Index

absolute transverse displacement, 21
absolute longitudinal displacement, 40
absolute tip velocity, 38, 102
acceleration measurement, 36, 98
accelerometer, 36, 98
AC-DC converter, 3, 325
admissible functions, 152
admissible trial functions, 157, 172, 185
aerodynamic control points, 286–9
aerodynamic damping, 291–2, 294
aerodynamic influence matrix, 290
aerodynamic lift, 275, 277, 284, 286, 288–9
aerodynamic loads, 274–5, 283, 288
aerodynamic mesh, 287
aerodynamic pressure distribution, 289
aeroelastic vibration, 273
aging, 323
air damping, 19–20, 23, 26, 28
air damping coefficient, 21, 23, 27, 52
airflow excitation, 290
airflow speed, 273, 289
airfoil, 273–4, 276–8, 282, 298
amplitude correction factor, 31–2, 34–5, 37, 42–3
analytical solution, 49
anisotropy, 323
anti-resonance frequency, 82
approximate analytical solution, 151
argument, see phase
asymmetric laminates, 13, 151–2, 155, 186, 194
asymptotes, 134
attractor, 243
autocorrelation function, 205–6
average power, 260–1, 265, 267, 328–9, 337, 339
axial displacement, 53, 153, 165, 194
axial stiffness, 40
backward coupling, 51, 54, 234
backward modal coupling, 66
band-pass filter, 92
base acceleration, 38, 45, 202
base displacement, 21
base excitation, 7, 19, 39, 64, 81, 114, 145, 157, 160, 168, 192, 199, 202, 247, 269, 290, 294, 317
base motion, 7, 51–2, 153
base rotation, see base motion
base translation, see base motion
bending displacement, see transverse displacement
bending stiffness, 20, 54
bending strength, 323
bending vibration, see transverse vibration
Bessel functions, 276
bias voltage, 332
bifurcation, 8, 247, 265, 267, 282
bifurcation diagrams, 265
bifurcations, subcritical, 282, 298

© 2011 John Wiley & Sons, Ltd. Published 2011 by John Wiley & Sons, Ltd.

385
bifurcations, supercritical, 282
bilinear stiffness, 280, 298
bimorph, 3, 36, 49, 97, 101, 144
bistable, 8, 233, 246–7
bistable beam, 247
bistable Duffing oscillator, 8, 247
bistable plate, 262
blower tunnel, 278
bookkeeping parameter, 234
boundary conditions, 22, 353, 361, 379
boundary value problem, 353, 361
bridge, see slender bridge
broadband, 92, 245, 258, 265
buck-boost converter, 333–5, 340
butterfly catastrophe, 247
cantilevered bar, 19, 40
cantilevered beams, 19–20, 49, 97, 151, 199
cantilever energy harvesters, 7
cantilevered plate, 286–7, 289, 291
capacitance, 44, 59, 67
capitive, 93
carbon-fiber-epoxy, 233, 262
Cartesian tensors, 10
centre, 274
chaos, see chaotic response
chaotic response, 247–9, 254–5, 265–6, 268
cubic nonlinearity, 239, 242, 246–7, 267
cubic stiffness, see cubic nonlinearity
current FRF, 76, 108, 117, 125
current output, 76, 109
current source, 57–8, 148
curvature eigenfunction, 58, 367
coupler curve, 222
coupling coefficient (coupling factor), 45, 329
coupling parameter, 233
coupled dynamical systems, 52, 200
damped natural frequency, 24, 41
damping, 19–21, 40
damping evolution, 290, 293
damping identification, 104, 138–9, 144
damping ratio, 23, 41, 60, 104
data acquisition, 98
DC-DC converter, 3, 325, 331–3
deterministic process, 204
detuning parameter, 235, 241–2
diode, 327, 332, 335, 340–1
Dirac delta function, 34, 52, 55, 200, 205–6, 208
direct piezoelectric effect, 9–10
discontinuous conduction mode (DCM), 332–5, 340
displacement eigenfunction, see
eigenfunction
displacement field, 153, 168
