

Index

Note: Page numbers followed by “*f*” indicate figures, “*t*” indicate tables, and “*np*” indicate footnotes.

A

Aalborg PID controller, 236
Added mass, 11–12, 18–20, 26
AMAZON-CW solution, for peak pressure, 117, 118^f
AMAZON-SC simulation
 LIMPET WEC model, 109, 110^f
 oscillating wave surge converter, 109, 112^f
ANN model. *See* Artificial neural network (ANN) model
AR model. *See* Autoregressive (AR) model
Array modelling techniques
 boundary element method, 151–152
 CFD model, 152–153
 frequency-domain WEC array models, 152, 156
 fundamental principles, 151–153
 hydrodynamic time domain WEC array model, 152
 internal numerical dissipation, 162
 limitations, 162
 linear potential flow models
 computational effort, 153
 cross-coupling impulse response functions, 157
 cross-coupling radiation coefficient, 154–155
 equations of motions, 154
 frequency components, 155, 155^f
 frequency dependent radiation impedance function, 157
 heaving buoy, array configuration for, 157, 158^f
 hydrodynamic coefficients, frequencies for, 153–154
 modal canonical form, 159

 Prony’s method, 161
 response amplitude operator, 159, 160^f
 multiple degrees-of-freedom, 151
 spectral-domain WEC array model, 152, 156
 time-domain WEC array models, 152, 156–161
Artificial neural network (ANN) model, 131–132
ARX model. *See* Autoregressive with exogenous input (ARX) model
Autoregressive (AR) model, wave forecasting, 239–240, 240^f
Autoregressive with exogenous input (ARX) model, 130–131

B

BEM. *See* Boundary element methods (BEM)
Bernoulli’s equation, 14, 86–87
Beyond linear theory, 83–84
BIEM. *See* Boundary-integral equation method (BIEM)
Black-box model, 131–132, 146
Block-oriented nonlinear (BONL) model, 132–133
BONL model. *See* Block-oriented nonlinear (BONL) model
Boundary element method (BEM), 11–12, 89–90, 151–152
Boundary-integral equation method (BIEM), 11, 18, 89–90
Boundary value problem (BVP), 84

C

Cartesian cut cell method, 109–113, 113^f
CFD models. *See* Computational fluid dynamics (CFD) models

Compressibility effects, 113–114
Compressible two-phase CFD models, 113–115, 114^f, 116^f
Computational fluid dynamics (CFD) models, 3, 83–84, 124, 152–153
 based NWT, 125
 compressible two-phase, 113–115, 114^f, 116^f
 fundamental principles, 105–107
 future developments, 119
 incompressible, 107–113, 114^f
 limitations, 117–118
 smoothed-particle hydrodynamic models, 115–117
Continuous-time (CT) models, 129–130
 identified from free responses, 137–140
Convolution integral, 32–33, 37–39, 53, 55, 60
Coupling methodology
 description, 201
 wave field interaction, 204–205, 204^f
 WEC/WEC farm, 201–204, 203^f
CT models. *See* Continuous-time (CT) models
Cummins equation, 43, 125
 hydrostatic forces in, 54–55
 for modelling WECs, 32–33
 solution of, 55
Cummins method, 32

D

Damping, 11, 26
 PTO, 23–24, 27
Damping coefficient, 11–12, 18–20, 25^f, 26
Decutching control, 243, 246
Degree-of-freedom (DoF), WECs
 multiple, 25–27
 single, 17–25, 17^f

Design load case (DLC), 273–274
 Difference-frequency wave forces, 84
 Diffracted wave field, 211–212
 Diffraction
 code, 12
 potential, 20
 problem, 18
 Diffraction–radiation of harmonic waves, 18
 Direct matrix method, semianalytical methods, 182–184
 Discrete-time models, 130–133
 from forced oscillation, 141–142
 from input waves, 142–145
 Drift forces, 34

E

EKF. *See* Extended Kalman filter (EKF)
 End-stop mechanism, 13
 Environmental impact assessment
 ecological processes
 benthos distribution, 284
 biogeochemical process, 283
 coastal users, 284
 noise, 283–284
 organism transport, 282
 pollution, 282–283
 sediment transport, 281–282
 limitations, 287–288
 modelling approach
 calibration and validation data, 285–286
 considerations, 284–285
 current speeds, 286–287
 water level and bathymetry data, 285
 wind data and boundary wave data, 285
 modelling tools, 287
 Equal energy method, 36
 Equation of motion
 multiple degree-of-freedom WECs, 25–27
 single degree-of-freedom WECs, 17–25, 17f
 Eulerian CFD method, 105–106
 Excitation force, 20, 23
 convolution of, 37–38
 as superposition of harmonic components, 34–37
 wave, 19
 Excitation loads, 11–12, 25–27

