Table of Contents

Preface xix

PART I. TOLERANCE ANALYSIS AND SYNTHESIS 1

Chapter 1. A New Method of Expressing Functional Requirements and How to Allocate Tolerance to Parts 3
Pierre-Antoine ADRAGNA and Pascal HERNANDEZ

1.1. Introduction. 3
1.2. Brief review 4
1.2.1. How to compare. 4
1.2.2. Statistical tolerancing methods 6
1.3. Proposed method 10
1.3.1. Functional requirements 11
1.3.2. The tolerancing strategy 14
1.4. Discussion 17
1.4.1. Efficiency of the proposed method 17
1.4.2. Comparison to existing approaches 17
1.5. Bibliography 19

Chapter 2. A Parametric Approach to Determine Minimum Clearance in Overconstrained Mechanisms 21
Philippe SERRÉ, Faïda M'HENNI and André CLÉMENT

2.1. Introduction. 22
2.2. Compatibility relations between specification parameters 24
2.2.1. Modeling the geometric constraints problem. 24
2.2.2. Compatibility relations for assemblability requirement 25
2.2.3. Compatibility relations for mobility requirement 27
2.3. Framework for minimum clearance determination. 29

2.3.1. Nominal and associated mechanism 30
2.3.2. Actual and associated parts 31
2.3.3. Synthetic scheme 32
2.4. Application 33
2.4.1. First case 33
2.4.2. Second case 35
2.5. Conclusion 36
2.6. Bibliography 37

Chapter 3. Quick GPS: Tolerancing of an Isolated Part 39
Robin CHAVANNE and Bernard ANSELMETTI

3.1. Introduction. 39
3.2. Mechanism definition 40
3.2.1. The positioning plan 40
3.2.2. Description with positioning tables 41
3.3. Datum system specifications. 42
3.3.1. Positioning requirements 42
3.3.2. Positioning specifications 42
3.4. Relative position of reference frames 47
3.4.1. Links between reference frames 47
3.4.2. Specification corresponding to links. 49
3.5. VBA application 52
3.5.1. General structure 52
3.5.2. Data acquisition and verification 53
3.5.3. Tolerancing process 55
3.6. Conclusion 57
3.7. Bibliography 57

Chapter 4. Synthesis and Statistical Analysis for 3D Tolerancing 59
Max GIORDANO, Pascal HERNANDEZ and Dimitri DENIMAL

4.1. Introduction. 59
4.1.1. Literature review 60
4.1.2. The domain model 61
4.2. Stack-up tolerance synthesis 61
4.2.1. Serial mechanisms 61
4.2.2. Analysis for worst case stack-up tolerances 63
4.2.3. Analysis with the statistical approach 64
4.2.4. Synthesis for stack-up tolerances. 65
4.3. Serial mechanisms with non-perfect contacts 66
4.3.1. Analysis in the worst case 67
4.3.2. Analysis with the statistical approach 67
4.3.3. Synthesis for a serial mechanical system 68

4.4. "Reducible" structure 68
4.4.1. Parallel mechanical structure 68
4.4.2. Introduction to "reducible" structure 70
4.4.3. Algorithm and computational method 71
4.5. Example of the pin-hole assembly 72
4.5.1. Main data 72
4.5.2. Major results 74
4.6. Conclusion and discussion 75
4.6.1. Conclusion 75
4.6.2. Discussion and future works 75
4.7. Bibliography 76

Chapter 5. Reliability Analysis of the Functional Specification Applied to a Helicopter Gas Turbine 77
Yann LEDOUX, Denis TEISSANDIER and Samir SID-AHMED

5.1. Introduction 77
5.2. Studied case 78
5.2.1. Tolerancing model 79
5.3. Deterministic approach 83
5.3.1. Sensitivity and elasticity analysis 84
5.3.2. Discussion about the determinist results 86
5.4. Probabilistic approach 86
5.4.1. Definition of the state functions 88
5.4.2. Determination of the statistical parameters from the tolerancing model 89
5.4.3. Failure rate estimation 90
5.4.4. Influence of the tolerancing parameters on the failure probability 91
5.4.5. Sensibility analysis on the failure probability 93
5.4.6. Parametric analysis of the γ_8 parameter 94
5.5. Conclusion 96
5.6. Acknowledgments 96
5.7. Bibliography 97

Chapter 6. Inertial Tolerancing According to ISO GPS 99
Dimitri DENIMAL, Max GIORDANO, Maurice PILLET and Alain SERGENT

