

## INDEX

- acceleration, aortic flow, 66  
 admittance  
   characteristic, 100, 102, 110  
   effective, 110  
   input: aorta, 112–3; pulmonary  
     circulation, 114  
 afterload, ventricular, 62–3  
 airways  
   collapse, 302  
   lung, 235–6  
 Airy functions, 227, 273, 283, 405–7,  
 419  
 alveoli, 1, 32  
 anemometer  
   electromagnetic, 36, 47, 131  
   hot-film, 38–9, 47, 131–6, 263, 369–  
     422; frequency response, 133, 380;  
     unsteady calibration experiments  
     371, 396, 401; yawed, 402; *see also*  
     hot-film  
   hot-wire 218, 239  
   laser-Doppler, 218  
   pulsed wire, 239  
   ultrasonic Doppler, 131  
 aorta  
   area, 13  
   curvature, 9, 46  
   Dean number, 183  
   diameter, 1, 11  
   distensibility, 20, 24  
   elastic properties, 99  
   entry flow, 44–5, 60, 121  
   frequency parameter, 11  
   geometry, 4, 9–12  
   input impedance, 63  
   instability of flow, 48–51, 291–300  
   length, 11  
   pressure, 34–5  
   aorta (*cont.*)  
     Reynolds number, 11; steady stream-  
     ing, 183  
     taper, 9–12  
     turbulence, 48–51, 291–2  
     velocity, 11, 34  
     velocity profiles, 42–6, 60  
     velocity waveform, 39–40, 137  
     viscoelasticity, 99  
     wall shear, 215–7  
     wall shear waveform, 156–8  
     wall thickness, 11  
     wave speed, 11  
     Young's modulus, 11, 20  
 area ratio, bifurcation, 236, 260  
 arteries, systemic  
   anatomy, 9–22  
   elastic properties, 13–22  
 arteriole, 1  
   mechanical properties, 11  
 artery  
   backflow, 36, 40, 45, 122  
   carotid, 10; mechanical properties,  
     11  
   collapse, 56–7, 311  
   coronary, 8–10, geometry, 12, 14;  
     oscillations, 41–2, 124; pulse wave,  
     124, 128–30; velocity profiles, 47;  
     velocity waveform, 40–1; wall  
     shear, 128–30  
   elastic properties, 120  
   elasticity, orthotropic, 88  
   external pressure, 116  
   femoral, 10; mechanical properties,  
     11; input admittance, 113  
   flow rate, 99–100  
   geometry, 1  
   iliac, 9–10

