

# Contents

<b>1</b>	<b>The Concept of Continuum and Kinematics</b>	<b>1</b>
1.2	Kinematics . . . . .	1
Problem 1.2-1	Calculation of material coordinates for given pathlines . . . . .	1
Problem 1.2-2	Velocity and acceleration in material and spatial coordinates with given pathlines .	2
Problem 1.2-3	Material description of a potential vortex flow . . . . .	5
Problem 1.2-4	Material description of an axisymmetric stagnation point flow . . . . .	7
Problem 1.2-5	Pathlines, streamlines, and streaklines of an unsteady flow field . . . . .	9
Problem 1.2-6	Kinematics of an irrotational and divergence free flow field . . . . .	14
Problem 1.2-7	Kinematics of an unsteady, plane stagnation point flow . . . . .	19
Problem 1.2-8	Streakline of a water jet . . . . .	23
Problem 1.2-9	Streamlines and Streaklines in cylindrical coordinates . . . . .	26
Problem 1.2-10	Streamlines and pathlines of standing gravity waves . . . . .	29
Problem 1.2-11	Change of material line elements in a Couette-flow . . . . .	31
Problem 1.2-12	Change of material line elements in a three-dimensional flow . . . . .	34
Problem 1.2-13	Angular velocity vector and the change of material line elements in a two-dimensional flow field . . . . .	38

Problem 1.2-14	Rate of deformation and spin tensors of an unsteady two-dimensional flow . . . . .	43
Problem 1.2-15	Time change of the kinetic energy of a fluid body . . . . .	45
<b>2</b>	<b>Fundamental Laws of Continuum Mechanics</b>	50
2.1	Conservation of Mass, Equation of Continuity . . . . .	50
Problem 2.1-1	One-dimensional unsteady flow with given density field . . . . .	50
Problem 2.1-2	Plane, steady flow with a given density field	52
Problem 2.1-3	Velocity at the exit of a container . . . . .	54
Problem 2.1-4	Steady flow through a circular channel . . . . .	56
Problem 2.1-5	Squeeze film flow . . . . .	58
Problem 2.1-6	Moving Piston . . . . .	60
Problem 2.1-7	Flow between two inclined flat plates . . . . .	63
Problem 2.1-8	Oscillating journal bearing . . . . .	65
Problem 2.1-9	Effect of boundary layer displacement thickness . . . . .	68
Problem 2.1-10	Flow through a diffuser with a linear velocity change in flow direction . . . . .	71
Problem 2.1-11	Temperature boundary layer along a cold wall . . . . .	73
Problem 2.1-12	Flow in a lubrication gap . . . . .	74
2.2	Balance of Momentum . . . . .	78
Problem 2.2-1	Principal axes of a stress tensor . . . . .	78
Problem 2.2-2	Fluid forces on a manifold . . . . .	80
Problem 2.2-3	Calculation of drag force . . . . .	82
Problem 2.2-4	Force on a slender nozzle . . . . .	85
2.3	Balance of Angular Momentum . . . . .	87
Problem 2.3-1	Torque on pipe with slot . . . . .	87
Problem 2.3-2	Moment exerted on the inlet guide vanes of a water turbine . . . . .	90
Problem 2.3-3	Curvature radius of circular arc profiles of a circular cascade . . . . .	93
2.4	Momentum and Angular Momentum in an Accelerating Frame	96
Problem 2.4-1	Fluid sprayed on a rotating disk . . . . .	96
Problem 2.4-2	Velocity of a moving container with a nozzle	100
Problem 2.4-3	Acceleration and velocity of a rocket . . . . .	107
Problem 2.4-4	Thrust reversal . . . . .	109
Problem 2.4-5	Torque on a rotating bent pipe . . . . .	111
Problem 2.4-6	Thrust of a jet engine . . . . .	114