displacement influence functions, 21, 349–51
displacement transmissibility functions, 29–32, 35, 37, 42, 296
distributed-parameter model, 19, 49, 151, 273
domain of attraction, 245
double synchronous switch harvesting (DSSH), 340
dimensionless electromechanical coupling, 134
dimensionless forms, 133
dimensionless representation, 132
dimensionless resistance, 134
dimensionless resonance frequency, 136–7
diode, 327, 332, 335, 340–1
Dirac delta function, 34, 52, 55, 200, 205–6, 208
direct piezoelectric effect, 9–10
discontinuous conduction mode (DCM), 332–5, 340
displacement eigenfunction, see
eigenfunction
displacement field, 153, 168
displacement influence functions, 21, 349–51
displacement transmissibility functions, 29–32, 35, 37, 42, 296
distributed-parameter model, 19, 49, 151, 273
domain of attraction, 245
double synchronous switch harvesting (DSSH), 340
Index

doublet singularity, 289
doublet-lattice method (DLM), 9, 273, 286, 288, 291, 293
downwash, 289
Duffing equation, 233, 247
Duffing oscillator, 8, 233, 239, 247, 269
Duhamel integral, 24, 360, 366
duty cycle, 332–3, 335, 340
effective input resistance, 335
eigenfunction, 33, 41, 55, 356, 363
eigenvalue, 22, 41, 56, 356, 362
eigenvector, piezoaeroelastic, 277
elastic compliance, 11, 302, 307
elastic modulus, 20, 53, 153, 375
electric displacement, 10, 57, 156, 215, 343
electric displacement tensor, 10, 343
electric enthalpy density, 11
electric field tensor, 10, 343
electrically induced viscous damping, 82
electroactive polymer (EAP), 2
electrode area, 57, 216
electrodes, 51, 57
electromagnetic shaker, 98
electromagnetic transduction, 2
electromechanical coupling, 60–1, 63, 67, 201, 214, 234, 248, 274
electromechanical energy formulation, 153, 166, 168
electromechanical equations, 67
electromechanical FRF, 69
electromechanical Lagrange equations, 159, 163, 167–8, 174, 178, 381
electrostatic transduction, 2
enhanced synchronous switch harvesting (ESSH), 341
epoxy, 5–6, 50, 192
essential boundary conditions, 186, 379
etching, 368
Euler-Bernoulli model, 31, 49, 152, 181, 183
Euler’s formula, 240
expected value, 206–7
experimental identification, 141
experimental validation, see model validation
feedback, 51, 56, 59, 81
finite-element, 7, 9, 13, 47, 90, 273, 285–8, 290–1, 297, 341
finite-element mesh, 287
finite-element nodes, 288
first law of thermodynamics, 10
first-order equations, 249–50, 288, see also state-space
fixed reference frame, 20
flutter, 273, 282, 285, 296
flutter boundary, 9, 276, 278, 280, 291–2
flutter frequency, 279, 296–7
flutter speed, 9, 14, 277–82, 291–6
focus, 250–1, 254, 260
forced vibrations, 21, 359, 365
forward coupling, 51, 58, 234
forward modal coupling, 66
four-bar mechanism, 222
Fourier coefficients, 202, 224
Fourier frequencies, 224
Fourier series expansion, 199, 202–4, 223, 226
free play, 280
free-stream air mass density, 277, 289, 291
free-stream velocity, see airflow speed
frequency evolution, 280, 290, 293
frequency parameter, see eigenvalue
frequency response analyzer, 98–9
frequency response function (FRF), 12–13, 35, 37–9, 44, 46, 69, 97, 131, 165, 181, 188–91, 193, 199
fundamental natural frequency, 27
Galerkin solution, 269
Gauss’s law, integral form, 49, 57, 213, 216
Index

geometric boundary conditions, 41, see also essential boundary conditions