Extended Kalman filter (EKF), 233–234, 239–240
 Extra-array effect, 192

F

Fast Fourier transforms (FFTs), 90–91
 Finite difference method, 105–106
 Finite element method (FEM), 90
 Finite volume method, 105–106
 First-order excitation forces, 33
 FNPF models. *See* Fully nonlinear potential flow (FNPF) models
 Forced oscillation, discrete-time models from, 141–142
 Force-to-velocity model, WECs, 232
 Fourier transform, 37
 Free decay experiment, 125, 126f
 Free surface elevation (FSE), 125–126
 Free-surface Green function, 12
 Frequency-domain
 analysis, 11
 approach, 31
 identification, 44, 52–54
 model, 31, 67–68
 limitations, 28–29
 WECs array models, 152, 156
 Froude–Krylov force, 19, 38–39
 nonlinear, 38–39, 241
 Fully nonlinear potential flow (FNPF) models
 beyond linear theory, 83–84
 computation of hydrodynamic body forces and motions, 91–92
 formulation of, 86–88
 fundamental principles, 84–85
 high-order spectral methods, 90–91
 limitations, 99–101
 mixed Eulerian–Lagrangian method, 89–90
 in wave energy, 85–86
 wave–structure interactions, 84

G

Gauss divergence theorem, 105–106
 Gaussian closure, 70, 76, 79–80
 Gaussian process, 67–68, 70
 Gauss–Newton algorithm, 48
 Gauss–Newton method, 53
 Green’s function, 18, 90
 free-surface, 12
 Green’s theorem, 11–12

H

Hammerstein model, 132–133, 133f
 Harmonic component, superposition of, 34–37
 Haskind relation, hydrodynamic force, 20
 High-order spectral (HOS) methods, 90–91
 models, 88–89
 Ho and Kalman realization theory, 51
 Ho–Kalman method, 48
 HOS. *See* High-order spectral (HOS)
 HOS Tank (HOST) model, 91
 Hybrid WEC array model, 219
 Hydraulic PTO, 56–57, 56f
 Hydrodynamic body forces, and motions, 91–92
 Hydrodynamic forces
 Haskind relation, 20
 Kramers–Kronig relations, 20–21
 potential flow boundary value problem, 18–20
 Hydrodynamic interactions, 11
 direct matrix method, 182–184
 multiple scattering method, 179–182
 plane wave method, 176–179
 point absorber method, 173–176
 Hydrodynamic models, 125, 128–130
 Hydrodynamic problem, 11
 Hydrodynamic time domain WEC array model, 152
 Hydrodynamic wave-body interaction problem, 31–32
 Hydrostatic coefficient, 21
 Hydrostatic forces, 12, 21, 54–55
 in Cummins equation, 54–55

I

IMC. *See* Internal model control (IMC)
 Impulse response function
 radiation, 32–33
 numerical computation of, 41–43, 43f
 properties of, 39–41
 of wave excitation force, 38f
 Incompressible CFD models, 107–113, 114f
 Input force experiment, 126–128, 127–128f
 Input waves experiment, 125–126
 Internal model control (IMC), 233–236
 Internal numerical dissipation, 162

