

Contents

1	Introduction	1
1.1	Structure of this Book	4
1.2	Motivation for a Holistic Assessment of the System “Energy Storage—Vehicle—Environment”	5
1.3	Initial Situation: Europe in the Energy Revolution	12
1.4	The Role of the Transport Sector	13
1.5	The Future of Transportation	15
	References	18
2	Complexity, Importance, and Overall System Dependency of the Vehicle Operating Strategy	21
2.1	A Holistic View: Vehicle, Driver, and Environment	21
2.2	<i>Subsystem</i> of Flywheel Energy Storage	22
2.2.1	Fundamentals of Kinetic Energy Storage	23
2.2.2	Differentiation According to Transmission of the Stored Energy	24
2.2.3	System Components of a FESS	32
2.3	State of the Art in the Field of Flywheel Energy Storage Systems	35
2.3.1	Existing Systems: Stationary FESS	35
2.3.2	Mobile Flywheel Energy Storage Systems for Vehicles	36
	References	45
3	<i>Supersystem</i> of Mobile Flywheel Energy Storage	49
3.1	Vehicle and Vehicle Topology	49
3.2	Features of the Primary Drive	52
3.3	Properties of Mobile Energy Storage Devices	53
3.4	Geography, Infrastructure, and Intended Use of the Vehicle	54
3.4.1	Geography and Infrastructure	54
3.4.2	Intended Use of the Vehicle	59

3.5	Driver and Energy Psychology	61
	References	64
4	Interaction Between <i>Subsystem</i> and <i>Supersystem</i> of Mobile Flywheel Energy Storage	67
4.1	Examples of Direct Influence on the <i>Super-</i> and <i>Subsystem</i> of FESS	68
4.2	Optimization of the <i>Supersystem</i>	71
4.2.1	Influence of the Driving Cycle on the FESS	71
4.2.2	Energy Requirements of the Vehicle	72
4.2.3	Profitability of a FESS in a Vehicle	78
	References	82
5	Optimizing the <i>Supersystem</i> of Mobile Energy Storage	83
5.1	Emotion Versus Ratio: Passenger Car Versus Commercial Vehicle	83
5.2	Aspects of the <i>Supersystem</i> of Public Transport and Commercial Vehicles	85
5.2.1	Energy Efficiency of Commercial Vehicles	86
5.2.2	Operating Conditions for Hybrid Propulsion Systems and Energy Storage Requirements	89
5.3	Individual Transport and Personal Cars	92
5.3.1	Aspects of the <i>Supersystem</i> “Personal Car”	92
5.3.2	Driver and Psychology	96
5.3.3	Target Characteristics of Mobile Flywheel Energy Storage Devices	99
5.4	Energetic Threshold Specifications	100
5.4.1	Determination of Energetic <i>Threshold Specifications</i> for FESS	102
5.5	Relevant Findings of the System Analysis	105
5.5.1	Summary: Optimization of the <i>Supersystem</i> of a FESS	106
5.5.2	General, Desirable FESS Improvements	106
	References	107
6	<i>Subsystem</i> Optimization	111
6.1	Deviation of <i>Desired</i> from <i>Actual Characteristics</i>	111
6.1.1	Analysis of the Cost and Weight of the System Components of Two FESS Prototypes	112
6.2	<i>Internal System Interdependencies</i> : Interactions Between Critical Components	115
6.2.1	Categorization of the Interdependencies	118
6.2.2	Critical Interdependencies in the FESS <i>Subsystem</i>	120
6.2.3	Identification of Critical Components	122