geometric nonlinearity, 8, 90, 130, 239, 269, 280
Gaussian white noise, 205, 232
Hamilton’s principle, 151, 157, 159, 171, 174, 274, 283, 381
Hamilton’s principle, piezoaeroelastic, 274
Hamilton’s principle, piezoelectric, 157
Hankel functions, 276
hard ceramics, 301, 310–11, 316, 322
hard crystals, 301, 310–11
hardening stiffness, 8, 233, 239, 242–3
harmonic base displacement, 27, 61–2, 67, 163, 168, 178
harmonic base excitation, 25–6
Heaviside function, 53
high-energy orbits (or attractor), 243, 250–2, 256–8
homogeneous solution, 210
Hooke’s law, 153, 376
human walking, 203
ideal voltage inversion, 339
identification of mechanical damping, 104, 138, 144, 318
IEEE standard, 10, 343
impedance matching, 331, 334
permittivity constants, 11
incompressible, 273, 286
inductive, 93
inductor, 92, 335
inflection points, 58, 367
influence coefficients, 286
inherent capacitance, see internal capacitance
initial conditions, 24, 210, 219, 221, 244–5, 249–50, 265, 268–9, 291, 357, 363
integrating factor, 214
internal bending moment, 52
internal capacitance, 59
internal damping, 21
internal electrical energy, 157–8, 166, 275, 284, 381
inversion quality factor, 337
Joule heating, 81–2
kapton, 5–6, 50, 192
Kelvin-Voigt damping, see strain-rate damping
kernel function, 289
kinematic analysis, 222
kinetic energy, 154–5, 166, 170–1
Kirchhoff plate, 214, 346, 374, 376
Kirchhoff’s laws, 59
Kronecker delta, 11, 23, 56, 358
Kutta condition, 287
Lagrangian equations, 151, 383
Lagrangian equations for Euler-Bernoulli model, 163
Lagrangian equations for Rayleigh model, 167
Lagrangian equations for Timoshenko model, 178
Laplace equation, 286
laser vibrometer, 98, 102
LC filter, 335
lead-free piezoelectric materials, 323
leakage resistance, 44, 51
limit cycle, see limit-cycle oscillation (LCO)
limit-cycle oscillation (LCO), 250–1, 260, 265, 267, 282
Lindstedt-Poincaré method, 234, 241
load resistance, 44, 102, 105
longitudinal vibration, 39, 42–3, 361
loss factor, 277
low-energy orbits (or attractor), 243, 251, 260–1
lumped-parameter, 26, 31, 39, 43–4, 234, 236, 239, 247, 250, 256, 269, 273, 278, 284–5, 325–6, 334
lumped-vortex method, 298
macro-fiber composite (MFC), 215, 298
magnetostriction, 2
magnitude, 132–3
mass moment of inertia, 93, 112
mass normalization, longitudinal vibrations, 364
mass normalization, transverse vibrations, 358
mass per length, 20, 40, 52, 55, 186, 200, 208
mass-normalized eigenfunction, 22, 41, 201, 209, 358, 365
material nonlinearity, 280
material properties, 72, 99, 223
maximum current output, 108, 121
maximum power output, 108, 121
maximum power transfer, 332
maximum voltage output, 108, 121
mean square value, 206
mechanical damping ratio, 44, 104, 124, 310, 312, 320–2
mechanical quality factor, 302, 310–12, 318
mesh transformation, 288
modal amplitude constant, 33, 56, 356
modal analysis, 40, 51, 56, 193, 200, 350, 353
modal coordinates, 49, 52, 60, 200–1, 209, 219, 285, 287, 290, 357
modal damping, 24, 55, 73, 103, 131, 137–9, 149, 201, 331
modal electromechanical coupling, see electromechanical coupling
modal excitation, 68
modal forcing function, 24, 41, 60
mode coupling in flutter, 285, 296
mode shape, 357, 363, 368, see also eigenfunction
model validation, 97, 103, 113, 124, 187, 191, 278
modulation equations, 238
modulus, see magnitude
