3. Other examples of	instability	due to d	centrifug	gal force	s.		505
3.	Thermal instability .							506
	3.1. Mathematical resul	lts for them	nal inst	ability	•	•	•	510
	3.2. Experimental worl	k on therms	l instal	oility	•	•	•	511
4.	The instability of two	limonaional	norallo	l florma	•	•	•	~10
		umensionai	parane.	nows	•	•	. •	512
	4.1. Energy consideration	ions in two	dimensi	onal pa	rallel flo	ws		516
	4.2. The instability of	two-dime	nsional	paralle	l flows	at infi	nite	
	Reynolds numbe	er .	•	` .	•			518
	4.3. The theory of the	instability	of two-	limensio	onal para	allel flow	vs at	0
	finite Reynolds	number						521
	v		-	-	-		. •	041

4	4.4. Results for the instability of plane Poiseuille flow	•		530
	4.5. Numerical results and comparison with experiment f	or I	3lasius	
	flow	•	•	533
4	.6. Some important stability problems	•	•	538
5. 4	Applications of the instability theory to two-dimensional	boı	indary	
	layers	•	•	540
ł	5.1. Effects of pressure gradient	•		540
ł	5.2. Effects of suction		•	544
ł	5.3. Effects of density stratification	•		548
6. [The instability of three-dimensional boundary layers		•	549
(5.1. The flow on swept wings			553
(3.2. The flow due to a rotating disk			555
(3.3. Other work on, or related to, the instability of three-d	imei	nsional	
	flows	•	•	557
7. 1	The instability of wakes, jets, and laminar mixing regions			558
8. 1	Non-linear aspects of the mechanics of instability .		•	562
8	3.1. Finite disturbances under subcritical conditions in Pois	seuil	le flow	
	between parallel planes	•	•	565
8	3.2. Finite disturbances under supercritical conditions, wi	ith s	special	
	reference to flow between rotating cylinders .	•	•	568
8	3.3. The development of turbulence from instability wa	ves	in a	
	boundary layer	·	•	572
Арр	ENDIX: Reynolds stresses	•	•	578

X. EXPERIMENTAL METHODS

By R. C. PANKHURST and N. GREGORY

1.	Introduction		•	•				•	580
2.	Various methods of p	producin	ig relativ	ze motio	n				580
3.	Types of measurement	nt		•		•	•		582
4.	Wind-tunnels			•		•	•		583
5.	Water-tunnels				•	•			586
6.	Tunnel balances				•				587
7.	Tunnel interference		•				•		588
8.	Measurement of velo	city					•	•	592
9.	The pitot-static tube	in a un	iform st	ream					593
10.	Yawmeters .		•						598
11.	Manometers .								600
12.	Lag in leads						•		605
13.	Hot-wire anemometry	y; turbu	lence m	easurem	ents		•		606
14.	Flow visualization						•		608
15.	Visualization of boun	dary-lay	yer flow	•			•		611
16.	Other techniques for	detection	ng the st	ate of th	ie bound	lary lay	er		618

 $\mathbf{x}\mathbf{x}$

17.	Transition fixing	•	•,	•	•	•	•	•	617
18.	Boundary-layer profi	les		•	•	•	•	•	619
19.	Determination of int	ensity o	f surface	friction		•	•	•	622
20.	Estimation of profile	drag fro	om wake	travers	e measu	rements			625
\mathbf{RE}	FERENCES ANI	AUT	HOR I	NDEX				•	629
su	BJECT INDEX			•	•	•	•	•	671
AD	DITIONAL REF	ERENG	CES on	Hydrody	ynamic (Stability	r (Chapt	er	

aDDITIONAD MEE.	13101314	O EDO	on ilyuro	uynan	ne stasmty	(Onapio)	L	
IX). Added in proof		•	•	•	•	•	. 688	;

The following figures appear as plates:

II. 20	facing page	96
II. 26		
II. 27	between pages	$104 \; and \; 105$
II. 28)		
II. 32	facing page	108
II. 33		109
VII. 3		368
IX. 1		496
IX. 5		512
IX. 20		550
X.15		608
X. 16		608