

Contents

1	Suspension Systems Basics	1
1.1	Requirements for Suspension Systems	1
1.1.1	Minimize Accelerations on the Isolated Side	2
1.1.2	Equalize Variations of Vertical Wheel Forces	4
1.2	Suspension Technology Basics	5
1.2.1	General Setup of a Suspension System	6
1.2.2	General Behavior of a Suspension System	6
1.2.3	Alteration of Suspension Parameters	10
1.3	Hydropneumatic Suspension Compared to Other Suspension Methods	12
1.3.1	Comparison of Spring Characteristics	12
1.3.2	Comparison of Damping Characteristics	16
1.3.3	Level Control	17
1.3.4	Non-functional Requirements	18
1.4	Applications for Hydropneumatic Suspension Systems	21
2	Spring and Damping Characteristics of Hydropneumatic Suspension Systems	23
2.1	General Setup and Working Principle	23
2.2	Spring Characteristics	25
2.2.1	Thermodynamic Background	26
2.2.2	Calculation Predeterminations	29
2.2.3	Non Preloaded Hydropneumatic Suspension Systems	30
2.2.4	Systems with Mechanical Preload	39
2.2.5	Systems with Constant Hydraulic Preload	45
2.2.6	Systems with Variable Hydraulic Preload	53
2.3	Damping Characteristics	57
2.3.1	Boundary Friction Damping	59
2.3.2	Fluid Friction Damping	64
2.3.3	End-of-Stroke Damping	71
2.4	Combined Operation of Spring and Damper	73

3	Dimensioning of the Hydropneumatic Suspension Hardware	77
3.1	Dimensioning of the Hydraulic Spring Components	77
3.1.1	Cylinder	79
3.1.2	Accumulator Gas Precharge	81
3.1.3	Detailed Calculation of p_0 and V_0	84
3.2	Dimensioning of the Hydraulic Damping Elements	96
3.2.1	Single-Acting Cylinder in a System Without Hydraulic Preload	97
3.2.2	Double-Acting Cylinder in a System Without Hydraulic Preload	99
3.2.3	Double-Acting Cylinder in a System with Hydraulic Preload	102
3.2.4	End-of-Stroke Damping	103
4	Hydraulic Components Design	107
4.1	Cylinders	107
4.1.1	Function and Requirements	107
4.1.2	Types of Cylinders	108
4.1.3	Sealing Elements	114
4.1.4	End-of-Stroke Damping	119
4.1.5	Types of Support Elements	122
4.2	Accumulators	124
4.2.1	Function and Requirements	124
4.2.2	Types of Accumulators	126
4.2.3	Methods to Reduce Diffusion Pressure Loss	129
4.2.4	Usage of Pressure Relief Valves	131
4.2.5	Integration into Available Design Space	133
4.3	Flow Resistors	135
4.3.1	Non Adjustable Orifices and Throttles	135
4.3.2	Flow Direction Depending Resistors	137
4.3.3	Adjustable Flow Resistors	141
4.4	Hydraulic Lines and Fittings	145
4.4.1	Function and Requirements	145
4.4.2	Required Flow Cross Section	147
4.4.3	Tubes	148
4.4.4	Hoses	151
4.4.5	Fittings	154
4.5	Control Manifolds	155
4.5.1	Functions and Requirements	156
4.5.2	Block Design	158
5	Level Control	163
5.1	Self-Pumping Suspension Elements	163
5.2	Mechanical Level Control with External Hydraulic Power Supply	166

5.3	Electronic Level Control with External Hydraulic Power Supply	169
5.3.1	Function	169
5.3.2	Hydraulic Circuits Using On/Off-Valves	170
5.3.3	Hydraulic Circuits Using Proportional Valves	174
5.3.4	Control Algorithms	178
5.4	Electronic Level Control with Dedicated Power Supply	187
6	Special Functions of Hydropneumatic Suspension Systems	191
6.1	Suspension Lockout	191
6.1.1	Lockout by Blocking the Hydraulic Circuit	192
6.1.2	Lockout at the Compression End Stop	194
6.1.3	“Quasi-lockout” Through High Spring Stiffness	195
6.2	Adjustment of the Zero Position	196
6.3	Alteration of Roll and Pitch Behavior	198
6.3.1	Coupling Cylinders on Corresponding Sides	199
6.3.2	Decoupling Cylinders	200
6.3.3	Coupling Double-Action Cylinders on Opposite Sides	201
6.4	Spring Rate Adjustment by Selective Connection of Accumulators	205
6.5	Tire-to-Ground Force Optimization in All-Wheel Suspension Systems	207
7	Suspension Testing	215
7.1	Goals of Suspension Testing	216
7.1.1	Functional Testing	216
7.1.2	Durability Testing	218
7.2	Test Scenarios and Methods	220
7.3	Measurements, Evaluation and Optimization	223
7.3.1	Pressure	224
7.3.2	Position/Displacement	225
7.3.3	Acceleration	226
7.3.4	Online Versus Offline Evaluation	227
7.4	Typical Project Testing Steps	228
7.4.1	Initial Function Testing/Analysis	229
7.4.2	Hardware-In-The-Loop (HIL) Testing	230
7.4.3	Laboratory Functional Testing	231
7.4.4	Machine Functional Testing	232
7.4.5	Durability Testing	233
8	Design Examples	235
8.1	Tractor Front Axle Suspension TLS by John Deere	235
8.2	Passenger Car Axle Suspension by Citroen	242
8.3	Suspension Projects—Lessons Learned	252

9	Important Patents	257
9.1	Improvement of Suspension Characteristics	258
9.1.1	DE1755095	258
9.1.2	DE19719076	259
9.1.3	DE10107631	259
9.1.4	DE10337600	262
9.1.5	DE4221126	263
9.1.6	DE4234217	263
9.1.7	US9039021	264
9.1.8	DE4223783	266
9.1.9	US6167701	267
9.1.10	DE19949152	267
9.1.11	US6398227	269
9.1.12	DE102008012704	270
9.2	Roll Stabilization and Slope Compensation	271
9.2.1	GB890089	271
9.2.2	DE3427508	272
9.2.3	DE10112082	273
9.2.4	US4411447	273
9.2.5	US6923453	275
9.3	Suspension Lockout	277
9.3.1	US3953040	277
9.3.2	DE4308460	277
9.3.3	DE4032893	279
10	Looking into the Future	281
10.1	Components	281
10.2	Systems	282
10.3	Energy Consumption	284
10.4	Trend Towards Electronics	285
	Index of Symbols and Abbreviations	287
	References	291
	Index	297