6.1. Introduction 99
6.2. Tolerance synthesis 100
6.2.1. Definition of the functional requirement domain (FRD) applied to localization specification 101
6.2.2. Tolerance synthesis of a stack of parts 103
6.2.3. Example of tolerance synthesis 105

6.2.4. Process capability indices applied to SDT 109
6.2.5. Statistical tolerancing risk 110
6.2.6. Inertial tolerancing: short reminder 111
6.2.7. Inertial tolerancing with stack-up problem 112
6.3. 3D inertia 114
6.3.1. 3D inertia definitions and comparison. 114
6.3.2. 3D inertia definitions comparison 117
6.3.3. 3D inertia in the industrial context. 119
6.3.4. 3D inertia - conclusions 121
6.4. Conclusions. 121
6.5. Bibliography 122

Chapter 7. Tolerance Analysis based on Quantified Constraint Satisfaction Problems 125
Ahmed Jawad QURESHI, Jean-Yves DANTAN, Jérome BRUYÈRE and Régis BIGOT

7.1. Introduction. 125
7.2. Quantifier notion and mathematical formulation of tolerance synthesis 127
7.2.1. Quantifier notion for geometrical product requirement. 127
7.2.2. Mathematical formulation of tolerance analysis for geometrical product requirement 128
7.3. Worst case tolerance analysis based on quantified constraint satisfaction problems 132
7.3.1. QCSP 132
7.3.2. New mathematical formulation of tolerance analysis for QCSP solver 133
7.4. Statistical tolerance analysis based on constraint satisfaction problems and Monte Carlo simulation 134
7.4.1. Algorithm for statistical tolerance analysis by Monte Carlo simulation and CSP technique 135
7.5. Applications 139
7.6. Discussion 141
7.7. Bibliography 142

Chapter 8. Tolerance Analysis in Manufacturing Using the MMP, Comparison and Evaluation of Three Different Approaches 145
Mojtaba KAMALI NEJAD, Frédéric VIGNAT and François VILLENEUVE

8.1. Introduction. 146
8.2. MMP. 147
8.3. Tolerance analysis and virtual gauge 149
8.4. Worst case searching 150

8.4.1. Optimization technique 150
8.5. Combined approach 155
8.5.1. The combined approach functional elements. 155
8.6. Monte Carlo simulation. 158
8.7. Example and comparison. 160
8.7.1. First section 160
8.7.2. Second section 164
8.7.3. Discussion 168
8.8. Conclusion 169
8.9. Bibliography 170

PART II. SIMULATION OF ASSEMBLIES 173

Chapter 9. A Chronological Framework for Virtual Sheet Metal Assembly Design 175
Johan SEGEBORN, Anders CARLSSON, Johan S. CARLSON and Rikard SÖDERBERG

9.1. Introduction. 175
9.1.1. A generic product development process 176
9.1.2. Automotive sheet metal assembly 177
9.2. Proposed framework 179
9.2.1. Planning 181
9.2.2. Concept development 181
9.2.3. System-level design 182
9.2.4. Detail design. 185
9.3. Summary and future work 188
9.4. Acknowledgments. 189
9.5. Bibliography 189

Chapter 10. A Method to Optimize Geometric Quality and Motion Feasibility of Assembly Sequences 191
Domenico SPENSIERI, Johan S. CARLSON, Lars LINDKVIST, Robert BOHLIN and Rikard SÖDERBERG

10.1. Introduction 191
10.1.1. Problem motivation. 191
10.1.2. Related work. 192
10.2. Modeling and algorithms 194
10.2.1. Modeling connections 194
10.2.2. Stability and variation analysis 199
10.2.3. Assembly sequences 200
10.2.4. Path planning 203
10.3. Assembly planning. 204

10.4. Industrial test case 204
10.5. Conclusions and future work 206
10.6. Acknowledgments 207
10.7. Bibliography 207

Chapter 11. Modeling and Simulation of Assembly Constraints in Tolerance Analysis of Rigid Part Assemblies 209
Pasquale FRANCIOSA, Salvatore GERBINO and Stanislao PATALANO

11.1. Introduction 209
11.2. SVA-TOL methodology overview 211
11.3. Assembly constraint modeling 212
11.3.1. Fully-constrained assembly 217
11.3.2. Over-constrained assembly 221
11.4. Case study one: assembly of two-part assembly 222
11.5. Case study two: industrial application 225
11.6. Conclusions 227
11.7. Bibliography 228

Chapter 12. Tolerance Analysis with detailed Part Modeling 231
Tobias STOLL, Stefan WITTMANN and Harald MEERKAMM

