

Contents

The DFG Priority Programme 'System Dynamics and Long-Term Behaviour of Vehicle, Track and Subgrade' 1
Klaus Knothe, Karl Popp

1 Introduction 1

2 Where did we start from? 2

 2.1 Preliminary Comments 2

 2.2 Limits of the Wheel/Rail System (1975-1985) 2

 2.3 New Problems (1985-1994) 5

 2.4 Explanation and Counter-Measures 6

3 What has been achieved? 7

 3.1 The Project Idea of the DFG Priority Programme 7

 3.2 About Structure and Management of the DFG Priority Programme 9

 3.3 What has been achieved? 10

4 What still needs to be done? 12

References 13

INVITED LECTURES 15

Vehicle/Track Interaction Optimisation within Spoornet 17
Robert Fröhling

1 Introduction 17

2 Wagon Bogie Development 17

3 Developments on the Heavy Haul Export Lines 20

 3.1 Iron Ore Export Line 21

 3.2 Coal Export Line 23

4 Wheel Profile Development 24

5 Measurement and Monitoring 26

 5.1 Wheel Profiles 27

 5.2 Sinusoidal Gauge Corner Wear 27

 5.3 Pummeling 27

 5.4 Flat Wheel Detection 28

 5.5 Lateral Wheel/Rail Forces 30

6 Differential Track Settlement 30

7 Future Projects 31

8 Conclusion 32

References 32

Active Suspension Technology and its Effect upon Vehicle-Track Interaction	35
<i>Roger Goodall</i>	
1 Introduction	35
2 Active Railway Suspension Principles	35
3 The Basics of Wheelset Control	38
3.1 Ideal Curving	38
3.2 Control Strategies	41
3.3 Solid-Axle vs. IRW Wheelsets	43
4 Performance of Active-Steered Rail Vehicles	43
5 Research Challenges	45
6 Impact of Active Suspensions	46
6.1 Benefits of Active Wheelset Control	46
6.2 Vehicle-Track Cost Tradeoff	48
7 Conclusions	49
References	49

Rolling-Contact-Fatigue and Wear of Rails: Economic and Technical Aspects

<i>Peter Pointner</i>	
1 Introduction	51
2 Our Environment	52
3 Rolling-Contact-Fatigue (RCF)	52
4 Wear	56
5 The Wear - Crack-Length - Diagramm	57
6 Fields of Research and the Link to the System Costs	59
7 The Chain from Research to the Customer	61
References	61

VEHICLE DYNAMICS

System Dynamics of Railcars with Radial- and Lateralelastic Wheels

<i>Holger Claus, Werner Schiehlen</i>	
1 Motivation	65
2 Flexible Multibody Systems	66
2.1 Kinematics and Kinetics	67
2.2 Dynamic Stresses	67
2.3 Stability of Motion	68
2.4 Optimization and Parallel Computing	69
3 Excitation of Wheelsets	70
4 Strength of Conventional Wheelsets	72
4.1 Speeds with Resonance Phenomena	74
4.2 Dynamic Stresses of Wheelset	74
5 Feasibility of Radial- and Lateralelastic Wheels	75

5.1	Vertical Dynamics	77
5.2	Stability of Motion	79
6	Summary	82
	References	83

Distributed Numerical Calculations of Wear in the Wheel-Rail Contact 85

Kurt Frischmuth, Dirk Langemann

1	Introduction	85
2	Components	87
2.1	Nonlinear Dynamics	87
2.2	Rolling Contact and Dry Friction	87
2.3	Geometry	88
2.4	Wear Laws	90
3	Models	91
4	Numerics	92
4.1	Discretization	93
4.2	Distributed Calculations	94
4.3	Testing the Speed Function	95
5	Results	96
5.1	Randomized Control	98
6	Conclusions	98
7	Acknowledgements	99
	References	99

Modeling and Simulation of the Mid-Frequency Behaviour of an Elastic Bogie 101

Ingo Kaiser, Karl Popp

1	Introduction	101
2	Modeling	102
2.1	Modeling of the Vehicle	102
2.2	Finite Element Model of the Wheelset	105
2.3	Modeling of the Contact	106
2.4	Modeling of the Track	108
3	Simulation Results	109
3.1	Frequency Response of the Vehicle	109
3.2	Stationary Behaviour of the Vehicle-Track System	112
3.3	Limit Cycle Behaviour of the Vehicle-Track System	114
3.4	Transient Behaviour of the Vehicle-Track System	116
4	Conclusion	118
	References	120

