

Contents

- 1 General 1**
 - 1.1 Introduction 1
 - 1.2 Literature 3

- 2 Design Process 5**
 - 2.1 Introduction 5
 - 2.2 Design criteria 5
 - 2.3 Design specification 5
 - 2.4 Design 6
 - 2.5 Design control 6
 - 2.6 Exercises 7
 - 2.6.1 Design and development 7

- 3 Launch Vehicle Systems 9**
 - 3.1 Introduction 9
 - 3.1.1 Launch Vehicle User’s manual 10
 - 3.2 Literature 11
 - 3.3 Exercises 11
 - 3.3.1 Definition the mechanical design specification. 11

- 4 Spacecraft Subsystems 13**
 - 4.1 Introduction 13
 - 4.2 Power Supply 14
 - 4.3 Attitude Control system 14
 - 4.4 Data Systems 14
 - 4.5 Thermal Control System 14
 - 4.6 Telecommunication Systems 15

- 4.7 Propulsion System 15
- 4.8 Structure. 15
- 4.9 Mutual Interaction of Subsystems 15
 - 4.9.1 Power Supply versus Attitude control System 15
 - 4.9.2 Power Supply versus Thermal Control System. 16
 - 4.9.3 Attitude Control System versus Thermal Control System 16
 - 4.9.4 Thermal Control System versus Structure. 16
- 4.10 Literature 17

- 5 Design and Safety factors. 19**
 - 5.1 Introduction 19
 - 5.2 Terminology. 19
 - 5.2.1 Flight Limit Load 19
 - 5.2.2 Design Limit Load. 19
 - 5.2.3 Ultimate Load 20
 - 5.2.4 Buckling Load 20
 - 5.2.5 Yield Load 20
 - 5.2.6 Proof Load. 20
 - 5.2.7 Allowable stress. 20
 - 5.2.8 Material Strength 20
 - 5.2.9 A-value (A basis). 21
 - 5.2.10 B-value (B basis). 21
 - 5.2.11 S-Value (S-basis). 22
 - 5.2.12 Qualification Loads 23
 - 5.2.13 Flight Acceptance Loads 23
 - 5.2.14 Margin of Safety 23
 - 5.2.15 Fail-Safe 23
 - 5.2.16 Safe-life 23
 - 5.3 Factors of Safety for Spacecraft 24
 - 5.4 Literature 25
 - 5.5 Exercises 25
 - 5.5.1 Survey of Applied Factors of Safety 25

- 6 Spacecraft Design Loads 27**
 - 6.1 Introduction 27
 - 6.2 Transportation load factors 29
 - 6.3 Steady-State Loads 29
 - 6.4 Mechanical Dynamic loads 30
 - 6.4.1 Sinusoidal loads. 30
 - 6.4.2 Random loads 38

6.5	Acoustic loads	45
6.5.1	Sound Pressure Level	46
6.5.2	Octave band	49
6.5.3	Centre frequency	49
6.5.4	Relative bandwidth	49
6.5.5	Power Spectral Density	51
6.5.6	Conversions of SPL	52
6.5.7	Acoustic Fill Factor	55
6.6	Shock loads	56
6.6.1	Introduction	56
6.6.2	Enforced acceleration	58
6.6.3	Shock Attenuation Rules	61
6.6.4	SRS Tolerance Limit	62
6.7	Static pressure variations	62
6.8	Micro-meteorites / Orbital Debris	63
6.8.1	Introduction	63
6.8.2	Simple Micro Meteoroid Flux Model	64
6.8.3	Simple Debris flux Model	64
6.9	Literature	66
6.10	Exercises	66
6.10.1	Sinusoidal Vibrations	66
6.10.2	Tuned Damper	67
6.10.3	Calculation of PSD's and Grms	68
6.10.4	Prove of conversion formulae	69
6.10.5	Calculation of OASPL and conversion to 1/3-octave band.	69
7	Test Verification	71
7.1	Introduction	71
7.2	Tests	71
7.3	Goal of the tests	72
7.4	Test Plan	73
7.5	Test Procedure	74
7.6	Model philosophy	74
7.7	Static Test	75
7.7.1	Sine-burst test	76
7.7.2	Sine-dwell test	77
7.8	Mechanical Vibration/Acoustic Tests	77
7.8.1	Sine Vibration Test	78
7.8.2	Random Vibration Test	82
7.8.3	Acoustic Vibration Test	83

- 7.8.4 Shock test 85
- 7.8.5 Modal Survey/Modal Analysis Test 85
- 7.9 Notching 86
 - 7.9.1 Notching at Equipment Level 86
 - 7.9.2 Notching at main resonances on basis of quasi-static loads 93
 - 7.9.3 Force Limiting Vibration Testing 96
- 7.10 Plots 97
- 7.11 Test Facilities West-Europe 98
- 7.12 Literature 99