2.5	Applications to Turbomachines . . . . .	117
Problem 2.5-1	Circulation around a blade profile in a circular cascade . . . . .	117
Problem 2.5-2	Axial turbine stage . . . . .	119
Problem 2.5-3	Kaplan turbine . . . . .	121
Problem 2.5-4	Torque converter . . . . .	125
Problem 2.5-5	Balancing of axial thrust . . . . .	129
2.6	Conservation of Energy . . . . .	131
Problem 2.6-1	Cylinder with heat flux . . . . .	131
Problem 2.6-2	Energy balance in an axial turbine stage .	134
<b>3</b>	<b>Constitutive equations</b>	138
Problem 3-1	Velocity of a raft . . . . .	138
Problem 3-2	Energy balance in a journal bearing . . . . .	140
Problem 3-3	Pressure driven flow of paper pulp . . . . .	144
Problem 3-4	Flow of a non-Newtonian fluid . . . . .	146
Problem 3-5	Extensional flow . . . . .	148
<b>4</b>	<b>Equation of Motion for Particular Fluids</b>	152
4.1	Newtonian Fluids . . . . .	152
Problem 4.1-1	Poiseuille flow . . . . .	152
Problem 4.1-2	Temperature distribution in a Poiseuille flow	156
Problem 4.1-3	Pressure driven flow in a channel with porous walls . . . . .	159
Problem 4.1-4	Boundary layer suction . . . . .	161
Problem 4.1-5	Mixing of streams of fluids . . . . .	165
Problem 4.1-6	Drag on a flat plate . . . . .	168
Problem 4.1-7	Two-dimensional water jet impinging on a wedge . . . . .	173
Problem 4.1-8	Rigid body rotation and potential vortex	175
Problem 4.1-9	Energy balance in a potential vortex flow	180
4.2	Inviscid flow . . . . .	184
Problem 4.2-1	Pressure and energy increase of fluid in a centrifugal pump . . . . .	184
Problem 4.2-2	Pressure distribution within a spiral casing	189
Problem 4.2-3	Free surface in a potential vortex . . . . .	190
Problem 4.2-4	Circulation in a Couette flow . . . . .	192
Problem 4.2-5	Velocity induced by a vortex ring . . . . .	193
Problem 4.2-6	Two infinitely long vortex filaments near a wall . . . . .	194

Problem 4.2-7	Wing with an elliptic spanwise distribution of circulation . . . . .	198
Problem 4.2-8	Airfoil in parallel flow . . . . .	201
Problem 4.2-9	Jet angle in a Betz diffuser . . . . .	204
Problem 4.2-10	Contraction coefficient of a Borda mouth-piece . . . . .	206
Problem 4.2-11	Pressure distribution in an inviscid and axisymmetric flow . . . . .	208
Problem 4.2-12	Increase of static pressure in a Betz diffuser . . . . .	210
Problem 4.2-13	Fluid flowing out of a tank . . . . .	212
Problem 4.2-14	Air bubble moving in a channel . . . . .	214
Problem 4.2-15	Aircraft above the ground . . . . .	217
Problem 4.2-16	Flow between two rotating cylinders, circulation and vorticity . . . . .	223
Problem 4.2-17	Power of a Pelton turbine . . . . .	225
4.3	<b>Initial and Boundary Conditions . . . . .</b>	230
Problem 4.3-1	Oscillation of an elliptic cylinder in fluid . . . . .	230
Problem 4.3-2	Flat plate with a pitching and oscillating motion . . . . .	231
Problem 4.3-3	Rotating cylinder moving through fluid . . . . .	232
Problem 4.3-4	Vortical flow inside an elliptic cylinder . . . . .	234
<b>5 Hydrostatics . . . . .</b>		236
5.1	<b>Hydrostatic Pressure Distribution . . . . .</b>	236
Problem 5.1-1	U-tube manometer . . . . .	236
Problem 5.1-2	Hydraulic safety clutch . . . . .	237
Problem 5.1-3	Rotating container filled with fluid . . . . .	239
Problem 5.1-4	Centrifugal casting process . . . . .	241
Problem 5.1-5	Depth gauge . . . . .	242
5.2	<b>Hydrostatic Lift, Force on Walls . . . . .</b>	244
Problem 5.2-1	Force and moment on a throttle valve . . . . .	244
Problem 5.2-2	Half sphere closing an orifice . . . . .	246
Problem 5.2-3	Force on a dam . . . . .	248
Problem 5.2-4	Half sphere cup sealing by its own weight . . . . .	250
Problem 5.2-5	Cylindrical submarine . . . . .	252
Problem 5.2-6	Car under water . . . . .	254
<b>6 Laminar Unidirectional Flow . . . . .</b>		257
Problem 6-1	Flow in an annular gap . . . . .	257
Problem 6-2	Crude oil transport through pipeline . . . . .	261
Problem 6-3	Oscillating pipe flow . . . . .	264