Intra-array effect, 192

Inviscid flow, 13

IRF, 37, 39

K

k-means algorithm (KMA), 260

Kochin functions, 222

Kolmogorov–Gabor polynomial (KGP) model, 130–131

Kramers–Kronig relations, 40
hydrodynamic force, 20–21

L

Lagrangian CFD method, 106

Laplace equation, 13–14

Latching control, 243, 246

Levelized cost of energy (LCOE), 253

Levenberg–Marquardt algorithm, 48

LIMPET WEC model, 109

AMAZON-SC simulation

of, 109, 110*f*

Linear approach, 11

Linear frequency-domain model, 83

Linear optimization algorithms,
134–136

model parameters identification,
135–136

time delay and dynamical order
estimation, 135

Linear potential flow theory

array modelling techniques

computational effort, 153

cross-coupling impulse response
functions, 157

cross-coupling radiation

coefficient, 154–155

equations of motions, 154

frequency components, 155, 155*f*

frequency dependent radiation

impedance function, 157

heaving buoy, array configuration
for, 157, 158*f*

hydrodynamic coefficients,

frequencies for, 153–154

modal canonical form, 159

Prony's method, 161

response amplitude operator, 159,
160*f*

Linear PTO, 56

Linear theory, 11*np*, 14, 15*np*, 17–18,
28–29

potential, 12

wave, 39

M

Matlab toolbox, 52

Maximum distance algorithm (MDA),
260–261

Mean annual energy production
(MAEP), 3

abridged power

performance–extensive wave
climate, 264

extensive/abridged

power performance, 264

wave climate, 264

limitations and constraints, 264–265
power matrix

extensive/abridged wave climate,
263

scatter table, 262–263

power performance representation,
261–262

wave climate

abridged representation, 260–261

extensive representation, 258–260

sea-state parameters, 255

traditional (scatter table)

representation, 256–258, 257*f*

WEC modelling techniques,
254, 254*t*

Mixed Euler–Lagrange (MEL) method

FNPF model, 89–90

time-stepping scheme, 88–89

Model predictive control (MPC),

WECs, 233–237, 235*f*

Monochromatic waves, 15*f*

Monotone upstream centred schemes for
conservation law (MUSCL), 115

Mooring/foundation system, 13, 17–18,
21–22

Morison's equation, 68–69

type drag forces, 69

MPC. *See* Model predictive control
(MPC)

Multilayer perceptron (MLP) artificial
neural network, 131–132

Multiple degree-of-freedom WECs,
25–27

Multiple scattering method,
semianalytical methods,
179–182

N

Navier–Stokes equation (NSE), 83–84,
105, 107

Newton's second law, 12–13

Nonlinear autoregressive with
exogenous input (NARX)
models, 130, 130*f*

Nonlinear force, 71, 73–74, 79

Nonlinear Froude–Krylov force,
38–39

Nonlinear hydrodynamics, 84–85,
92–93

problem, 68–69

Nonlinear interactions, 97

Nonlinear optimization algorithms,
136, 137*f*

Nonlinear program (NLP), WEC,
237–238

Nonlinear static (NLS) model, 132

Nonlinear systems, 68–69, 128
complex, 69

Nonlinear wave forces, 38–39

NSE. *See* Navier–Stokes equation (NSE)

Numerical modelling of WECs, 1–2

Numerical wave tank (NWT), 86, 88, 91,
106, 109, 124–125

CFD based, 125

experiment, 138–139*f*

simulation results and linear models'
predictions, 142*f*

O

Ocean waves, 11

ODEs. *See* Ordinary differential
equations (ODEs)

OpenFoam simulation, of oscillating
WECs, 120*f*

OpenFOAM software, 2

Optimization algorithm

linear, 134–136

model parameters identification,
135–136

time delay and dynamical order
estimation, 135

nonlinear, 136, 137*f*

Ordinary differential equations
(ODEs), 33, 70

Oscillating water column (OWC), 12,
27–28, 85, 107

model, 1–2

plants, 27–28, 28*f*

Oscillating wave surge converter, 109
AMAZON-SC simulation of, 109,
112*f*

OpenFoam simulation of, 120*f*

OWC. *See* Oscillating water column
(OWC)