- 8 Design of Spacecraft structure 101**
 - 8.1 Introduction 101
 - 8.2 Determination of Spacecraft Configuration 101
 - 8.2.1 Boundary Conditions Launch Vehicle 103
 - 8.2.2 Launch mass 103
 - 8.2.3 Available Launch Volume 103
 - 8.2.4 Launch Vehicle Adapter (LVA) 104
 - 8.2.5 Payload Separation System 104
 - 8.2.6 Functional requirements spacecraft 105
 - 8.3 First Design Spacecraft Structure 105
 - 8.3.1 Design Loads 106
 - 8.3.2 Stiffness requirements (natural frequencies) 107
 - 8.3.3 Quasi-static loads 108
 - 8.3.4 Mass Acceleration Curve (MAC) 109
 - 8.3.5 Random Loads 110
 - 8.3.6 Factors of Safety 110
 - 8.4 Basic Design Supporting Structure 111
 - 8.4.1 Design criteria 111
 - 8.4.2 Standard structural elements of spacecraft structures 112
 - 8.4.3 Selection of materials 114
 - 8.5 Detailed Analyses 116
 - 8.5.1 Finite Element Model 117
 - 8.5.2 Finite Element Model Verification 117
 - 8.5.3 Finite Element Analyses 118
 - 8.6 Manufacturing of the spacecraft structure 119
 - 8.7 Testing 120
 - 8.8 Literature 121
 - 8.9 Exercises 121
 - 8.9.1 Use of the User’s Manual of ARIANE 5 121

9	Strength and Stiffness of Structural Elements	123
9.1	Introduction	123
9.2	Trusses and Truss frames	124
9.3	Bending of Beams, Myosotis Method	127
9.3.1	Bending of Beams by transverse forces and bending moments	127
9.3.2	Buckling of Struts	128
9.3.3	Bending stresses in beams	133
9.3.4	Shear stresses in beams	134
9.3.5	Torsion of Beams	136
9.3.6	Local buckling of thin-walled tubes	139
9.3.7	Rings	141
9.4	Platforms	142
9.5	Panels	142
9.6	Shells of revolution: cylinders / cones	143
9.6.1	Stability of Cylinders	143
9.6.2	Stiffness of Cylinders	145
9.6.3	Running Loads in Cylinder	146
9.6.4	Stiffness of Cones	147
9.6.5	Stability of Cones	149
9.7	Stresses in Lap Joints	150
9.8	Literature	151
9.9	Exercises	152
9.9.1	Deflection of truss frame	152
9.9.2	Deflection of a beam	152
9.9.3	Deflection and bending moment in a clamped-clamped beam .	153
9.9.4	Buckling of Beam with Variable Cross-section	153
9.9.5	Buckling of Square Tube	154
9.9.6	Torsion and Shear Force	155
9.9.7	Stiffness and Buckling of a Cone	155
10	Sandwich Construction	157
10.1	Introduction	157
10.1.1	Design aspects	158
10.2	Optimum design: Determination of core and face sheet thickness for minimum mass	159
10.3	Stresses	160
10.3.1	Stresses in face sheets	161
10.3.2	Shear stress	162
10.3.3	Failure modes	162
10.4	Buckling Sandwich Columns	163

- 10.5 Global Buckling Cylinder 164
- 10.6 Local Buckling 166
 - 10.6.1 Combined Loads 168
- 10.7 Inserts 168
- 10.8 Honeycomb mechanical properties 170
- 10.9 Typical connections 171
- 10.10 Literature 172
- 10.11 Exercises 172
 - 10.11.1 Stiffness Sandwich Beam 172
- 11 Finite Element Analysis 175**
 - 11.1 Introduction 175
 - 11.2 Theory 175
 - 11.2.1 Static Calculations 176
 - 11.2.2 Dynamic Calculations 181
 - 11.3 Mathematical Model 184
 - 11.4 Finite element type 185
 - 11.5 Number of degrees of freedom 186
 - 11.6 Joints 186
 - 11.7 Damping 186
 - 11.7.1 Spacecraft 188
 - 11.7.2 Launch vehicles 188
 - 11.8 Modifications 188
 - 11.9 Finite element model to be delivered 189
 - 11.9.1 Coordinate systems 189
 - 11.9.2 Units 189
 - 11.9.3 Numbering schemes 190
 - 11.9.4 Reaction forces in case unit forces of inertia occur 190
 - 11.9.5 Elastic Energy as Rigid Body 190
 - 11.9.6 Reduced finite element model 193
 - 11.9.7 Reports regarding the finite element model 193
 - 11.9.8 Electronic Carrier 194
 - 11.10 Literature 195
 - 11.11 Exercises 195
 - 11.11.1 Application Lagrange’s Equations 195
 - 11.11.2 Deployed Natural Frequency 196
 - 11.11.3 Natural frequency cantilever beam 196