12.1. Introduction 231
12.2. Related work 232
12.3. The proposed modeling and analysis of toleranced assemblies. 233
12.4. Simulation of non-ideal parts 234
12.5. Relative positioning 235
12.5.1. Defined objective functions 236
12.5.2. Particle swarm optimization 237
12.5.3. Independence of the positioning steps 238
12.5.4. Parallelization 238
12.6. Analysis of the positioned assemblies 239
12.7. Example 239
12.8. Summary 241
12.9. Acknowledgements 242
12.10. Bibliography. 242

Chapter 13. Assembly Method Comparison Including Form Defect 245
Stéphane MORIÈRE, Jean MAILHÉ, Jean-Marc LINARES and Jean-Michel SPRAUEL

13.1. Introduction 245
13.1.1. Topic 245
13.1.2. Actual lack of CAD 246
13.1.3. State of the art and proposal 246

13.2. Geometric model for simulation 248
13.2.1. Part with form defects 248
13.2.2. Assembly process 250
13.2.3. Function for optimization 250
13.2.4. Constraints 252
13.3. Experimentation 252
13.3.1. Case study 252
13.3.2. Simulation setup 253
13.4. Result discussion 253
13.4.1. Case 1 253
13.4.2. Case 2 254
13.4.3. Case 3 255
13.4.4. Case 4 255
13.5. Summary 256
13.6. Bibliography 256

Chapter 14. Influence of Geometric Defects on Service Life 259
Laurent ZAMPONI, Emmanuel MERMOZ, Jean-Marc LINARES and Jean-Michel SPRAUEL

14.1. Introduction 259
14.1.1. Topic 259
14.1.2. Service life functional requirements 260
14.1.3. State of the art 261
14.2. Calculation methodology of contact pressure and orbital speed variation 263
14.2.1. Schedule of the methodology 265
14.2.2. Introduction of geometric defects in FEM 265
14.2.3. Model of geometric defect 266
14.3. Simulation 268
14.3.1. Studied case 268
14.3.2. Effect of the localization defect on orbital speed variation 269
14.3.3. Effect of the orientation defect on the contact load and orbital speed variation 269
14.3.4. Effect of the form defects and undulation on speed variation 270
14.4. Summary 271
14.5. Bibliography 272

Chapter 15. GapSpace Multi-dimensional Assembly Analysis 273
Edward MORSE and Xiaobin YOU

15.1. Introduction 273

15.2. Representing dimensions and tolerances . . . 275
15.3. Geometric tolerances . . . 276
15.4. Perfect form tolerance zones . . . 279
15.5. Assembly tolerance specification . . . 279
15.6. Floating assembly . . . 280
15.7. Kinematic assembly . . . 282
15.8. Manufacturing dimensioning schemes . . . 282
15.9. The revised 2D tolerance chart . . . 284
15.10. Parametric representation of the PF-tolerance zone of a CS-feature . . . 284
15.11. Surfaces of revolution . . . 288
15.12. Nominal dimensions of the CS . . . 288
15.13. 1D constraining simplices . . . 289
15.14. 2D constraining simplices . . . 290
15.15. Case study . . . 293
15.16. Conclusion . . . 297
15.17. Acknowledgements . . . 298
15.18. Bibliography . . . 298

PART III. MEASUREMENT . . . 299

Chapter 16. Impact of the Sampling Strategy on Geometrical Checking Uncertainties . . . 301
Jean MAILHÉ, Jean-Marc LINARES, Jean-Michel SPRAUEL and Jean-Paul RAYNAL

16.1. Introduction . . . 301
16.2. Geometrical verification and virtual gauges . . . 302
16.2.1. Verification by virtual gauge without best fit . . . 302
16.2.2. Verification with associated feature . . . 303
16.2.3. Statistical point of view . . . 304
16.3. Field of probability of the presence of matter . . . 304
16.4. Virtual gauges . . . 306
16.5. Interference probability map . . . 308
16.5.1. Geometrical verification process . . . 308
16.6. Experiment . . . 309
16.6.1. Envelope zone specification . . . 309
16.6.2. Perpendicularity specification . . . 312
16.7. Conclusion . . . 314
16.8. Bibliography . . . 315

Chapter 17. Predetermination of Measurement Uncertainty in the Application of Computed Tomography 317
Albert WECKENMANN and Philipp KRÄMER