P

Partial differential equations (PDEs), 105

Perturbation theory, 84

Perturbed wave field, 192, 212–213

Phase-averaged wave propagation models, 69

continuity equation, 217–218

fundamental limitations, 223–224

sea-state, 217

third-generation spectral wave models, 218

advantages, 219

natural processes, 218

subgrid model, 219–221

supragrid model, 219, 221–223

Phase-resolving wave propagation models

coupling methodology

description, 201

wave field interaction, 204–205, 204*f*

WEC/WEC farm, 201–204, 203*f*

far-field effect, 192

limitations, 214

MILD wave formulation, 194–195

park effect, 192

perturbed wave field, 192

sponge layer technique, 191, 193, 195–201

absorption characteristics, 199

absorption coefficients, 196–199

frequency dependent absorption, 199–201

limitations, 195

in MILD wave, 196

overtopping principle, 196

wave generation circle, 195

Physical modelling of WECs, 106

PIP control. *See* Proportional-integral-plus (PIP) control

Plane wave method, semianalytical methods, 176–179

Point absorber

approximation, 173

method, semianalytical methods, 173–176

Potential flow theory, 13

boundary conditions, 14–15

Laplace equation, 13–14

limitation of, 99

problem decomposition, 16–17, 17*f*

sinusoidal waves, 15–16

Power absorption, WECs, 22–25

absorption bandwidth, 25

constrained motion, 24

mean power absorption, 22–23

optimal PTO control, 23–24

suboptimal PTO control, 24

Power capture, 22–24, 27

Power take-off (PTO), 232

component, 231, 231*f*

configurations, 31

control of WECs, 230–231

damping, 23–24, 27

equipment, 13

force, 21, 125

lower-loop control strategies, 233

optimal force, 238–239

Prony identification method, 45–46

Proportional-integral-plus (PIP) control, 233

Pseudo-spectral approach, WEC control, 238

PTO. *See* Power take-off (PTO)

Q

Quasi arbitrary Lagrangian–Eulerian finite element method (QALE-FEM), 90

R

Radial basis functions (RBFs) method, 263

Radiated wave field, 210, 211*f*

Radiation force, 13, 19–20, 39–40

convolution of, 43–54

design and verification of

time-domain models, 57–60

direct numerical integration, 44–45

frequency-domain identification, 52–54

Prony identification method, 45–46

time-domain identification, 46–52

Radiation impulse response function (RIRF), 32–33

numerical computation of, 41–43, 43*f*

properties of, 39–41

Radiation transfer function (RTF), 39

RAO. *See* Response amplitude operator (RAO)

Reaction forces, 21–22

Realization theory, 44, 51, 52*f*

Response amplitude operator (RAO), 24, 97, 243

Riemann-based approach, 108–109

RIRF. *See* Radiation impulse response function (RIRF)

RTF. *See* Radiation transfer function (RTF)