Problem 6-4	Comparison of a Couette-Poiseuille flow of a Newtonian fluid, a Stokes fluid, and a Bingham material . . . . .	267
<b>7 Fundamentals of Turbulent Flows . . . . .</b>		274
Problem 7-1	Turbulent Couette flow . . . . .	274
Problem 7-2	Velocity distribution in turbulent Couette flow with given Reynolds number . . . . .	277
Problem 7-3	Turbulent pipe flow . . . . .	278
Problem 7-4	Crystal growth on pipe walls . . . . .	280
Problem 7-5	Comparison of momentum and energy flux in laminar and turbulent flow in a pipe . . . . .	282
Problem 7-6	Velocity distribution in a turbulent pipe flow resulting from the Blasius friction law . . . . .	285
Problem 7-7	Location of a pipe leakage . . . . .	287
Problem 7-8	Cooling of superheated steam by water injection . . . . .	289
<b>8 Hydrodynamic Lubrication . . . . .</b>		293
Problem 8-1	Bearing with step slider . . . . .	293
Problem 8-2	Friction torque transmitted by the shaft to the journal . . . . .	297
Problem 8-3	Slider load in squeeze flow: Comparison between different slider geometries . . . . .	299
<b>9 Stream filament theory . . . . .</b>		302
9.1	<b>Incompressible Flow . . . . .</b>	302
Problem 9.1-1	Rotating tube acting as pump . . . . .	302
Problem 9.1-2	Volume flux through an orifice . . . . .	305
Problem 9.1-3	Injector pump . . . . .	306
Problem 9.1-4	Radial pump . . . . .	308
Problem 9.1-5	Bulb turbine . . . . .	312
Problem 9.1-6	Coanda effect . . . . .	315
Problem 9.1-7	Principle of a shaped charge . . . . .	316
Problem 9.1-8	Penstock and nozzle of a Pelton turbine . . . . .	319
Problem 9.1-9	Operating characteristic of a fan . . . . .	321
Problem 9.1-10	Water power plant . . . . .	325
Problem 9.1-11	Flow through an exhaust gas analyser . . . . .	328
Problem 9.1-12	Flow deflection through a screen . . . . .	329
Problem 9.1-13	Hovercraft . . . . .	331
Problem 9.1-14	Wind turbine . . . . .	333