Mohr’s circle, 217
monostable, 8, 233, 239, 261, 267, 269
monostable Duffing oscillator, 8, 233, 239, 269
moving loads, 199, 208, 213
multifunctionality, 4
multi-mode, 69
multi-mode electromechanical FRF, 70, 125
multi-mode vibration FRF, 70
multi-mode voltage FRF, 70
multimorph, 91
multiple cantilevers, 91
multiple scales, 234
multi-segment, 195
multivalued response, see coexisting response
natural boundary conditions, 22, 41
natural frequency, 23, 41, 56, 357, 363
non-conservative, 157, 166, 274–5, 381
non-deterministic process, see random process
non-harmonic excitation, 199
non-ideal voltage inversion, 339
nonlinear circuits, 325
nonlinear dissipation, 128, 269–70
nonlinear effects, 128–9, 269–70
nonlinear stiffness, 242–3, 245, 280
nonlinearities, mechanical, 239
normalization (of eigenfunctions), 23, 33, 41, 56, 358, 364
normal-mode system, 33, 52, 162, 177
numerical solution, 218, 239, 241–4
Nyquist plot, 24, 144
off-resonance frequency, 78
off-resonant excitation, 314
one-stage interface, see AC-DC converter
open circuit, 73, 131
open-circuit asymptotes, 134–5
open-circuit natural frequency, 166
open-circuit resonance frequency, 75, 106–7, 110, 116, 137
optimal control, 231
optimization, 131
optimum electrical load, 80, 86, 107–8, 118, 121, 139–43, 147, 217
orthogonality (of eigenfunctions), 357, 359, 361, 363
panels, 286–7, 289
parallel axis theorem, 56, 94, 112, 354
parallel connection, 50–1, 54, 64, 71, 83, 254, 263, 305
parameter identification, 131
parametric excitation, 269
particular solution, 210
patch, see piezoceramic patch
patterned polarization, 368
periodic attractor, large amplitude, 249–50, 255
periodic excitation, 202, 222
periodic function, 202
periodic power output, 204
permittivity constants, 11, 302, 308
perturbation solution, 234, 236, 239, 242
phase, 133
phase portrait, 248–9, 251, 254–6
phase space, 250, 256–7
phase trajectory, electromechanical, 250–2, 256–8, 261
piezoeaeroelastic, 9, 273, 280, 282, 285
piezoeaeroelastic Lagrange equations, 275, 285
piezoeaeroelastic eigenvalue problem, 276, 290
piezoceramic patch, 208, 212–17, 226
piezoelectric configuration, 250, 254, 256
piezoelectric nonlinearities, 8, 128–9, 269–70
piezoelectric constants, 11
piezoelectric constitutive equations, 10–11, 53, 57, 154, 169, 215–16, 254, 343
piezoelectric effect, 9
piezoelectric transduction, 1
piezoelectric strain constant, 53
piezoelectric stress constant, 53
piezoelectricity, 9
piezomagnetoelastic, 233, 247, 253, 256
pipe flutter, 298
pitch displacement, 274, 280–1
pitching moment, 275, 284
p-\(k\) scheme, 290
plane -stress properties, 304
plane-stress conditions, Euler-Bernoulli beam and Rayleigh beam, 344
plane-stress conditions, Timoshenko beam, 345
plane-stress conditions, Kirchhoff plate, 346
plane-stress elastic modulus, 304
plane-stress permittivity constant, 305
plane-stress piezoelectric constant, 304
plunge displacement, 273, 280–1
PMN-PT, 301–5
PMN-PZT, 301–5, 311, 314
PMN-PZT-Mn, 301, 311, 314
Poincaré map, 248, 254–5
point mass assumption, 93, 119
Poisson’s ratio, 169, 376
poling axis, 343
poling direction, 53
polyvinylidene fluoride (PVDF), 3
Poisson effect, 54, 347, 377
potential energy, 153, 155, 166, 169–71
potential flow, 273, 286
power density, 2, 109, 121
power FRF, 44, 46, 78–9, 108, 117, 125, 291
