

Contents

Preface.....	v
--------------	---

DIVISION I. VOLTERRA LINEAR MODEL

Chapter 1 Statistics of Waves

1.1 Introduction.....	3
1.1.1 Linear random wave.....	3
1.1.2 Laboratory and field waves.....	5
1.1.2.1 Gaussian laboratory wave	6
1.1.2.2 Non-Gaussian laboratory wave.....	6
1.1.2.3 Hurricane Camille.....	7
1.1.2.4 Draupner freak wave.....	8
1.2 Basics of Statistics	8
1.2.1 Mean, expected value, variance, skewness and kurtosis.....	9
1.2.2 Probability of one variable	10
1.2.2.1 Gaussian distribution	13
1.2.2.2 Uniform distribution	14
1.2.2.3 Cumulative distribution	14

1.2.3	Joint probability of two variables.....	14
1.2.3.1	Conditional probability density.....	16
1.2.3.2	Joint cumulative probability distribution	17
1.2.4	Ensemble averages, stationary, and ergodic	18
1.2.4.1	Autocorrelation and spectral density.....	19
1.2.4.2	Cross-correlation and cross-spectrum.....	20
1.2.5	Energy spectrum of velocity and acceleration	21
1.2.5.1	The spectral moment.....	22
1.2.5.2	Statistical independence between x and \dot{x}	23
1.2.6	Gaussian narrow-band process.....	23
1.2.6.1	Probability of exceedence	25
1.2.6.2	Rayleigh probability density	27
1.2.6.3	Rayleigh cumulative probability	29
1.2.6.4	Average of $1/n$ th highest peaks.....	29
1.2.6.5	The probable extreme amplitude.....	30
1.2.6.6	Distribution of wave height	31
1.2.6.7	Average of $1/n$ th highest wave heights	33
1.2.7	Gaussian broad-band process.....	33
1.2.7.1	Alternative estimation of spectral bandwidth	35
1.2.7.2	Probability density of all maxima	36
1.3	Joint Distribution of Wave Height and Period.....	38
1.3.1	Joint distribution of wave height and period.....	38
1.3.2	Joint distribution of H_s and T_z in the North Atlantic	41
1.3.2.1	Lognormal distribution of H_s and T_z	41
1.3.2.2	Weibull distribution	43
1.3.2.3	Conditional lognormal distribution.....	44
1.3.3	100 year return sea	46
1.3.3.1	Significant wave height.....	46
1.3.3.2	Zero-crossing period	49
1.3.3.3	B-spectra for 100 year return sea	51

Chapter 2 Fourier Transform and Wave Spectra

2.1	Introduction.....	55
2.1.1	Fourier transform	56
2.1.2	Note for using <i>fft</i> and <i>ifft</i> in MATLAB	59
2.1.3	One-sided complex amplitude and amplitude density spectrum.....	59
2.1.4	Nyquist frequency and aliasing	60
2.1.5	Various definitions of continuous Fourier transform.....	61
2.1.6	Properties of Dirac delta function	62
	2.1.6.1 Dirac delta function in time domain	62
	2.1.6.2 Dirac delta function in frequency domain.....	63
2.2	Estimation of Energy Density Spectra	64
2.2.1	Discrete energy and energy density spectrum.....	64
2.2.2	Parseval's theorem for energy density spectra.....	65
2.2.3	Summary of discrete auto- and cross-energy density spectra	67
2.2.4	Ensemble average method for energy density spectra	69
2.2.5	Blackman-Tukey's indirect estimates	69
	2.2.5.1 Estimate of one-sided auto-energy spectrum	69
	2.2.5.2 Estimate of one-sided cross-spectrum.....	71
	2.2.5.3 Guideline in determining maximum lag number	73
2.3	Wave Spectra	75
2.3.1	Introduction.....	75
2.3.2	Bretschneider two-parameter spectrum.....	76
2.3.3	One-parameter Pierson-Moskowitz spectrum.....	78
2.3.4	Modified one-parameter P-M spectrum	78
2.3.5	Modified two-parameter P-M spectrum.....	79
2.3.6	Definitions of wave periods	79
	2.3.6.1 Average period.....	79
	2.3.6.2 Zero-crossing period	80
	2.3.6.3 Average crest-to-crest period.....	80
	2.3.6.4 Significant period.....	80
	2.3.6.5 Summary of the periods in relation to modal period.....	81