Wavy Wear Pattern on the Tread of Railway Wheels 121

Michael Küsel, Eberhard Brommundt

1	Introduction	121
1.1	The Common View of the Evolution of Wavy Wear Pattern	122
1.2	Shape of Wheel Surface	123
2	Fast-Time Dynamics	124
2.1	Vehicle-Track Model	124
2.2	Contact Conditions	125
2.3	Fast-Time Equations	126
3	Slow-Time Behaviour	126
4	Evolution of the Coefficients of the Wavy Wear Pattern	128
5	Numerical Results	130
6	Conclusions and Outlook	131
	References	132

Rotor Dynamics and Irregular Wear of Elastic Wheelsets 133

Thomas Meinders, Peter Meinke

1	Motivation	133
2	Flexible Multibody Systems	133
2.1	Kinematics and Dynamics	134
2.2	Procedure of a Dynamic Analysis for a Flexible System	136
3	Modeling of Rotating Wheelsets	136
3.1	FE-Model of the Wheelset	137
3.2	Modal Analysis and Selection of the Elastic Coordinates	138
3.3	Consideration of Static and Dynamic Unbalances	140
4	Wheel-Rail Contact Module	141
4.1	Modular Organization of the Contact Module	142
4.2	Varying Wheel Radii During Time Integration	143
5	Long-Term Wear Model	143
5.1	Wear Hypothesis and Model for the Mass Loss	144
5.2	Feedback of Worn Profiles in the Sense of Long-Term Wear	146
6	System and Wear Behaviour of Elastic Wheelsets	147
6.1	Eigenbehaviour of the Wheelset	147
6.2	Wear Development due to Initial Out-Of-Roundness	148
6.3	Wear Development due to Unbalances	149
7	Summary	151
	References	151

CONTACT, FRICTION, WEAR 153

On the Numerical Analysis of the Wheel-Rail System in Rolling Contact 155

Sabine Damme, Udo Nackenhorst, Anja Wetzel, Bernd W. Zastraun

1	Introduction	155
2	The Arbitrary LAGRANGIAN-EULERIAN Approach for Rolling Contact	157

3	Equations of Motion	159
4	Description of Contact	160
4.1	The Normal Contact Problem	160
4.2	The Tangential Contact Problem for Rolling Contact	162
4.3	Kinematical Description of the Contact	164
5	The Finite Element Formulation (FEM)	165
6	Numerical Analysis of Transient Rolling Contact	166
6.1	Fundamentals for Transient Rolling	166
6.2	Classification of Irregularities and Mechanisms of Excitation ..	167
6.3	Transient Formulation of the Contact Conditions	168
7	Numerical Results	169
8	Conclusion and Outlook	173
	References	173

Experimental Analysis of the Cyclic Deformation and Damage Behavior of Characteristic Wheel and Rail Steels 175

Bernhard Denne, Karl-Heinz Lang, Detlef Löh

1	Scope of the Project	175
2	TEM Investigations of the Microstructure of a Cyclic Loaded Rail Steel	177
2.1	Materials and Testing Specimens	177
2.2	Results	177
2.3	Discussion	179
2.4	Conclusions	182
3	Deformation and Lifetime Behavior of a Cyclic Loaded Wheel Steel	182
3.1	Material and Testing Specimens	182
3.2	Experimental Details	183
3.3	Results and Discussion	185
3.4	Conclusions	188
	References	189

Friction and Wear of Tractive Rolling Contacts 191

Ludger Deters, Steffen Engel, Matthias Proksch

1	Tasks and Objectives	191
2	Two Roller Model	192
3	Calculation of Friction	192
3.1	Traction-to-Creep-Behaviour	192
3.2	Description of the Tribotechnical System	193
3.3	Contact Parameters under Tribological Loading	194
3.4	Deformation Component of Friction Force	197
3.5	Adhesion Components of Friction Force	198
3.6	Friction Coefficient	200
4	Test Machine and Test Rollers	200
4.1	Test Machine Design	200
4.2	Test Rollers	200

5	Results	201
5.1	Comparison Between Theoretical and Experimental Traction Coefficients	201
5.2	Experimental Friction and Wear Data	202
5.3	Comparison Between Wear Occurring in Original Rails and Test Rollers	207
6	Summary	208
	References	209