12 Stiffness/Flexibility Analysis	199
12.1 Introduction	199
12.2 Examples	200
12.2.1 ATV Cargo Carrier	200
12.2.2 ARIANE 5 Bati-Moteur (BME)	200
12.3 The unit force method	201
12.4 Reduced stiffness matrix	202
12.5 Unit displacement	202
12.6 Principal directions	203
12.7 Literature	206
12.8 Exercises	206
12.8.1 Stiffness Pin-joined Frame	206
13 Material Selection	207
13.1 Introduction	207
13.2 Metal alloys	207
13.3 Composite materials	208
13.3.1 Physical-mechanical properties of fillers	209
13.3.2 Properties of Non-metal Matrices	210
13.3.3 Properties of Metal Matrices	211
13.4 Sandwich Honeycomb Core	211
13.5 Design considerations	212
13.6 Literature	224
14 Spacecraft Mass	215
14.1 Introduction	215
14.2 Structure Mass	217
14.3 Total Mass Calculation	217
14.3.1 Mass Matrix	217
14.3.2 Mass matrix with respect to the centre of mass	223
14.3.3 Centre of mass	223
14.3.4 Second Moments of Mass	224
14.3.5 Finite Element Model Mass Matrix	225
14.4 Literature	228
14.5 Exercises	228
14.5.1 Mass computer programme	228
15 Natural Frequencies, an Approximation	229
15.1 Introduction	229

- 15.2 Static Displacement Method 229
- 15.3 Rayleigh’s Quotient 232
- 15.4 Dunkerley’s Method 234
- 15.5 Literature 241
- 15.6 Exercises 241
 - 15.6.1 Natural frequency of airplane 241
 - 15.6.2 Rayleigh’s method 241
 - 15.6.3 Rayleigh’s method 241
 - 15.6.4 Equations of motion and natural frequencies 242
 - 15.6.5 Calculation natural frequencies 243
 - 15.6.6 Equations of motion and natural frequencies 244
 - 15.6.7 Deployed Natural Frequency 245

- 16 Modal Effective Mass 247**
 - 16.1 Introduction 247
 - 16.2 Enforced Acceleration 247
 - 16.3 Modal Effective Masses of an MDOF System 250
 - 16.4 Literature 259
 - 16.5 Exercises 259
 - 16.5.1 Large mass solution 259
 - 16.5.2 Calculation modal effective masses cantilevered beam 260
 - 16.5.3 Modal Effective Mass of a Cantilevered Beam 261
 - 16.5.4 Calculation of Base Force 262

- 17 Dynamic Model Reduction Methods 265**
 - 17.1 Introduction 265
 - 17.2 Static Condensation Method 266
 - 17.3 Craig–Bampton Reduced Models 271
 - 17.4 System Equivalent Reduction Expansion Process (SEREP) 274
 - 17.5 Conclusion 277
 - 17.6 Literature 278
 - 17.7 Exercises 278
 - 17.7.1 Reduction Finite Element Model 278
 - 17.7.2 Reduction of dynamic 10 DOF model 279

- 18 Dynamic Substructuring, Component Mode Synthesis 281**
 - 18.1 Introduction 281
 - 18.2 Special CMS Methods 282
 - 18.2.1 Craig–Bampton Fixed-Interface Method 282

18.2.2	Free-Interface Method	287
18.2.3	General-Purpose CMS Method	294
18.3	Literature	299
18.4	Exercises	299
18.4.1	Substructure Analysis 1	299
18.4.2	Substructure Analysis	300
19	Output Transformation Matrices	303
19.1	Introduction	303
19.2	Reduced Free-Free Dynamic Model	304
19.3	References	310
19.4	Exercises	310
19.4.1	Problem 1	310
19.4.2	Problem 2	311
20	Coupled Dynamic Loads Analysis	313
20.1	Introduction	313
20.2	Finite Element Validation	315
20.3	Literature	318
20.4	Exercises	318
20.4.1	Internet search	318
21	Random Vibrations Simplified Response Analysis	319
21.1	Introduction	319
21.2	Low frequency	319
21.2.1	The response of a single mass-spring system due to a random force or base excitation	320
21.2.2	Damping	325
21.2.3	Static Assumed Mode Random Vibration Response Analysis	325
21.2.4	Passages	326
21.2.5	Calculation of the rms stresses / forces	329
21.2.6	Reaction Forces	333
21.3	Acoustic Analysis	334
21.3.1	Introduction	334
21.3.2	Acoustic loads transformed into mechanical random vibrations	335
21.3.3	Component Vibration Requirements	337
21.3.4	Static approach	339
21.3.5	The stress in an acoustically loaded panel	340
21.4	Literature	344