2.3.7	ISSC spectrum (1964).....	81
2.3.8	ITTC spectrum (1978)	81
2.3.9	JONSWAP spectrum.....	81
2.3.10	JONSWAP spectrum in circular frequency	84
2.3.11	Norwegian west-coast sea spectra.....	84
2.3.12	Ochi-Hubble six parameter spectrum.....	84
2.3.13	Modified two-parameter JONSWAP spectrum.....	85
2.3.14	Isherwood formula	86
2.4	Family of Wave Spectra.....	88
2.4.1	Family of B-spectrum	88

Chapter 3 Volterra Linear Model and Extreme Response

3.1	Introduction.....	93
3.1.1	Volterra linear model	93
3.1.2	Frequency response function	94
3.1.3	Impulse response function.....	95
3.1.4	Relation between frequency response and impulse response.....	96
3.1.5	Impulse response to random excitation.....	97
3.1.5.1	Linear filter for random wave simulation	98
3.2	Relation Between Input and Output Energy Spectra	99
3.2.1	Relation between input and output auto-energy spectra	99
3.2.2	RAO from cross- and auto-spectra.....	100
3.2.3	Linear coherency function.....	101
3.2.4	Wave spectra for moving frame	102
3.2.5	Response to short-crested seas.....	103
3.3	Extreme Responses to Severe Seas.....	107
3.3.1	Operation time.....	108
3.3.2	Design extreme response	109
3.3.3	Short term prediction	109
3.3.4	Long-term prediction	111
3.3.4.1	Weighting factors for the energy spectra w_j	111

3.3.4.2	Weighting factor for frequency of encounter w_i	111
3.3.4.3	Example of long term prediction	111

Division II. Linear Wave-Body Interaction

Chapter 4 Basics of Hydrodynamics and Linear Waves

4.1	Review of Vector Analysis	117
4.1.1	Differential operators	117
4.1.2	Differential operators and surface integrals	118
4.1.3	Gauss's theorem.....	120
4.1.4	Stokes' theorem.....	121
4.1.5	Green's theorem.....	122
4.1.6	Green's function.....	126
4.2	Basics of Hydrodynamics	127
4.2.1	Kinematics of fluid flow	127
4.2.1.1	Lagrangian method	127
4.2.1.2	Eulerian method.....	128
4.2.1.3	Material derivative	129
4.2.1.4	The Reynolds transport theorem.....	130
4.2.2	Conservation laws	131
4.2.2.1	Mass conservation law.....	131
4.2.2.2	Momentum conservation law.....	132
4.2.2.3	Conservation of circulation.....	134
4.2.3	Bernoulli's equations	136
4.2.4	Boundary value problems	138
4.2.4.1	Kinematical boundary condition.....	138
4.2.4.2	Dynamical boundary condition.....	139
4.2.5	Energy flux.....	139
4.3	Linear Wave Theory	141
4.3.1	General formulation	141

4.3.2	Formulation of linear wave	143
4.3.2.1	The linear wave in uniform current.....	143
4.3.3	Formulation of standing waves	144
4.3.3.1	Solution of standing wave for $-k^2$	145
4.3.3.2	Solution for standing wave for $+k_2$	146
4.3.3.3	Seiches in lakes and harbors	148
4.3.3.4	Standing wave on model test in wave tank.....	149
4.3.3.5	Streamlines of standing waves (Eulerian method).....	150
4.3.3.6	Paths of particles of standing waves	150
4.3.4	Progressing wave	152
4.3.4.1	The streamlines of progressing wave.....	154
4.3.4.2	Paths of particles in progressing wave.....	154
4.3.5	Wave energy and energy flux	155
4.3.6	Circular waves.....	156
4.3.6.1	Circular standing waves.....	156
4.3.6.2	Circular progressing waves.....	159