power spectral density (PSD), 205–8
power switch, 335
predictor-corrector, 288
primary resonance, 239
principal strains, 215, 218
probe, 102
proof mass, see tip mass
proportional damping, 24
PZT, 10
PZT-5A, 10, 72, 126–7, 129, 254, 263, 278, 291, 301, 373
PZT-5H, 10, 144, 187–9, 223, 269, 301, 373
PZT-8, 301, 310, 314
radius of gyration, 277
random process, 205
Raven’s method, 222
Rayleigh damping, 21, 73, 162, 177
Rayleigh model, 151, 166, 168, 181, 183–4, 344
Rayleigh-Ritz method, 7, 90, 152, 182, 196
Rayleigh’s quotient, 26
RC network, 335
rectification, 327
rectifier, 325, 327
reduced constitutive equations, 344–6
reduced elastic constant, 347
reduced frequency, 276, 290
reduced permittivity constant, 347
reduced piezoelectric constant, 347
relative displacement, 28, 44
relative displacement transmissibility, 29, 37
relative motion transmissibility, 30–2, 42
relative transverse displacement, 21
relative longitudinal displacement, 40
resistive, 93
resistive impedance matching, 333–4
resistive load, 3, 44, 51
resonance, 4
resonance frequency, see short-circuit resonance frequency and open circuit resonance frequency
resonant excitation, 314
rigid body motion, 222
rigid body translation, 101
rotary inertia, 119–20, 166, 171
saddle, 248
safety factor, 81
saturation of power output, 331
segmented electrodes, 285, 368
self-charging structures, 4–6, 191–2
separation of variables, 354, 361
series connection, 50–1, 54, 59, 67, 71, 73, 99, 122, 192, 223, 312, 317
shaker dynamics, 102
shear correction factor, 169, 346, 376
shear modulus, 169, 376
shear stress, 169, 345–6, 376
short circuit, 35, 38, 51, 54, 56, 73, 131
short-circuit asymptotes, 134–5
short-circuit natural frequency, 56, 165, 329
short-circuit resonance frequency, 75, 103, 106–7, 110, 116, 137
shunt damping, 35, 82, 97, 224, 246, 280, 292, 296
signum function, 133
single crystal, 301–2, 310, 322–3
single-degree-of-freedom, 6–7
single-mode, 69
single-mode electromechanical equations, 68–9
single-mode vibration FRF, 71, 127
single-mode voltage FRF, 71, 126
sink, 248
slender bridge, 208
smoothing capacitor, 326
soft ceramics, 301, 310–11
soft crystals, 301, 314–15
softening stiffness, 233, 239, 242, 247, 270
solar panels, 4, 6
span, 274, 284, 286, 289, 291
spatial discretization, 157, 167, 171
specific power, 109–10, 121
spectral density, 206
SPICE, 332–4, 338, 341
stability, 240, 250
standard interface, see AC-DC converter
state-space, 199, 219, 221, 231, 241
stationary random process, 205
steady-state power, 45, 217
steady-state response, 25, 44, 360, 366
steady-state voltage, 45, 217
step-down converter, 332
storage device voltage, 332
stochastic excitation, 231
stochastic process, see random process
stochastic resonance, 8, 269
strain components, 215, 218, 228, 230, 343
strain fluctuations, 215, 226
strain gage, 217
strain gage measurement, 217–18
strain gage rosette, 217–18
strain mode shape, 368
strain nodes, 58–9, 128, 367, 369, 371
strain resultant, 218
strain tensor, 10, 343
strain transformation, 217
strain field, Euler-Bernoulli model, 53, 153
strain field, Rayleigh model, 153
strain field, Timoshenko model, 168
strain-rate damping, 21, 23, 52
strange attractor, 247–9, 254–5
stress tensor, 10, 343
strongly coupled system, 137, 150, 331, 339
strongly nonlinear system, 233, 248
<table>
<thead>