- artery (*cont.*)  
  intercostal, 9–10; atherosclerosis, 54, 276, 291  
  outflow, 115–8  
  pressure waveform, 36, 40  
  pulmonary, 1, 4; admittance, 114; collapse, 302; mechanical properties, 11, 22–4; pressure, 34; pressure waveform, 36, 38; velocity, 11, 34; velocity waveform, 38–9, 41–3; wave speed, 11, 114  
  reflection sites, 109, 112–4  
  shock wave, 77, 123  
  smooth muscle, 22  
  tethering, 21, 89, 95–8  
  velocity profiles, 42–8  
  velocity waveforms, 36, 40–1, 101  
  viscoelasticity, 17, 20–1, 79, 84, 105, 116, 120  
  wall: anisotropy, 17–18; buckling, 314; permeability, 52; thickness, 15  
  wall shear, 53–5, 99–100, 267–8  
  wave speed, 74–7  
asymptotic expansions, matched, 143–7, 381–3, 418–21  
atherosclerosis, 51–5  
  intercostal arteries, 276, 291  
atrium  
  left, 1, 4  
  right, 1, 4  
dispersion relation, waves in arteries, 92  
backflow, arteries, 36, 40, 45, 122  
bend, effect on Poiseuille flow, 224–34  
Bernoulli's equation  
  aortic valve, 61  
  collapsible tubes, 336  
  mitral valve, 58  
bifurcation  
  area ratio, 12  
  asymmetric: experiments, 260–9; geometry, 260–1  
  branching angle, 12  
  multiple, 109–11  
  reflection, 106–9  
  right-angled: flow patterns, 261–2; velocity profiles, 262–6; wall shear, 274–5  
  splitting of Poiseuille flow, 252–60  
  bifurcation (*cont.*)  
    symmetric: experiments, 235–45; geometry, 236–7  
    unsteady flow, 249  
    well-matched, 106  
Blasius boundary layer, 138, 140, 146, 204–6, 253–4  
blood  
  density, 31  
  mechanical properties, 2, 29–31  
  structure, 29–30, 374  
  viscosity, 31  
blood pressure, 31–3  
  measurement, 55–7  
boundary layer  
  aorta, 44  
  arteries, 131  
  Blasius, 138, 140, 146, 204, 206, 253–4  
  breakdown of theory 199, 217, 231, 275  
  curved tube: Poiseuille core flow, 225; steady, 169, 172, 174  
  displacement effect, 138  
  displacement thickness, 141, 152, 388  
  effect of transverse curvature, 401  
  Falkner–Skan, instability, 298  
  flow divider, 236, 239–41, 252, 267  
  heat thickness, 392  
  multiple, 181, 253  
  quasi-steady, 140, 150–1  
  Rayleigh, 150–1; curved tube, 194–7  
  reversing flow, 150–3, 386–9  
  steady streaming, 181  
  Stokes, 92, 143, 146, 387  
  thermal: hot-film, 372–403; oscillatory, 381–3; quasi-steady, 378–9; reversing flow, 390–6; steady, 375–6  
  unsteady, curved tube, 195  
  viscous, hot-film, 372–3, 386–9  
boundary layer approximation, accuracy, 402–18  
branching angles, bifurcation, 236, 260  
buckling  
  compressed artery, 315  
  elastic tubes, 336  
capillary, 1

- capillary (*cont.*)  
  mechanical properties, 11  
choking, collapsible tubes, 365  
circulation time 1  
collagen, elastic properties, 16–17  
collapse  
  airways, 302  
  arteries, 56–7, 302, 311  
  catastrophic, 349–50, 352, 354, 358–62  
  gradual, 349–50, 352, 362  
  mechanisms, 336  
  rubber tubes, 27–8  
  veins, 26–7, 301  
collapsible tube  
  choking, 365  
  constant-perimeter condition, 322, 348  
  elasticity, 351  
  equilibrium, 349–54  
  experiments, 304–16  
  instability, 354–9; constant inflow, 358, 361  
  reversed flow, 360–1  
  roll-wave instability, 367  
  self-excited oscillations, 307, 310–15, 338, 359–62  
  separation, 337–8  
  shape, 29, 306, 343  
  shock wave, 365  
  viscous flow, 326  
  wave speed, 364  
contractility, cardiac, 9  
corridor, downstream of side-branch, 276, 290  
cuff pressure, 55–7, 309–15, 327–8  
curvature  
  aorta, 46  
  non-uniform, 165–7, 199–203, 207, 213–8, 224  
  wall, bifurcation, 236, 238  
curvature ratio,  $\delta$ , 161  
curved tube  
  equations of motion, 162–4  
  experiments, 170–1, 218–23  
  fully developed flow: from rest 192–203; oscillatory, 177–92; steady, 163–76  
  instability of flow, 295  
  curved tube (*cont.*)  
    irrotational flow, 194, 199–200  
  Dean number, 164, 218, 224  
    aorta, 183  
  diastole, 4  
    duration, 39  
  dispersion relation, waves in arteries, 92  
  displacement effect, boundary layer, 138  
  displacement thickness, boundary layer, 141, 152, 388  
  distensibility, 18–20, 73  
    aorta, 20, 24  
    pulmonary artery, 24  
    rubber tubes, 26  
    veins, 24, 26  
  eigenfunctions, boundary layer theory, 147, 382–4  
  elastin, elastic properties, 15–16  
  electrochemical technique, 132, 267, 369, 372, 380, 421  
  elliptical tube  
    secondary flow, 243–4, 250; viscous, 321  
    slowly varying: inviscid flow, 250; viscous flow, 318–24  
  endothelium, 14  
  energy dissipation  
    branched tubes, 246, 248  
    collapsed tube, 337  
    separated jet, 306  
  energy equation, branched tubes, 246  
  energy flux, pulse wave, 106, 109  
  energy loss, constriction, 345–7  
  entry flow  
    aorta, 44–5, 60  
    curved tube: quasi-steady, 206; unsteady, 204  
    elastic tube, 136  
    straight tube: reversing, 149–59; steady, 137–9; unsteady, 139–59  
  entry length  
    curved tube, 212, 219  
    mean flow, 158  
    oscillatory flow, 158  
    steady flow, 138