Chapter 5 Propagation of Wave Group and Pulsating Source Wave

5.1	Propagation of Wave Groups	161
5.1.1	Amplitude-modulated wave.....	161
5.1.2	Propagation of Gaussian transient.....	164
5.1.2.1	Propagation of even Gaussian transient.....	166
5.1.3	Propagation of odd Gaussian transient.....	169
5.1.4	Transient wave due to impulse on the free surface	171
5.2	Waves Due to 2-D Pulsating Source.....	176
5.2.1	Remarks on the radiation condition	182
5.2.2	2-D Green's function	183
5.2.3	Far-field waves due to 2-D pulsating source.....	183
5.2.4	Cauchy PV integral in the near-field.....	185
5.3	Waves Due to 3-D Pulsating Source.....	188
5.3.1	Radiation condition.....	191

5.3.2 Resultant 3-D source potentials	192
5.3.3 3-D Green's function	193

Chapter 6 Linear Wave-Body Interaction

6.1 Introduction.....	197
6.1.1 Linear radiation boundary condition.....	198
6.1.2 Linear diffraction boundary condition	203
6.1.3 Formulation of radiation problem	203
6.1.4 Formulation of diffraction problem	206
6.1.5 Haskind-Newman relation	207
6.2 Computation of Radiation and Diffraction Potentials.....	208
6.2.1 Green's 3rd identity method.....	208
6.2.2 Source distribution method	209
6.2.3 Discretization of IBIE by CPM.....	210
6.2.4 Modified Green's 3rd identity-DBIE	211
6.2.5 Quadratic higher order boundary element.....	211
6.2.5.1 Removal of singularity.....	214
6.2.5.2 Comparison of CPM and HOBEM	215
6.3 2-D Radiation and Diffraction	216
6.3.1 2-D radiation problem.....	216
6.3.2 2-D diffraction problem	218
6.3.3 Far-field radiation and diffraction.....	220
6.3.3.1 Wave-exciting force versus radiation amplitude.....	221
6.3.4 Radiation and radiation damping	223
6.3.5 Hydrodynamic force of Lewis section	224
6.4 Wavemaker Transfer Function.....	226
6.4.1 Flap-type wavemaker.....	226
6.4.2 Plunger-type wavemaker.....	228
6.4.3 Reflection of waves in wave tank	229
6.5 Hydrodynamic Loads in Oblique Seas.....	230
6.5.1 Strip-method.....	230

6.5.1.1	Added mass and damping	230
6.5.1.2	Wave-exciting force.....	230
6.6	Motion of Structure.....	232
6.6.1	Linear equation of motion in frequency domain.....	232
6.6.1.1	Hydrostatic restoring force and moment.....	233
6.6.1.2	Viscous damping.....	234
6.6.1.3	RAO of SDOF motion	235
6.6.2	Deck-wetting and slamming of ship	236
6.6.2.1	Vertical relative motion	236
6.6.2.2	Hydrodynamic pressure on the hull surface.....	237
6.6.2.3	Ship's slamming.....	238
6.7	Hydrodynamic Interaction Between Two Bodies	238
6.7.1	Relative heaving motions of two cylinders in beam seas.....	238
6.7.1.1	Linear hydrodynamic coupling	239
6.7.1.2	The coupled equations of heaving motions.....	240
6.7.2	Radiation problem.....	240
6.7.3	Diffraction problem.....	241
6.7.4	Loads on Catamaran ship.....	242

Division III. Volterra Quadratic Model

Chapter 7 Volterra Quadratic Model and Cross-Bi-Spectrum

7.1	Volterra Quadratic Model	251
7.1.1	Volterra quadratic model in time domain	252
7.1.2	Volterra quadratic model in frequency responses	253
7.1.3	Difference and sum frequency coordinate system	257
7.1.4	Slowly-varying surge drift motion of a barge	258
7.1.5	Longitudinal drift force of a tanker model.....	260