<tr>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>structural damping, 27, 274–5</td>
</tr>
<tr>
<td>subharmonic, 265–6</td>
</tr>
<tr>
<td>superharmonic, 265</td>
</tr>
<tr>
<td>support motion, 349</td>
</tr>
<tr>
<td>switching period, 335</td>
</tr>
<tr>
<td>symmetric laminates, analytical solution, 49</td>
</tr>
<tr>
<td>symmetric laminates, assumed-modes solution, 181</td>
</tr>
<tr>
<td>synchronous switch damping, 336</td>
</tr>
<tr>
<td>synchronous switch harvesting on inductor (SSHI), 325, 336, 338–41</td>
</tr>
<tr>
<td>temporary storage capacitor, 332</td>
</tr>
<tr>
<td>Theodorsen function, 276</td>
</tr>
<tr>
<td>Theodorsen model, 284</td>
</tr>
<tr>
<td>thin-film battery, 4–6, 192</td>
</tr>
<tr>
<td>Timoshenko model, 152, 168, 182–4, 186, 345, 373–4, 376, 379</td>
</tr>
<tr>
<td>tip displacement FRF, 81</td>
</tr>
<tr>
<td>tip mass, 19, 23, 27, 32, 34, 39, 41–2, 53, 56, 93, 97, 111, 183, 200, 222, 223, 353, 369</td>
</tr>
<tr>
<td>tip velocity FRF, 104, 108, 117, 125</td>
</tr>
<tr>
<td>total solution, 210</td>
</tr>
<tr>
<td>transducer, 3, 103</td>
</tr>
<tr>
<td>transduction, 1–2, 9</td>
</tr>
<tr>
<td>transformer, 39</td>
</tr>
<tr>
<td>transient excitation, 218</td>
</tr>
<tr>
<td>transverse displacement, 52, 165</td>
</tr>
<tr>
<td>transverse support excitation, 349–50</td>
</tr>
<tr>
<td>transverse vibration, 20, 37, 353</td>
</tr>
<tr>
<td>transversely isotropic, 343</td>
</tr>
<tr>
<td>truncated series, 203</td>
</tr>
<tr>
<td>truncated electromechanical system, 221</td>
</tr>
<tr>
<td>turn ratio, transformer, 334</td>
</tr>
<tr>
<td>two-segment cantilever, 190</td>
</tr>
<tr>
<td>two-stage interface, 331–3, 340</td>
</tr>
<tr>
<td>unimorph, 3, 152</td>
</tr>
<tr>
<td>unmanned aerial vehicle (UAV), 4–5</td>
</tr>
<tr>
<td>unsteady aerodynamics, 285–6, 290, 296</td>
</tr>
<tr>
<td>unsteady Bernoulli equation, 287</td>
</tr>
<tr>
<td>unsteady Euler equations, 288</td>
</tr>
<tr>
<td>unsymmetric laminates, see asymmetric laminates</td>
</tr>
<tr>
<td>Van der Pol oscillator, 9</td>
</tr>
<tr>
<td>varying cross-section, 151, 195</td>
</tr>
<tr>
<td>vehicle speed, 208</td>
</tr>
<tr>
<td>velocity measurement, 102</td>
</tr>
<tr>
<td>virtual work, 157, 166, 275, 283, 382</td>
</tr>
<tr>
<td>viscous air damping, see air damping</td>
</tr>
<tr>
<td>Voigt’s notation, see contracted notation</td>
</tr>
<tr>
<td>voltage asymptotes, 134–5, 141, 146</td>
</tr>
<tr>
<td>voltage FRF, 73, 104, 108, 117, 125</td>
</tr>
<tr>
<td>voltage inversion, 336</td>
</tr>
<tr>
<td>voltage measurement, 102</td>
</tr>
<tr>
<td>voltage output, 73</td>
</tr>
<tr>
<td>voltage waveforms, 328, 336</td>
</tr>
<tr>
<td>von Kármán vortex street, 298</td>
</tr>
<tr>
<td>vortex ring, 286–8</td>
</tr>
<tr>
<td>vortex singularity, 286</td>
</tr>
<tr>
<td>vortex-induced oscillations, 298</td>
</tr>
<tr>
<td>vortex-lattice method (VLM), 9, 273, 286, 291, 293</td>
</tr>
<tr>
<td>wake, 286–7</td>
</tr>
<tr>
<td>wave equation, 361</td>
</tr>
<tr>
<td>weakly coupled system, 325, 339</td>
</tr>
<tr>
<td>weakly nonlinear, 246, 248</td>
</tr>
<tr>
<td>white noise excitation, 199, 204–5, 207</td>
</tr>
<tr>
<td>wideband, see broadband</td>
</tr>
<tr>
<td>wing section, 273</td>
</tr>
<tr>
<td>Young’s modulus, 20, 53, see also elastic modulus</td>
</tr>
</tbody>
</table>