Model-Based Validation within the Rail-Wheel-Subgrade Modeling

Dirk Söffker, Svenja Kirchenkamp, Peter C. Müller

1	Motivation	211
2	The Rail-Wheel Contact	213
3	The Proportional-Integral-Observer	214
3.1	History of Disturbance Estimation	214
3.2	Estimation Behavior	217
3.3	Known System without External Inputs	218
3.4	Known Systems with Constant External Inputs	219
3.5	Known Systems with Arbitrary External Inputs	220
4	Modeling and Simulation	221
4.1	Simulation Results	223
5	Concluding Remarks and Future Aspects	225
	References	227

TRACK DYNAMICS

Monitoring the Dynamics of Railway Tracks by Means of the Karhunen–Loève–Transformation

Ute Feldmann, Edwin Kreuzer, Ferdinand Pinto, Volker Schlegel

1	Introduction	231
2	Dynamic System	232
3	Measurements	235
4	Karhunen–Loève–Transformation	237
5	Small Scale Experiment	239
6	Evaluation of Full Scale Measurements	242
7	Evaluation of the Results and Outlook	245
8	Conclusion	245
9	Acknowledgment	246
	References	246

Combined Modelling of Discretely Supported Track Models and Subgrade Models – Vertical and Lateral Dynamics

Ulf Gerstberger, Klaus Knothe, Yongfang Wu

1	Introduction	247
2	Frequency Domain Model for Vertical and Lateral Dynamics	248

3	Fast Time Domain Model for Vertical Dynamics	257
4	General Time Domain Model for Vertical Dynamics	259
5	Conclusions	263
	References	264

Measurement and Modelling of Resilient Rubber Rail-Pads... 265

Klaus Knothe, Minyi Yu, Heike Ilias

1	Introduction	265
2	General Concept	267
3	Quasi-Static Experiments	268
4	Low Frequency Measurements	269
5	High Frequency Experiments	271
6	Interpretation of Measurement Results	272
7	Frequency Domain Model of Rail-Pads	273
8	Concluding Remarks	273
	References	274

Model-Based Investigation of the Dynamic Behaviour of Railway Ballast 275

Holger Kruse, Karl Popp

1	Introduction	275
2	Railway Ballast in Conventional Track Models	276
3	The Software Package Train Track Interaction (TTI)	277
4	Molecular Dynamics Method	279
5	Application to Railway Ballast	280
5.1	Model Geometry	281
5.2	Contact Forces	281
5.3	Input and Output Data	283
5.4	Simulation Steps	284
6	Simulation Results	285
6.1	Plausibility and Robustness Tests	285
6.2	Short-Time Dynamics	289
6.3	Long-Term Behaviour	291
7	Concluding Remarks	292
	References	294

The Dynamics of Railway Track and Subgrade with Respect to Deteriorated Sleeper Support 295

Michael Plenge, Rolf Lammering

1	Introduction	295
2	Experimental Set-Up	296
3	Scope of Experimental Investigations	298
4	Identification of the Concrete Sleeper B70W60	299
4.1	Sleeper with Free - Free Boundary Conditions	299
4.2	Ideal Contact Between Sleeper and Subsoil	300

4.3	Partially Unsupported Sleepers due to Voids	302
5	Structural Dynamics of a Track Segment	304
6	Comparison Between Laboratory and In-Situ Experiments	309
7	Comparison Between Experimental and Numerical Investigations ..	310
8	Conclusions and Outlook	312
9	Acknowledgement	313
	References	313

SUBGRADE DYNAMICS..... 315

Numerical Model and Laboratory Tests on Settlement of Ballast Track..... 317

*Sven Augustin, Gerd Gudehus, Gerhard Huber,
Andreas Schünemann*

1	Questions	317
2	Irregular Settlements of Model Railway Tracks.....	317
2.1	Model Circular Track	317
2.2	Ballast Loading Test	321
2.3	Summary of Model Tests	321
3	Long Term Behaviour of Railroad Ballast in Laboratory Tests and Numerical Simulation	323
3.1	Cyclic Element Tests	323
3.2	Numerical Simulation of Cyclic Element Tests.....	326
4	A Numerical Track-Train Model	329
4.1	The Model of the Track	329
4.2	Troughs as Reasons of Additional Permanent Deformation	331
4.3	Simulation Results	332
	References	335