S

Semianalytical array methods

direct matrix method, 182–184

limitations and capabilities

comparison, 184–186, 185*t*

considerations, 186

restrictions, 186

verification and validation, 187–188, 187–188*f*

mathematical model

Cartesian coordinate system, 166–167

time-dependent velocity potential, 167–168

multiple scattering method, 179–182

partial wave operators

coordinate transformation operator, 171–172

diffraction transfer operator, 172–173

plane wave method, 176–179

point absorber method, 173–176

assumptions, 173–176

background, 173

velocity potential

ambient incident wave potential, 168–169

governing equations, 168

radiation potential, 171

scattered potential, 169–171

Simple but effective (SE) controller, WEC, 233–236, 235*f*

Simulation duration, influence of, 60–62

Single-body heaving WECs

hydraulic PTO, 56–57

linear PTO, 56

Single degree-of-freedom WECs, 17–25, 17*f*, 72*f*

complex amplitude of body motion, 22

hydrodynamic force, 18–21

hydrostatic force, 21

power absorption, 22–25

reaction forces, 21–22

Singular value decomposition (SVD), 49–50

Sinusoidal waves, 15–16

- Slack-moored devices, 34
- Slow-drift forces, 33
- Smoothed-particle hydrodynamic (SPH) models, 106, 115–117
- Spectral-domain model
- examples of, 74–76
 - formulation of, 70–72
 - fundamental principles, 67–69
 - limitations, 79–80
 - power capture and loss for, 75*f*
 - solving, 73–74
 - spectral variance density for, 78*f*
 - structure of, 70*f*
- Spectral-domain WEC array model, 152, 156
- Spectral wave models. *See* Phase-averaged wave propagation models
- SPH models. *See* Smoothed-particle hydrodynamic (SPH) models
- Sponge layer technique, 191, 193, 195–201
- absorption characteristics, 199
 - absorption coefficients, 196–199
 - frequency dependent absorption, 199–201
 - limitations, 195
 - in MILDwave, 196
 - overtopping principle, 196
- State-space model, 44
- Structural loads and design
- design criteria
 - characteristic loads, 273
 - design load cases, 273–274
 - limit state, 272–273
 - load factors, 274
 - resistance factors, 275
 - design methods
 - load processes, 268
 - partial safety factor method, 268
 - probability-based design, 268–269
 - by testing, 268
 - numerical modelling
 - computational fluid dynamics methods, 272
 - coupled *vs.* uncoupled, 271–272
 - frequency *vs.* time domain, 271
 - semiempirical and potential flow methods, 272
 - physical modelling, 272
 - safety philosophy and classes, 269
 - site conditions characterization
 - current and water level, 270–271
 - waves, 269–270
 - wind, 271
- structural assessment
- extreme event analysis, 275
 - fatigue analysis, 275–276
 - technology qualification, 267–268
- Subgrid models of WEC arrays, 219–221
- components, 221
 - considerations, 221
 - definition, 221–222
 - Kochin functions, 222
 - pitching cylinder, diffraction and radiation, 222–223
- Supragrid models of WEC arrays, 219–221
- Surface capturing method, 109
- System identification
- algorithms, 133–134
 - ANN model, 131–132
 - artificial neural network model, 131–132
 - ARX model, 131
 - BONL model, 132–133
 - continuous-time models, 129–130
 - data generation, 124–129
 - discrete-time models, 130–133
 - free decay experiment, 125, 126*f*
 - fundamental principles, 123–124, 133–134
 - input force experiment, 126–128, 127–128*f*
 - input waves experiment, 125–126, 127*f*
 - KGP model, 131
 - limitations, 146
 - linear optimization algorithms, 134–136
 - models for, 129–133
 - NLS model, 132
 - nonlinear optimization algorithms, 136, 137*f*
 - nonlinear static model, 132
 - prescribed motion experiment, 128–129
- T**
- Third-generation spectral wave models, 218
- advantages, 219
 - natural processes, 218
 - subgrid model, 219–221
 - supragrid model, 219, 221–223
- Time-domain analysis, 32, 51, 63
- Time-domain identification, 44, 46–52
- Time-domain methods, 31–32
- Time-domain models, 31–32, 37, 83
- design and verification of, 57–60
 - limitations, 63–64
 - power capture and loss for, 75*f*
 - wave loads in, 33–34
- Time-domain WEC array models, 152, 156–161
- V**
- Violent wave interaction, 113–114
- Volume of fluid (VoF) method, 108
- W**
- Wave-body interactions, 84
- problem, formulation of, 86
- Wave climate representation, MAEP
- abridged representation, 260–261
 - extensive representation, 258–260
 - sea-state parameters, 255
 - traditional (scatter table) representation, 256–258, 257*f*
- Wave energy
- challenge of, 1
 - conversion, 32, 44
 - absorption, 34
 - models, 33
 - FNPF models in, 85–86
- Wave energy converters (WECs)
- array
 - control, 230, 238–239
 - layout optimization, 246–248, 248–249*f*
 - autoregressive model, 239–240, 240*f*
 - challenges and future developments, 2–3
 - complex-conjugate control, 234–236
 - control effectors, 230–231
 - control perspectives, 240–242
 - device motion, 230–231
 - force-to-velocity model, 232
 - fundamental control results, 232–233
 - fundamental principles, 11–12
 - geometric optimization, 243–246, 243*f*, 246*t*
 - model-free approaches, 230
 - MPC, 233–237, 235*f*
 - nonlinear program, 237–238
 - numerical modelling of, 1–2

- Wave energy converters (WECs)
 (Continued)
 and ocean waves, interaction, 11
 optimization, 242
 phase control strategies, 233
 phenomenological discussion, 12–13, 13^f
 pseudo-spectral approach, 238
 real-time controller, 233–238
 Aalborg PID controller, 236
 on numerical optimization, 236–238
 simple but effective, 233–236, 235^f
 requirements, 229
 response
 calculation, 92–99
 subject to linear PTO forces, 93–99
 techno-economic optimization, 242^f
 use of, 229
 wave forecasting, 239–240, 239^f
 Wave energy spectrum, 67, 68^f
 Wave excitation, 18
 force, 19, 33–39
 impulse response function of, 38^f
 Wave force, nonlinear, 38–39
 Wave forecasting
 autoregressive model, 239–240, 240^f
 WEC control, 239–240, 239^f
 Wave load, in time-domain models, 33–34
- Wave/structure interaction (WSI), 117
 fluid domain for open ocean, 87^f
 FNPF model, 84
 hydrodynamic, 11–12
- Wave tank
 conventional, 124–125
 models, spectral variance density for, 78^f
 numerical, 124–125
 CFD based, 125
 experiment, 138–139^f
 simulation results and linear models' predictions, 142^f
 physical, 106, 123–124, 129–130
- WECs. *See* Wave energy converters (WECs)