Problem 9.1-15	Discharge pipe of a reservoir: Comparison between different pipe geometries . . . . .	337
Problem 9.1-16	Vibrating system consisting of a fluid column and a spring suspended piston . . . . .	339
Problem 9.1-17	Unsteady flow in a tube with flexible walls . . . . .	343
Problem 9.1-18	Plunger pump . . . . .	346
Problem 9.1-19	Flow within an urethra prothesis . . . . .	350
<b>9.2</b>	<b>Steady Compressible Flow . . . . .</b>	<b>352</b>
Problem 9.2-1	Force on a plate in subsonic flow . . . . .	352
Problem 9.2-2	Channel flow with heat addition . . . . .	355
Problem 9.2-3	Normal shocks in an inlet guide vane . . . . .	358
Problem 9.2-4	Blunt body in supersonic flow . . . . .	363
Problem 9.2-5	Shock waves in the divergent part of a Laval nozzle . . . . .	365
Problem 9.2-6	Supersonic nozzle in a spinneret . . . . .	367
Problem 9.2-7	Ram jet in subsonic flow . . . . .	370
Problem 9.2-8	High speed train in a tunnel . . . . .	373
Problem 9.2-9	Labyrinth seal of a turbomachine . . . . .	376
Problem 9.2-10	Gas flow through an orifice . . . . .	379
<b>9.3</b>	<b>Unsteady Compressible Flow . . . . .</b>	<b>381</b>
Problem 9.3-1	Traveling normal shock in a pipe . . . . .	381
Problem 9.3-2	Shock tube . . . . .	383
Problem 9.3-3	Motion of a piston in a tube . . . . .	386
Problem 9.3-4	Reflection of a normal shock wave at the open end of a tube . . . . .	389
Problem 9.3-5	Principle of an expansion tube . . . . .	392
Problem 9.3-6	Propagation of acoustic waves in a closed tube . . . . .	394
<b>10 Potential Flow</b>		<b>399</b>
<b>10.3</b>	<b>Incompressible Potential Flow . . . . .</b>	<b>399</b>
Problem 10.3-1	Expanding sphere . . . . .	399
Problem 10.3-2	Sphere in a translational flow . . . . .	402
Problem 10.3-3	Flow near the stagnation point of a body in parallel flow . . . . .	406
Problem 10.3-4	Point source in a rotationally symmetric stagnation point flow . . . . .	409
Problem 10.3-5	Point source above an impermeable wall . . . . .	412
Problem 10.3-6	Source distribution in parallel flow . . . . .	414
Problem 10.3-7	Expanding sphere in an inviscid and in a viscous flow . . . . .	416

Problem 10.3-8	Growth of a vapor filled cavity . . . . .	420
Problem 10.3-9	Contraction coefficient for a circular orifice . . . . .	423
Problem 10.3-10	Sphere rising in water . . . . .	427
Problem 10.3-11	Unsteady motion of a cylinder perpendicular to its axis . . . . .	430
Problem 10.3-12	Rotor oscillating in an inviscid fluid . . . . .	432
<b>10.4</b>	<b>Plane Potential Flow . . . . .</b>	<b>436</b>
Problem 10.4-1	Flow in the squeeze gap between a moving piston and a wall . . . . .	436
Problem 10.4-2	Sink distribution in a stagnation point flow . . . . .	439
Problem 10.4-3	Circle theorem . . . . .	442
Problem 10.4-4	Half cylinder in stagnation point flow . . . . .	447
Problem 10.4-5	Dipol flow around a circular cylinder . . . . .	451
Problem 10.4-6	Flow around a thin plate . . . . .	454
Problem 10.4-7	Airfoil over a fixed wall . . . . .	457
Problem 10.4-8	Semi infinite body in a channel . . . . .	461
Problem 10.4-9	Kármán's vortex street . . . . .	464
Problem 10.4-10	Joukowski mapping of a circular cylinder in a uniform flow . . . . .	467
Problem 10.4-11	Plane circular cascade . . . . .	470
Problem 10.4-12	Schwarz-Christoffel transformation of a wall of infinite extent . . . . .	473
Problem 10.4-13	Schwarz-Christoffel transformation of a convergent channel . . . . .	476
Problem 10.4-14	Cavitation in a channel . . . . .	480
Problem 10.4-15	Representation of a slender body by a source distribution . . . . .	483
Problem 10.4-16	Distribution of vortex intensity and mean camber line of a slender airfoil . . . . .	488
Problem 10.4-17	Straight cascade . . . . .	492
Problem 10.4-18	Vortex distribution of a flat-plate cascade . . . . .	497
Problem 10.4-19	Compressible flow over a wavy wall . . . . .	503
<b>11 Supersonic Flow</b>		<b>509</b>
<b>11.1</b>	<b>Oblique Shock Waves . . . . .</b>	<b>509</b>
Problem 11.1-1	Wedge with a thin plate in front of it . . . . .	509
Problem 11.1-2	Inlet of a plane channel . . . . .	511
<b>11.3</b>	<b>Reflection of Oblique Shock Waves . . . . .</b>	<b>514</b>
Problem 11.3-1	Flow over a wedge in a supersonic wind tunnel . . . . .	514
Problem 11.3-2	Supersonic flow in a convergent channel . . . . .	516

