

Contents

Symbols	ix
Abstract	xiii
Zusammenfassung	xv
Acknowledgements	xvii
1 Introduction	1
1.1 Role of Electric Power Steering (EPS) in Autonomous Driving	3
1.2 Related Works	6
1.2.1 Driver feel	6
1.2.2 Front steer position control	7
1.2.3 Frictional Effects within the EPS system	8
1.3 Goal of this thesis	9
1.4 Structure of this thesis	10
2 System Modelling and Identification	13

2.1	Description of the Electric power steering (EPS)	15
2.1.1	Components of the Steering Gear	16
2.1.2	The Power-Assistance Unit	18
2.2	Identification of the Steering Gear	21
2.2.1	Test Setup	21
2.2.2	Qualitative Approach	23
2.2.2.1	Investigating the electromagnetic effect of the motor	25
2.2.2.2	Investigating the effect of the belt coupling to the motor	28
2.2.2.3	Investigating the effect of the pinion	28
2.2.2.4	Conclusion of the qualitative analysis	29
2.2.3	Input-Output Behaviour	31
2.2.3.1	Identification of the gear ratio	32
2.2.3.2	Identification of the kinetic friction on an unloaded steering gear	33
2.2.3.3	Identification of the dynamic behaviour on an un- loaded steering gear	39
2.2.3.4	Identification of the static friction on an unloaded steering gear	43
2.2.3.5	Validation of an unloaded steering gear	46
2.2.3.6	Identification of the kinetic friction on a loaded steering gear	50
2.2.3.7	Identification of the static friction on a loaded steer- ing gear	57
2.2.3.8	Validation of the a loaded steering gear	59

2.2.4	Summary	63
2.3	Identification of the Primary Side	64
2.3.1	Description of the Steering Wheel, Upper Steering Shaft and adjustable steering Column	64
2.3.2	Description of the Intermediate Shaft	65
2.3.3	Test Setup	66
2.3.4	Input-Output behaviour	68
2.3.4.1	Qualitative analysis of the breakaway friction on the primary side	69
2.3.4.2	Identification of the kinetic friction on the primary side	71
2.3.4.3	Identification of the static friction on the primary side	76
3	System Analysis	81
3.1	Derivation of the Linear Model for Controller Design	82
3.1.1	Model Reduction	90
3.1.2	Comparison between the linear vs. non-linear systems	95
3.1.3	Comparison between the three-mass and reduced linear systems	97
3.2	Comparison Summary	100
3.3	Properties of Controllability and Observability	100
4	Controller Synthesis	105
4.1	Defining the control requirements	105
4.1.1	Performance criteria for the controller design	105

4.1.2	The problem with oscillatory behaviour of the steering wheel	108
4.1.3	Basic Control Design Framework	110
4.2	Frequency domain methods	112
4.2.1	PID control	112
4.2.2	Two degree of freedom control	115
4.2.3	Cascaded Control	119
4.2.4	Summary of the frequency domain controllers	123
4.3	State Space methods	124
4.3.1	Linear optimal control	125
4.3.1.1	Results in the LQI Control Scheme	131
4.3.1.2	Addressing the Steering Wheel Oscillation	134
4.3.2	Direct pole placement	137
4.3.2.1	Results of the Pole Placement Controller	139
4.4	Combined Frequency and State Space Control Design	142
4.4.1	Tuning process for the State feedback inner loop	144
4.4.2	Results of the state feedback inner loop	147
4.4.3	Outer loop Design	148
4.5	Friction Compensation	153
4.6	Chapter Summary	155
5	Analysis of the Controller Performance	157
5.1	Description of the test signals	158

5.2	Results of the controller performance against the selected signals . . .	159
5.3	Frequency bandwidth measured during the tracking	167
5.4	Summary	169
6	Estimation of the hand Torque	171
6.1	Inverse Model Approach	172
6.2	State Space Observer	174
6.3	Results of the hand torques estimation	175
6.4	Summary	176
7	Summary and future work	177
7.1	Summary and contributions	178
7.2	Future work	180
A	Parameter identification using Least Squares	181
A.1	Least Squares Estimation	181
A.1.1	Static Process	181
B	Explanation of friction models	183
B.1	Coulomb Model	184
B.2	Stribeck Curve model	184
B.3	Masing model	185
B.4	Dahl model	186
B.5	LuGre Model	187

C Further results for the identification	189
C.1 Further results for the identification of the kinetic friction under load	189
C.2 Further results for the validation of a loaded steering gear	189
C.3 Further results for the directional dependency of the static friction in the primary side	192
D Derivation of the Bicycle Model	195
D.1 Derivation of the Bicycle Model	195
E Example of tuning using the root locus results for the System Analysis	199
Bibliography	201