- expiration, forced, 302, 350
- Falkner–Skan boundary layer, 298
- flow-rate  
   arteries, 99–100  
   *see also* velocity
- flow-rate ratio, bifurcation, 260
- flutter, 293–4
- Fourier transform, 226, 273, 405, 419  
   double, 282
- frequency content  
   Korotkoff sounds, 56  
   pressure waveform, 42  
   velocity waveform, 42, 128  
   wall shear waveform, 128
- frequency parameter, 49, 91–2, 100,  
   127, 177, 249  
   aorta, 296  
   arteries, 11  
   veins, 11
- frequency response, hot-film, 133, 380
- heart  
   anatomy, 1, 3–5  
   muscle, 5–8  
   valves, 3; *see also* valve, aortic; valve,  
   mitral
- heart-rate  
   dog, 20  
   man, 20
- heat transfer, hot-film, 375  
   edge effects, 402, 422  
   experiment, 421  
   oscillatory flow, 383  
   phase lead, 397–403  
   quasi-steady, 379, 381  
   reversing flow, 390–403  
   short, 411–2, 415–6, 421  
   steady, 376
- Hill's muscle equation, 5
- hot-film, 38–9  
   departures from boundary layer  
   theory, 404–18  
   frequency response, 133, 380  
   heat transfer, *see* heat transfer, hot-  
   film  
   thermal wake, 377, 415  
   *see also* anemometer, hot-film
- hydraulic jump, 77
- impedance, input, aorta, 63, 112–3  
   *see also* admittance
- inertance  
   collapsed tube, 348  
   rigid tube, 344
- inertia  
   effect on collapsible tubes, 329–31  
   effect on lubrication theory, 321–5  
   left ventricle, 64–71  
   thermal, 402  
   tube wall, 343
- inflection point, instability, 293, 296–  
   300
- instability  
   aortic flow, 48–51, 291–300  
   collapsible tubes, 354–9, 367  
   exponential, 356  
   mechanism: curvature, 294–6; elastic,  
   293; inflection point, 293, 296–  
   300; quasi-steady, 296; unsteady,  
   295  
   oscillatory, 357–9
- irrotational flow  
   curved tube, 194, 199–200  
   left ventricle, 68–71
- Korotkoff sounds, 55–7, 303  
   mechanisms, 308–16
- Lévêque,  
   thermal boundary layer, 376, 411,  
   421
- lubrication theory  
   curved tube, 165  
   elliptical tube, 317–24
- microcirculation, 2  
   physical properties, 11
- Moens–Korteweg wave-speed, 74, 91,  
   93
- momentum equation  
   left ventricle, 64  
   separated jet, 346  
   shock wave, 82
- momentum integral method, 173, 212
- network,  
   of branched tubes, 112, 245