17.1. Introduction 317
17.2. Prior investigations 318
17.3. Measurements of user-controllable influences 319
17.4. Estimation of influences 323
17.5. Calculation of the task-specific measurement uncertainty according to GUM 325
17.6. Summary 329
17.7. Acknowledgments 330
17.8. Bibliography 330

Chapter 18. Application of Function Oriented Parameters for Areal Measurements in Surface Engineering 331
Albert WECKENMANN and Özgür TAN

18.1. Introduction 331
18.2. Surface measurements 332
18.3. Functional parameters 333
18.3.1. 2D functional parameters from ISO 13565-2 333
18.3.2. 3D functional parameters 334
18.4. Characterization of the whole application 335
18.5. Case study: spreading liquid on metal surfaces 336
18.5.1. Step 1: gathering information 336
18.5.2. Step 2: modeling the system 336
18.5.3. Step 3: application of a functional test 337
18.5.4. Step 4: surface requirements 341
18.5.5. Step 5: measurement system 341
18.5.6. Step 6: functional parameters 342
18.6. Conclusions 343
18.7. Acknowledgments 343
18.8. Bibliography 343

Chapter 19. Validation of a Reception or Production Control Process by the Inertial Indicator I_G 345
Daniel DURET, Maurice PILLET, Alain SERGENT and Dimitri DENIMAL

19.1. Introduction 345
19.2. Comparison of the “production controls” and “reception controls” approaches 346
19.3. Production bias and measure bias 348
19.4. Inertial capability 348

19.5. Inertia of the control process and inertia of the production process . . 349
19.5.1. Law of composition 349
19.5.2. Disturbances due to bias 350
19.5.3. Definition of the inertial "ndc" 350
19.6. Inertia of the control process and total customer inertia (control of reception) 352
19.7. Conclusions 353
19.8. Bibliography 354

Chapter 20. Detection of Areas with Critically Reduced Thickness of Formed Sheet Metal Parts Using Two Oppositely Positioned Fringe Projection Systems 355
Albert WECKENMANN and Natasa PETROVIC

20.1. Introduction 355
20.2. Methods 356
20.2.1. Measuring system and data fusion 356
20.2.2. Methods of data analysis 360
20.2.3. Algorithm for the calculation of minimal wall thicknesses 362
20.3. Visualization and discussion of results 367
20.4. Summary 369
20.5. Acknowledgments 370
20.6. Bibliography 370

Chapter 21. Variability of the Manufacturing Process in the GPS Framework: A Case Study 371
Manuela DE MADDIS and Martina GANDINI

21.1. Introduction 371
21.2. Variability sources 373
21.2.1. Measurement uncertainty 374
21.2.2. Process variability 378
21.3. Simulations 378
21.3.1. Simulations with independent component analysis (ICA) 379
21.4. Simulation with seasonal trend decomposition (STL) 382
21.5. Summary 383
21.6. Bibliography 384

Chapter 22. Virtual CMM-based Sampling Strategy Optimization 385
Giovanni MORONI and Stefano PETRÒ

22.1. Introduction 385
22.1.1. Conformance to geometric tolerances 386
22.1.2. Evaluating geometric error 387
22.1.3. Goals 388

22.2. State of the art . . . 389
22.3. Proposed methodology . . . 390
22.3.1. Evaluation of C_M . . . 390
22.3.2. Evaluation of C_E . . . 391
22.3.3. Evaluating the uncertainty: the virtual CMM . . . 392
22.3.4. Cost function minimization . . . 395
22.4. Case study . . . 395
22.5. Conclusions . . . 399
22.6. Acknowledgments . . . 401
22.7. Bibliography . . . 401

Chapter 23. Impact of Workpiece Shape Deviations in Coordinate Metrology . . . 405
Gisela LANZA and Jochen PETERS

23.1. Introduction . . . 405
23.2. Evaluation in coordinate metrology . . . 407
23.3. The Jackknife . . . 409
23.4. Application to CMM data . . . 410
23.4.1. Resampling point clouds . . . 410
23.4.2. Influence of single measurement points . . . 411
23.4.3. Evaluation uncertainty . . . 412
23.4.4. Example of use . . . 413
23.5. Simulation . . . 415
23.5.1. Simulation procedure . . . 415
23.5.2. Simulation results . . . 416
23.6. Summary and outlook . . . 417
23.7. Bibliography . . . 418

Chapter 24. Quality Assurance of Micro-gears via 3D Surface Characterization . . . 419
Gisela LANZA and Benjamin VIERING

