

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 iden- tification	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