11.5 Prandtl-Meyer Flow . . . . .	518
Problem 11.5-1 Centered expansion wave in a divergent channel . . . . .	518
11.6 Shock Expansion Theory . . . . .	522
Problem 11.6-1 Airfoil in supersonic flow . . . . .	522
Problem 11.6-2 Inlet of a supersonic jet engine . . . . .	526
<b>12 Boundary Layer Theory</b>	<b>530</b>
Problem 12-1 Boundary layer momentum equation . . .	530
Problem 12-2 Flow over a wedge . . . . .	533
Problem 12-3 Diffuser with discontinuous change of the cross-section . . . . .	537
Problem 12-4 Drag coefficient of a diamond airfoil . . .	543
<b>A Tensor calculus</b>	<b>551</b>
Problem A-1 . . . . .	551
Problem A-2 . . . . .	551
Problem A-3 . . . . .	552
Problem A-4 . . . . .	553
Problem A-5 . . . . .	554
Problem A-6 . . . . .	555
Problem A-7 . . . . .	555
Problem A-8 . . . . .	556
Problem A-9 . . . . .	557
Problem A-10 . . . . .	558
Problem A-11 . . . . .	560
<b>B Examination problems</b>	<b>562</b>
Problem B-1 Streamlines and pathlines . . . . .	562
Problem B-2 Drag of a half cylinder shell . . . . .	563
Problem B-3 Awning in a storm . . . . .	564
Problem B-4 Stretching of a foil . . . . .	565
Problem B-5 Single stage, axial blower . . . . .	566
Problem B-6 Blade profile for given pressure distribution	567
Problem B-7 Combustion chamber of a piston engine .	568
Problem B-8 Two-dimensional oblique stagnation point flow . . . . .	569
Problem B-9 Generalized Hagen-Poiseuille flow . . . .	570
Problem B-10 Induced velocity of a horse-shoe vortex .	571
Problem B-11 Open channel flow through a weir . . . .	572
Problem B-12 Safety valve . . . . .	573

Problem B-13 Liquid in container . . . . .	574
Problem B-14 Sluice gate . . . . .	575
Problem B-15 Pressure driven flow in the radial gap between two concentric ring plates . . . . .	576
Problem B-16 Pressure driven channel flow with variable viscosity . . . . .	577
Problem B-17 Temperature induced flow . . . . .	578
Problem B-18 Shock absorber . . . . .	579
Problem B-19 Frequency of a Helmholtz resonator . . .	580
Problem B-20 Chamber and exhaust pipe of an internal combustion engine . . . . .	582
Problem B-21 Pump-turbine storage plant . . . . .	583
Problem B-22 Overexpanded Laval nozzle . . . . .	584
Problem B-23 Nozzle inlet . . . . .	585
Problem B-24 Solid propellant rocket engine . . . . .	586
Problem B-25 Ram jet . . . . .	587
Problem B-26 Ludwieg-tube . . . . .	588
Problem B-27 Dipol above an impermeable wall . . . . .	589
Problem B-28 Virtual mass of a thin plate . . . . .	591
Problem B-29 Removal of liquid through a plane channel	592
Problem B-30 Unsteady flow over a wavy wall . . . . .	593
Problem B-31 Wing section for given source and vortex distribution . . . . .	594
Problem B-32 Infinitely thin plate with aileron . . . . .	595
Problem B-33 Supersonic inlet . . . . .	596
Problem B-34 Infinitely thin, flat plate in two-dimensional supersonic flow . . . . .	598
Problem B-35 Guide vane cascade of a supersonic compressor . . . . .	599
Problem B-36 Boundary layer on a foil . . . . .	600