Track Settlement Due to Cyclic Loading with Low Minimum Pressure and Vibrations

Matthias Baessler, Werner Ruecker

1	Introduction.....	337
2	Loading Conditions in the Track	338
2.1	Minimum Load During Cyclic Loading	338
2.2	Vibrations and Impacts	338
3	Experimental Research and Findings	340
3.1	First Tests with a Large Track System	340
3.2	Simplified Tests - Minimum Load During Cyclic Loading	343
3.3	Simplified Tests – Dynamic Excitation	346
4	Summary and Outlook	354
	References	355

Simulation of the Dynamic Behavior of Bedding-Foundation-Soil in the Time Domain..... 357

Mohammad Firuziaan, Otto von Estorff

1	Introduction	357
2	Computational Model	360
2.1	Finite Element Method	360
2.2	Boundary Element Method	361
2.3	Coupling Strategy	363
2.4	Computational Aspects	364
3	Numerical Examples	365
3.1	Two-Dimensional Systems	365
3.2	Three-Dimensional Systems	371
4	Conclusion	373
	References	374

Dynamic Behavior of Railway Track Systems Analyzed in Frequency Domain..... 377

Klaus Friedrich, Günther Schmid

1	Introduction	377
2	Analysis Procedure	378
2.1	Boundary Element Method (BEM)	378
2.2	Finite Element Method (FEM)	379
2.3	Coupling of BEM and FEM	380
3	Numerical Results	382
3.1	Model Size	382
3.2	Influence of Different Track Geometry	383
3.3	Moving Load	386
4	Summary and Conclusion	391
	References	392

Experimental and Numerical Investigations on the Track Stability..... 395

Rolf Katzenbach, Stefan A. Heineke

1	Introduction and Motivation	395
2	Problem	396
3	Solving Method	396
4	Model Scale Tests	399
5	Transfer of the Results on a Prototype	404
6	Numeric Simulation	405
7	Possible Application of the Research Results to the Praxis	409
8	Summary	409
9	Outlook	410
	References	410

Experimental Investigation and Numerical Modelling of Soils and Ballast under Cyclic and Dynamic Loading	411
<i>Hans-Georg Kempfert, Alexander Gotschol, Yifeng Hu, Tim Stöcker</i>	
1 Introduction.....	411
2 Saturated Cohesive Soils	412
2.1 General	412
2.2 Quasi-Static Model	412
2.3 Verification of Numerical Model	415
2.4 Cyclic Triaxial Tests on a Saturated Cohesive Soil	416
3 Granular Soils and Ballast	418
3.1 Experimental Investigation and Derivation of a Cyclic-Viscoplastic Constitutive Approach	418
3.2 Numerical Implementation.....	423
3.3 Modelling Examples	427
4 Outlook and Future Objectives	430
References	430
 3D-Simulation of Dynamic Interaction Between Track and Layered Subground	431
<i>Stavros A. Savidis, Reinhold Hirschauer, Christopher Bode, Winfried Schepers</i>	
1 Introduction.....	431
2 Substructure Method	432
3 Structures on the Surface	433
3.1 Analysis in Frequency Domain	433
3.2 Analysis in Time Domain	439
4 Embedded Structures – Analysis in Frequency Domain	444
5 Outlook	448
6 Acknowledgement	448
References	448
 Rigid Body Dynamics of Railway Ballast	451
<i>Thomas Schwager and Thorsten Pöschel</i>	
1 Introduction.....	451
2 Molecular Dynamics Fails for the Simulation of Railway Ballast	452
3 Rigid Body Dynamics	454
4 Schedule of Rigid Body Simulations	456
5 Mathematical Description	457
6 Dantzig's Algorithm	462
7 Collisions	464
8 Resolution of Static Indeterminacy	466
9 Step Size Control	468
10 Conclusions	469
References	470

A Comparative Study of Results from Numerical Track-Subsoil Calculations	471
<i>W. Ruecker, L. Auersch, M. Baessler, K. Knothe, Y. Wu, U. Gerstberger, K. Popp, H. Kruse, S. Savidis, R. Hirschauer, C. Bode, W. Schepers, G. Schmid, K. Friedrich</i>	
1 Introduction	471
2 Approach and Participants	472
3 Calculated Systems	472
3.1 System Data	472
3.2 Ballasted Track	473
3.3 Slab Track	475
4 Calculating Procedure	475
5 Results	477
5.1 Ballasted Track	478
5.2 Slab Track	485
6 Summary	486
References	487