Contents

Summary **ix**

Nomenclature **xv**

1 Introduction **1**
1.1 Helicopters as Personal Aerial Vehicles 3
1.2 Helicopter identification 5
1.3 Helicopter augmentation 7
1.4 Research motivation 8
1.5 Objectives 8
1.6 Approach and outline of the thesis 10
1.7 Thesis scope 12
1.8 Publications 13

2 Identification of a civil light helicopter in hover **15**
2.1 Collection of flight test data 21
2.2 Development of the measurement setup 21
2.2.1 Required signals 21
2.2.2 Instrumentations for the output vehicle signals 22
2.2.3 Instrumentation for piloted control inputs . . . 22
2.2.4 Validation of the measurement setup for piloted control inputs 25

2.3 Choice of flight maneuvers 27
2.3.1 Pilot training phase 27
2.4 Flight tests 28
2.5 Frequency domain identification method 30
2.5.1 Non-parametric identification 30
2.5.2 Transfer function and state-space modeling . . 32
2.6 Non-parametric identification results 34
2.7 Transfer function modeling results 37
2.7.1 Pitch response 37
2.7.2 Heave response 40
2.8 Extended state-space identification 43
2.9 State space modeling results 47
2.10 Validation of the state-space model 54
2.11 Conclusions 57

3 Robust control methods to augment an identified helicopter model 59
3.1 Helicopter model 63
3.2 Robust control theory 64
3.2.1 H∞ control 64
3.2.2 μ-synthesis control 65
3.3 Control design 65
3.3.1 Control System Architecture 66
3.3.2 Weighting Function Selection 69
3.4 Results 72
3.4.1 Stability 72
3.4.2 Nominal Performance 73
3.4.3 Robust Performance 76
3.5 Discussion 80
3.6 Conclusions 81

4 Evaluation and validation of augmented control systems in piloted closed-loop control tasks 83
4.1 Experimental method 86
4.1.1 Apparatus 86
4.1.2 Independent variables 87
4.1.3 Mission Task Elements 88

4.1.4 Dependent measures 90
4.1.5 Participants and instructions 92
4.1.6 Experimental procedure 92
4.2 Hypotheses 94
4.3 Results 95
4.3.1 Hover MTE objective performance and workload 95
4.3.2 Hover MTE subjective rating 98
4.3.3 Lateral reposition MTE objective performance and workload 98
4.3.4 Lateral reposition MTE subjective rating . . . 101
4.4 Discussion 102
4.5 Conclusions 104

5 $\mathcal{L}_1$-based model following control to suppress model parametric uncertainties effects 107
5.1 Helicopter Model and Augmentation System 110
5.1.1 Helicopter Model 110
5.1.2 Dynamic Augmentation with a Baseline PID Controller 111
5.2 Uncertainties 113
5.3 $\mathcal{L}_1$-controller theory and implementation 118
5.3.1 Uncertain Plant 118
5.3.2 State Predictor 119
5.3.3 Adaptation Law 119
5.3.4 Control Law 120
5.4 Monte-Carlo Simulation and Results 122
5.5 Conclusions 124

6 Conclusions and Recommendations 127
6.1 Definition of new guidelines for state-space model identification 130
6.2 Weighting function selection in optimal control design 131
6.3 Assessment of augmented control systems in the MPI CyberMotion Simulator 132
6.4 Generalization of the results 134
6.5 Recommendations 135

Bibliography **137**

Appendices **145**

A Procedure for flight test data collection **147**

B Measurement setup for data collection **157**

C State space identification frequency responses **159**

D Experiment briefing **167**

E Mathematical proofs for adaptive control design **173**

Acknowledgments **175**