7.2	Statistical Estimates of Second-Order Response	261
7.2.1	One- and two-sided energy density spectra	261
7.2.2	Parseval's formula.....	262
7.2.3	Expected value of quadratic response.....	263
7.2.4	Energy density spectrum of quadratic response.....	264
7.2.5	Cross-bi-spectrum	266
7.2.6	Algorithm for cross-bi-spectrum.....	267
7.3	Volterra Quadratic Model with Non-Gaussian Input.....	268
7.3.1	Gaussian and non-Gaussian method	270
7.3.2	Routines for analyses of quadratic estimates	271
7.3.2.1	Coherency test.....	271
7.3.2.2	Reconstruction test.....	272
7.3.2.3	Convergence of mean slow drift response	272
7.4	Case Studies of Quadratic Volterra Model	273
7.4.1	Added resistance and slow drift force.....	273
7.4.1.1	Added resistance by Gaussian method.....	274
7.4.1.2	Slow drift by non-Gaussian method.....	275
7.4.1.3	Deterministic method for slow drift analysis	275
7.4.1.4	Interpretation of 2nd-order experiment.....	276
7.4.1.5	Mini TLP analysis by non-Gaussian method.....	277
7.4.2	2nd-order surge-exciting force on barge	277
7.4.2.1	Estimate of LTFs and QTFs of surge force.....	277
7.4.2.2	Surge force energy density.....	278
7.4.2.3	Coherency test of surge force.....	279
7.4.2.4	Reconstruction of surge force	280
7.4.2.5	Effects of sea severity on the mean surge force.....	281
7.4.2.6	Cumulative mean of surge force	282
7.4.2.7	The effects of nonlinearity of surge force	283
7.4.3	Surge drift of Mini TLP	283
7.4.3.1	QTFs and energy density spectrum of Mini TLP.....	283
7.4.3.2	Coherency test of Mini TLP.....	285
7.4.3.3	Reconstruction of response of Mini TLP.....	285
7.4.3.4	Detection of surge resonance of Mini TLP	286
7.4.3.5	Cumulative mean surge of Mini TLP	287

Chapter 8 Second-Order Response in Linear Wave

8.1	Introduction.....	293
8.1.1	Momentum method for mean drift force on cylinder.....	293
8.1.2	Reflection and transmission coefficient.....	295
8.1.3	3-D momentum equation.....	297
8.1.4	A review of various methods for mean drift force.....	297
8.2	Added Resistance.....	299
8.2.1	Formula of added wave resistance.....	299
8.2.1.1	Similarity between Volterra quadratic model and hydrodynamic QTFs.....	301
8.2.1.2	Computation of added resistance.....	302
8.2.1.3	Simulation of slowly surging drift in large wave group.....	307
8.3	Lateral Drift Force and Moment in Oblique Seas.....	309
8.3.1	Lateral drift force in beam seas.....	310
8.3.1.1	The 2nd-order mean transverse force.....	310
8.3.1.2	The vertical relative motion.....	314
8.3.1.3	QTFs for lateral drift force.....	316
8.4	Simulation of Slowly-Swaying Drift Force.....	317
8.4.1	An example of slowly-varying lateral drift force.....	318
8.4.2	Convergence of the mean drift force.....	320
8.5	Wave Drift Damping.....	320
8.5.1	Computation of wave drift damping.....	324
8.6	Mean Drift Forces on Tandemly Floating Ships.....	325