24.1. Introduction . . . 419
24.2. Test specimen and experimental equipment . . . 420
24.3. 3D characterization . . . 421
24.3.1. Benefits of a 3D characterization . . . 421
24.3.2. Approach . . . 423
24.4. Summary . . . 428
24.5. Acknowledgments . . . 428
24.6. Bibliography . . . 429

PART IV. TOLERANCING IN THE PLM 431

Chapter 25. Geometric Specification at the Beginning of the Product Lifecycle 433
Renaud COSTADOAT, Luc MATHIEU, Hugo FALGARONE and Benoît FRICERO

25.1. Introduction 433
25.2. Study of the skeleton 436
25.2.1. Presentation of the models used 436
25.2.2. Description of the mechanism and first simulations 437
25.2.3. Conclusion of the first step 441
25.3. Study of the functional surfaces 442
25.3.1. Presentation of the models used 442
25.3.2. Details of the mechanism and second step of simulation 443
25.3.3. Conclusion of the second step 450
25.4. Specification 450
25.5. Conclusion 451
25.6. Bibliography 452

Chapter 26. Ontological Model of Tolerances for Interoperability in Product Lifecycle 455
Gaurav AMETA and Patrick HOFFMANN

26.1. Introduction 455
26.2. Ontology 456
26.2.1. Information modeling as an ontology 457
26.2.2. Choice of ontology language 457
26.3. Literature survey 458
26.4. Ontology of tolerances 459
26.5. Example of tolerance ontology instantiation 464
26.6. Summary 465
26.7. Bibliography 466

Chapter 27. A PLM-Based Multi-Sensor Integration Measurement System for Geometry Processing 469
Zhao HAIBIN, Nabil ANWER and Pierre BOURDET

27.1. Introduction 469
27.2. Sensor integration methodology 471
27.2.1. System framework 471
27.2.2. Physical integration of multiple sensors 473
27.2.3. Laser guide metrology 474
27.3. Ontology modeling in a PLM-context 475
27.3.1. Description of ontology modeling 476
27.3.2. Ontology modeling in Protégé 476

27.4. Geometry processing 478
27.4.1. Shape analysis based on the shape index and curvedness 478
27.4.2. Quality evaluation. 479
27.5. Experiments validation 480
27.6. Conclusion 482
27.7. Acknowledgments 483
27.8. Bibliography 483

Chapter 28. Comparison of Gear Geometric Specification Models Regarding the Functional Aspect 485
Jean-Paul VINCENT, Jean-Yves DANTAN, Gerth GOCH and Régis BIGOT

28.1. Introduction 485
28.2. Specification models. 489
28.3. Comparison method 490
28.3.1. Global approach 490
28.3.2. Geometrical modeling 492
28.3.3. Virtual meshing simulation 493
28.3.4. Virtual metrology 495
28.3.5. Evaluation of the kinematic characteristics 496
28.4. Criteria comparison 497
28.4.1. Objective 497
28.4.2. Example. 497
28.4.3. Comparing the results 498
28.5. Conclusion 499
28.6. Bibliography 502

Chapter 29. Effects of Geometric Variation on Perceived Quality 503
Karin FORSLUND and Rikard SÖDERBERG

29.1. Introduction 503
29.1.1. Types of robustness 504
29.1.2. The product experience. 505
29.1.3. Perceived quality of non-nominal products 505
29.1.4. Design as a process of communication 506
29.2. A framework for describing visual robustness to geometric variation 507
29.2.1. Visual reference level. 508
29.2.2. Optical level 511
29.2.3. Perception level 512
29.2.4. Response level 513

29.3. Visual fit complexity assessment method 511
29.4. Discussion and conclusions 517
29.5. Bibliography 518

Chapter 30. Geometric Requirement Variations Throughout the Product Lifecycle 521
Guillaume MANDIL, Alain DESROCHERS and Alain RIVIÈRE

30.1. Introduction 521
30.2. Literature review 522
30.2.1. Related standards 522
30.2.2. Related research 522
30.3. Definitions and concepts 523
30.3.1. Dimensions 523
30.3.2. Functional requirements 524
30.4. Functional requirements throughout lifecycle stages 525
30.4.1. General principles 525
30.4.2. Computational rules 527
30.5. Case study: a simple 1D crosshead guide 531
30.5.1. Hypothesis 531
30.5.2. Dimension driven calculation 533
30.5.3. Functional requirement driven calculation 535
30.5.4. Geometry driven calculation 537
30.6. Conclusion and perspectives 539
30.6.1. High level management of functional requirements 539
30.6.2. Further work 540
30.7. Acknowledgments 540
30.8. Bibliography 541

List of Authors 543

Index 549