- non-linear effects, pulse wave, 76–7, 79–87, 115, 122
- non-uniqueness of mean flow in curved tube, 189
- oscillations  
coronary artery, 41–2, 124  
self-excited: collapsible tubes, 307, 310–5, 338, 359–62; lumped-parameter model, 340–63; mechanisms, 335–40
- Oseen approximation, 418  
modified, 153–5, 216
- Péclet number, 132, 375, 403–4, 417  
small, 418
- pericardium, 3
- pistol shot  
arterial, 77  
venous, 123–4
- Pohlhausen momentum integral method, 173, 212
- Poiseuille flow  
distortion by bend, 224  
distortion by bifurcation, 252–60  
effect of side-branch, 269–91
- Poisson's ratio, 17, 19  
complex, 88
- post-stenotic dilation, 50
- Prandtl number, 396
- pressure  
alveolar, 32  
aorta, 34, 66  
blood, *see* blood pressure  
left ventricle, 34, 64, 66  
pulmonary artery, 34  
pulse, 66  
right ventricle, 34  
tissue, 32  
transmural, *see* transmural pressure
- pressure–area curve  
arteries, 19  
collapsible tubes, 351; model equation, 326, 342, 351  
rubber tubes, 27  
veins, 27, 327
- pressure drop  
airways, 248  
branched tubes, 245–9
- pressure–flow relation  
collapsible tubes, 304–8; theoretical, 332–3, 352–4  
curved tube, 165, 171  
mean, in pulsatile flow, 188  
veins, 303
- pressure gradient  
induced by bend, 226  
induced by bifurcation, 257  
induced by side-branch, 271  
waveform, 127–30
- pressure waveform  
aorta, 35  
arteries, 36, 40  
pulmonary artery, 36, 38  
pulmonary vein, 38  
tapered tube, 103  
veins, 35–7
- pulmonary circulation, 114, 302
- pulse wave  
attenuation 92, 94, 105; arteries, 77–9; veins, 79  
coronary artery, 124, 128–30  
energy flux, 106, 109  
non-linear effects, 76–7, 79–87, 115, 122  
peaking, 34–6, 109, 122  
reflections, 106–14  
steepening, 34–6, 122  
veins, 35–7  
viscous effects, 78–9, 90–5, 119  
wavelength, 111
- Rayleigh layer, 150–1  
curved tube, 194–7
- reflection  
at bifurcation, 107  
closed-end, 108, 113  
open-end, 108  
pulse-wave, 106–14
- reflection coefficient, 109
- resistance,  
collapsed tube, 347, 367  
negative, 356–9  
peripheral, 118, 121  
rigid tube, 344  
slowly varying tube, 317
- resonance, 111

- Reynolds number  
 blood vessels, 11  
 steady-streaming, 177, 180
- Riemann, one-dimensional wave theory, 73, 80–1, 117  
 80–1, 117
- roll-wave instability, 366–7
- Routh's criterion, 355–6
- rubber tubes  
 collapse, 27–8  
 elastic properties, 26–7  
 non-linear waves, 83
- secondary flow  
 bifurcation, 236–45, 253, 258–9;  
 asymmetric, 261  
 curved tube, 160, 178, 219–23;  
 development, 194–7, 205; pulsatile  
 flow, 185–91; steady, 166, 169  
 elliptical tube, 243–4, 250; viscous,  
 321  
 reversed, 175
- separation  
 bifurcation, 238; asymmetric, 261–3  
 collapsing tube, 337–8  
 energy loss, 345  
 intermittent, 309, 345, 368  
 upstream, 259, 274, 337
- shock wave  
 arteries, 77, 123  
 collapsible tube, 365  
 elastic tube, 79–87  
 energy loss, 84  
 formation, 80  
 intermittent, 309  
 jump conditions, 81–3  
 structure, 86
- similarity solution, pressure-area curve,  
 collapsible tube, 342
- sinus of Valsalva, 3, 61
- smooth muscle  
 arteries, 22  
 elastic properties, 16–17
- Starling resistor, 307
- statics, artery wall, 89–90
- steady streaming  
 boundary layer, 181  
 in oscillatory flow, 178, 180–3  
 in pulsatile flow, 185–91
- steady streaming (*cont.*)  
 Reynolds number, 177, 180; aorta,  
 183
- stenosis, 50  
 turbulence, 56
- Stokes approximation, 418  
 breakdown, 281
- Stokes flow, 180  
 side-branch, 276–81
- Stokes layer, 92, 143, 146, 387  
 curved tube, 179
- Strouhal number, 396, 400–1
- systole, 4  
 duration, 39, 62
- taper  
 aorta, 9–12  
 arteries, 9–12  
 gradual, 102–4
- Taylor–Görtler vortices, 294
- tension, longitudinal, collapsible tubes,  
 339
- tethering, arteries, 21, 89, 95–8
- thrombosis,  
 deep-vein, 302
- transmission coefficient, 109
- transmural pressure, 17, 31–3  
 pulmonary arteries, 22  
 systemic arteries, 18, 22
- turbulence  
 aorta, 48–51, 291–2  
 constriction, 309, 314; intermittent,  
 337–8, 345  
 stenosis, 56
- upstream interaction  
 bend, 228–9  
 side-branch, 272
- Valsalva,  
 sinus of, 3, 61
- valve  
 aortic, 3, 4, 33, 39; incompetence, 76;  
 mechanics, 60–2  
 mitral, 3, 4; mechanics, 57–9  
 pulmonary, 3  
 venous, 25, 35  
 vortices, 57–62
- vasa vasorum*, 15