Chapter 9 2nd-Order Wave and 2nd-Order Force

9.1	Introduction.....	329
-----	-------------------	-----

9.2	2nd-Order Wave Theory	330
9.2.1	Formulation of 2nd-order free surface boundary conditions	330
9.2.2	2nd-order wave potential in bichromatic wave	333
9.2.2.1	Similarity between Volterra quadratic model and 2nd-order wave theory	336
9.2.2.2	Energy spectrum of 2nd-order random wave	337
9.2.3	Self-interacting Stokes 2nd-order wave	338
9.2.3.1	Phase-locked 2nd-order wave	339
9.2.3.2	Stokes 2nd-order progressing wave in deep water	339
9.2.3.3	2nd-order wave group	340
9.2.4	Simulation of 2nd-order random waves	342
9.2.4.1	Long-crested sea	342
9.2.4.2	2nd-order short-crested sea waves	343
9.2.4.3	Comparison of 2nd-order wave to field wave	345
9.3	2nd-Order Wave Force on Bottom-Mounted Column	347
9.3.1	1st-order diffraction	347
9.3.2	2nd-order diffraction	349
9.3.3	2nd-order wave force on bottom-mounted column	353
9.4	2nd-Order Force on Main-Platform of ISSC TLP by HOBEM	357
9.4.1	General formulation of 2nd-order force	357
9.4.2	Formulation of 2nd-order diffraction potential force	360
9.4.3	The 1st- and 2nd-order force	363
9.4.4	2nd-order radiation potential	364
9.4.5	2nd-order diffraction and radiation in bichromatic waves	365
9.4.6	Similarity between Volterra quadratic model and 2nd-order force	366
9.5	HOBEM for Main-Platform of ISSC TLP	367
9.5.1	The features of HOBEM	368
9.5.1.1	HOBEM discretization	368
9.5.1.2	Comparison of HOBEM with other analyses	368
9.5.1.3	Double derivatives of the linear potential	370

9.5.1.4	Computation of the 2nd-order force of main platform of ISSC TLP	372
9.5.1.5	Comparison of 2nd-order force of main-platform of ISSC TLP with experiment	373
9.6	The Impulse Response Function Method for Simulation.....	373
9.7	Response of Coupled TLP System.....	374
9.7.1	Introduction to coupled TLP system.....	375
9.7.2	The basic strategy to deal with environmental loads	377
9.7.3	Dynamic equation of the coupled TLP system	378
9.7.4	Simulation of coupled ISSC TLP response in random sea	382
9.7.5	The wave drift damping of the coupled ISSC TLP.....	382
9.7.6	Springing and fatigue analysis	383
9.8	Limitedness of 2nd-Order Theories	385
9.8.1	Limitedness of 2nd-order wave theory	385
9.8.2	Limitedness of 2nd-order wave force	388
9.8.3	Limitedness of Volterra quadratic model.....	388
9.9	Brief Review of Springing and Ringing.....	389
9.9.1	Pure theoretical approach.....	389
9.9.2	Experimental approach with model	389
9.9.2.1	Extreme kinematics and impact	390
9.9.2.2	ULSM-kinematics.....	391
9.9.2.3	ULSM-diffraction	391
9.9.2.4	Progress report of springing and ringing of ISSC TLP	392
9.9.2.5	Ringling of ISSC TLP in a storm sea.....	392
9.9.2.6	Simulation of ringling of ISSC TLP in Heidrun ringling wave.....	393
9.9.2.7	Ringling of Heidrun TLP due to Heidrun ringling wave	393

Division IV. Universal Nonlinear Input-Output Model

Chapter 10 Volterra Cubic Model and 3rd-Order Wave and Force

10.1	Introduction.....	401
10.2	The Volterra Cubic Model	401
10.2.1	Volterra cubic model in time domain.....	402
10.2.2	Volterra cubic model in frequency domain.....	403
10.2.2.1	Result of the experiment in monochromatic wave.....	403
10.2.2.2	Result of the experiment in bichromatic wave.....	404
10.2.2.3	Result of the experiment in trichromatic wave	405
10.3	Deterministic Identification of Frequency Response Functions	406
10.4	Simulation of Nonlinear Response.....	409
10.5	3rd-Order Stokes Wave.....	411
10.5.1	Introduction	411
10.5.2	Properties of 3rd-order solution referring to sample solutions	413
10.5.2.1	Sample solution of 3rd-order interaction (Kim et al., 1993)	414
10.5.2.2	Sample solution of 3rd-order interaction (Pierson, 1993)	418
10.5.3	3rd-order wave group	421
10.6	3rd-Order Wave Force	423