- 21.5 Exercises 345
 - 21.5.1 Calculation of PSD Function. 345
 - 21.5.2 Peak Pressure Values. 345
 - 21.5.3 Simply Supported Plate [Blevins 1989] 346
 - 21.5.4 Waves 346
- 22 Fatigue Life Prediction 349**
 - 22.1 Introduction 349
 - 22.2 Palmgren-Miner Linear Cumulative Damage Rule. 349
 - 22.3 Analysis of Load-time Histories 351
 - 22.4 Failure due to Sinusoidal Vibrations 353
 - 22.5 Failure due to Narrow-banded Random Vibrations. 355
 - 22.6 Literature 363
 - 22.7 Internet. 363
 - 22.8 Exercises 363
 - 22.8.1 Fatigue life prediction sinusoidal vibration. 363
 - 22.8.2 Fatigue life prediction random vibration. 365
- 23 Shock-Response Spectrum 367**
 - 23.1 Introduction 367
 - 23.2 Enforced Acceleration. 368
 - 23.3 Numerical Calculation of the SRS, the Piece wise Exact Method . . . 370
 - 23.4 Response Analysis in Combination with Shock-Response Spectra . . 375
 - 23.5 Matching Shock Spectra with Synthesised Time Histories. 385
 - 23.6 Literature 396
 - 23.7 Exercises 396
 - 23.7.1 Calculation of Shock Response Curves. 396
 - 23.7.2 Problem 2. 398
- 24 Damage to Spacecraft by Meteoroids and Orbital Debris 399**
 - 24.1 Introduction 399
 - 24.2 Micro-Meteoroids and Space Debris Environment. 400
 - 24.2.1 Micro-Meteoroids Environment 400
 - 24.2.2 Orbital debris Environment. 402
 - 24.3 Hyper Velocity Impact Damage Models 405
 - 24.3.1 Single Plate Penetration Equations 405
 - 24.3.2 Multi-shock shield. 406
 - 24.4 Probability of Impacts 409
 - 24.5 Literature 411

25 Prescribed Averaged Temperatures	413
25.1 Introduction	413
25.2 PAT method	413
25.3 PAT Method Applied to a Simplified Solar Array.	418
25.4 Literature	430
25.5 Exercises	430
25.5.1 Temperature interpolation in finite element model	430
26 Thermal-elastic Stresses	433
26.1 Introduction	433
26.2 Material properties.	439
26.3 Literature	440
26.4 Exercises	440
26.4.1 Thermal stress in beam	440
26.4.2 Self Strained Structure.	440
27 Coefficients of thermal & moisture expansion	443
27.1 Introduction	443
27.2 Coefficient of thermal expansion	443
27.2.1 The CTE as a derivative of the thermal expansibility	443
27.2.2 The Secant CTE.	444
27.3 Moisture coefficient of expansion (CME).	445
28 Venting Holes	447
28.1 Introduction	447
28.2 Venting Holes	447
28.2.1 Beryline method	447
28.2.2 The convergent Nozzle	449
28.2.3 Rule of Thumb.	450
28.3 Literature	451
29 Examples	453
29.1 Introduction	453
29.2 Natural Frequencies, an Approximation	454
29.2.1 Displacement method	454
29.3 Design Example Fixed-Free Beam	455
29.3.1 Introduction	455
29.3.2 Stiffness calculations.	456
29.3.3 Strength calculations	458

- 29.3.4 Effective stress. 459
- 29.3.5 Iterations 460
- 29.4 Equivalent dynamic systems 462
 - 29.4.1 Introduction 462
- 29.5 Random Vibrations 464
 - 29.5.1 Comparison of two random vibration specifications. 464
 - 29.5.2 Enforced random Acceleration 467
- 29.6 Strength and Stiffness Analysis SIMPSAT 476
 - 29.6.1 Introduction 476
 - 29.6.2 Design Philosophy. 477
 - 29.6.3 Quasi-Static Loads (QSL) 478
 - 29.6.4 Minimum Natural Frequencies 478
 - 29.6.5 Material properties. 478
 - 29.6.6 Natural Frequencies. 478
 - 29.6.7 Selection of the type of structure. 481
 - 29.6.8 Strength aspects 482
 - 29.6.9 Summary MS values 487
- 29.7 Stiffnes calculations using Castigliano’s second theorem. 487
- 29.8 Modal Effective Mass of a Cantilevered Beam. 490
- 29.9 Component Mode Synthesis (Craig-Bampton Method) 492
- Subject Index 497**