6.3	Results: Critical Components in FESS	122
	References	126
7	Rotors for Mobile Flywheel Energy Storage	127
7.1	Essential Physical Relationships of FESS Rotor Design	127
7.2	Analysis of Existing Systems/State of the Art	131
7.2.1	Composite Flywheels	131
7.2.2	Steel Flywheels	143
7.3	Requirements Derived from the <i>Supersystem Analysis</i>	145
7.4	Solution Approach/Case Study: <i>CMO Rotor</i>	148
7.4.1	System Description <i>Clean Motion Offensive</i> Flywheel	148
7.4.2	The CMO Rotor Concept	149
7.5	Solution Approach/Case Study: <i>FIMD Flywheel</i>	154
7.5.1	Structure of the <i>FIMD</i> Rotor	157
7.5.2	Burst Testing the <i>FIMD Rotor</i>	163
7.5.3	Summary of Results: Fully Integrated Multi-Disk Rotor (<i>FIMD</i>)	173
	References	176
8	Flywheel Energy Storage Housing	179
8.1	Requirements Derived from <i>Supersystem Analysis</i>	179
8.2	Safety Requirements for Mobile Energy Storage Devices	182
8.3	Analysis of Existing Systems/State of the Art	185
8.3.1	Example: Safety Housing for Composite Rotors of Stationary FESS	186
8.4	Relevant Findings from Past Research Projects	187
8.4.1	Particle Kinematics	189
8.5	Practical Design of FESS Housings	192
8.6	Analytical Calculation Methods for Designing FESS Burst Containments	194
8.6.1	Calculation According to Lockheed Missiles Company	194
8.6.2	Calculation According to <i>Giancarlo Genta</i>	197
8.6.3	Calculation According to <i>NASA</i>	198
8.7	Application of the Calculation Methods and Comparison of the Results	199
8.7.1	Summary and Plea for Empirical Burst Containment Studies	201
8.8	Qualitative Analysis and Overview of Previous Burst Tests	202
8.9	Empirical Investigation of FESS Burst Containments	204
8.9.1	Commercially Available Spin Pits and Testing Services	205
8.9.2	Structure of the Burst Test Bench	208
8.9.3	Method and Experimental Procedure	209

8.9.4	Energy Balance	211
8.9.5	Summary of Previous Findings	216
	References	219
9	Bearings for Flywheel Energy Storage	223
9.1	Analysis of Existing Systems and State of the Art	223
9.2	Requirements Derived from the <i>Supersystem Analysis</i>	225
9.2.1	Determination of Bearing Loads	225
9.3	Gyroscopic Reaction Forces in Flywheel Energy Storage	227
9.3.1	The <i>Supersystem</i> of FESS Bearings: Analysis of Environmental Parameters	227
9.3.2	Influence of FESS-Specific Operating Conditions on Bearing Design	228
9.4	Complexity and Importance of FESS Bearing Design	231
9.5	Determination of Gyroscopic Bearing Loads	232
9.5.1	Step 1: Analytical Estimation	232
9.5.2	Step 2: Numerical Simulation	235
9.5.3	Step 3: Empirical Verification	241
9.5.4	Conclusion Regarding Gyroscopic FESS Bearing Loads	245
9.6	Imbalance Forces in Energy Storage Flywheels	246
9.6.1	Balancing and Balancing Options of the <i>FIMD Rotor</i> Case Study	249
9.7	Resilient Bearing Seats for Rolling Bearings in FESS	263
9.7.1	Case Study <i>CMO Flywheel Energy Storage System</i>	264
9.7.2	Investigation of Alternative Bearing Seat Concepts: Practical Example <i>LESS</i>	266
9.8	Thermal Properties of FESS Bearings	273
9.8.1	Test Rig for Determining the Thermal Conductivity of Rolling Bearings	274
	References	277
10	Stationary FESS for Modern Mobility	279
10.1	Reduction of Torque Loss of FESS Bearings	280
10.1.1	Bearing Concepts for Stationary Flywheel Energy Storage Systems	280
10.2	Loads and Friction Losses in Rolling Bearings for FESS Applications	281
10.2.1	Bearing Loads of Stationary Flywheel Energy Storage Systems	282
10.2.2	Analytical Determination of Bearing Torque Loss	282
10.3	Bearing Load Reduction for Energy Storage Flywheels with Roller Bearings	284
10.3.1	Reduction of Axial Loads	284

10.4	Reduction of Radial Bearing Loads	290
10.4.1	Cast Silicone Bearing Seat	290
10.5	<i>FlyGrid</i> : Flywheel Energy Storage for EV Fast Charging and Grid Integration	297
10.5.1	Developments in Electric Mobility	297
10.5.2	Aims of the <i>FlyGrid</i> Project	297
10.5.3	Core Element Flywheel Energy Storage	298
	References	300
11	Summary and Outlook	303