Chapter 11 Highly Nonlinear Waves and UNIOM

11.1	Introduction.....	425
11.2	Background of UNIOM	427
11.2.1	Review of springing and ringing	428

11.3	UNIOM-Kinematics.....	429
11.3.1	Wheeler's method	429
11.3.2	1st-version of UNIOM-kinematics.....	430
11.3.3	2nd-version of UNIOM-kinematics	431
11.4	UNIOM-Diffraction	432
11.4.1	UNIOM-linear diffraction	432
11.4.2	UNIOM-linear and quadratic diffraction.....	433
11.4.3	UNIOM-linear and quadratic system	433
11.5	Generation of Nonlinear Waves in Wave Tank	434
11.5.1	Introduction	434
11.5.1.1	Generation of Stokes 5th-order wave	434
11.5.1.2	Generation of transient wave	436
11.5.2	Definition of strongly asymmetric wave	438
11.5.2.1	Generation of strongly asymmetric wave in random seas	439
11.5.2.2	Distortion of a large wave.....	440
11.5.2.3	Computer program for generation of freak wave ...	442
11.5.2.4	Generation of Draupner freak wave.....	443
11.6	Wave Kinematics	444
11.6.1	Measurement of transient wave kinematics	445
11.6.2	Hybrid wave model for transient wave by perturbation.....	447
11.6.3	UNIOM-kinematics for strongly asymmetric wave kinematics.....	447
11.7	Wave Impact	449
11.7.1	Wave impacts for series of cylinders.....	449
11.7.2	UNIOM-kinematics or diffraction for impact	451
11.7.3	Morison equation for impact	451
11.7.4	Analysis of impact frequency by wavelet	453
11.7.5	Kinematics of strongly asymmetric freak wave	455
11.8	Application of UNIOM-Diffraction.....	456
11.8.1	Load on large column in Heidrun ringing wave.....	456
11.8.2	Uniom-diffraction for Heidrun ringing	457

Chapter 12 Numerical Wave Tank

12.1	Introduction.....	465
12.1.1	Highly and weakly nonlinear wave	467
12.2	Numerical Wave Tank	467
12.2.1	Typical formulation in potential theory-fixed body	468
12.2.2	Marching solution of free surface-MEL procedure.....	471
12.2.3	Typical formulation in potential theory — floating body motion.....	472
12.3	Numerical Implementations	475
12.3.1	Boundary element method.....	475
12.3.2	Control of corners and edges	477
12.3.3	Efficient matrix equation solvers	478
12.3.4	Time-stepping integration	479
12.3.5	Control of saw-tooth instability.....	480
12.3.6	Choosing time increment.....	481
12.3.7	Radiation (open) boundary.....	481
12.3.8	Absorbing beach and wavemaker absorber.....	482
12.3.9	Active absorption of waves	484
12.3.10	Accuracy test.....	484
12.4	Method of Wave Generation in NWT.....	485
12.4.1	Space periodic waves	485
12.4.2	Wavemaker driven waves	485
12.4.3	Feeding velocity on inflow boundary.....	486
12.4.4	Prescription of incident wave	486
12.4.5	Discrete internal singularities method.....	486
12.5	Application of NWT	487
12.5.1	Highly nonlinear waves.....	487
12.5.2	Simulation of weakly nonlinear waves	488
12.6	Wave Force	489
12.6.1	Wave force on fixed body	489
12.6.2	Hybrid NWT for wave force on fixed body	492

12.6.3 Force due to forced heaving body	494
12.6.4 Submerged body advancing in calm water.....	495
12.7 Floating Body Motion	495
12.8 Benchmark Test	498
Index	507