- veins  
 anatomy, 25  
 collapse, 26–7, 301  
 distensibility, 24, 26  
 elastic properties, 25–9  
 geometry, 1  
 grafts, velocity profile, 263  
 intermittent compression, 302  
 pressure waveform, 35–7  
 pulmonary, 29; pressure waveform, 38; velocity waveform, 38, 41–3  
 pulse wave, 35–7  
 valves, 25, 35  
 wave speed, 11, 79
- velocity  
 aorta, 34  
 measurement, 36–9, 131–6; *see also* anemometer  
 pulmonary artery, 34, 43  
 right ventricle, 43
- velocity profile  
 aorta, 42–6, 60  
 arteries, 42–8  
 coronary arteries, 47  
 curved tube, 218–23  
 right-angled bifurcation, 262–6  
 secondary, symmetric bifurcation 241–3  
 skewed, 44–6  
 symmetric bifurcation, 239–45
- velocity waveform, 127–30  
 aorta, 39–40, 137; idealised, 194  
 arteries, 36, 40–1, 101  
 pulmonary artery, 38–9, 41–3  
 pulmonary vein, 38, 41–3  
 tapered tube, 103
- vena cava, 1  
 mechanical properties, 11
- venous return, effect of intrathoracic pressure, 302
- ventricle  
 left, 1, 4; ejection, 4, 62–71; inertia, 64–71; pressure, 34, 64; velocity, 34; volume, 5, 66; wall structure, 8  
 right, 1, 4, 5; pressure, 34; velocity, 34
- venule, 1  
 mechanical properties, 11
- viscoelasticity  
 aorta, 99
- viscoelasticity (*cont.*)  
 arteries, 17, 20–1, 79, 84, 105, 116, 120  
 tube wall, 343
- WKB method, 102–3
- wake  
 of side-branch, 276, 286–91  
 thermal, hot-film, 377, 415
- wall shear  
 and atherosclerosis, 51–5  
 aorta, 215–7, 267; entrance, 156–8  
 arteries, 53–5, 99–100, 267–8  
 branched tube, 263, 266–7; unsteady, 267–8  
 coronary artery, 128–30  
 curved tube: development, 197, 202; entry flow, 215; oscillatory flow, 183; steady, 167, 172; unsteady, 195; unsteady entry flow, 210–1  
 effect of wall irregularities, 268  
 estimation from pressure gradient, 135  
 estimation from velocity, 135  
 hot-film, 372–3; reversing flow, 388–90  
 impulsively started flat plate, 155  
 in a bend, 230  
 measurement, 55, 131–6, 263; hot-film, 372  
 perturbation induced by side-branch, 280, 285–91  
 reversal, 156–8, 198, 388–90  
 right-angled bifurcation, 274–5  
 straight tube: oscillatory, 148; quasi-steady, 141–2  
 symmetric bifurcation, 241  
 upstream of bend, 229  
 waveform, 127–30
- wave  
 axial, 94, 98  
 pressure, elastic tube, 72 *et seq.*  
*see also* pulse wave
- wave speed  
 arteries, 11, 74–7  
 collapsible tube, 364  
 elastic tube, 73  
 Moens–Korteweg, 74, 91, 93  
 pulmonary artery, 114  
 veins, 11, 79

Cambridge University Press

978-0-521-08956-2 - The Fluid Mechanics of Large Blood Vessels

T. J. Pedley

Index

[More information](#)

446

## INDEX

Wiener–Hopf technique, 405–8, 413

Womersley parameter, *see* frequency  
parameterWomersley pulse-wave theory, 87–95,  
119, 127

work, of heart, 67

Young's modulus

aorta, 20

arteries, 11

complex, 88

veins, 11