TABLE OF CONTENTS

1. INTRODUCTION 1
2. DYNAMIC PROCESS MODEL 5
2.1. Physical process model 5
2.2. Simplifications of linear process model 7
2.3. Friction 9
2.3.1. Static friction models 10
2.3.2. Dynamic friction models 12
2.4. Limp-home nonlinearity and process static curve 17
2.5. Amplitude quantization effects and measurement noise 19
3. ETB PROCESS IDENTIFICATION 21
3.1. Experimental setup 21
3.2. Identification of linear part of process model 22
3.2.1. Identification of physical process model 23
3.2.2. Identification of integral+lag process model 32
3.2.3. Identification of discrete-time ARX process model 33
3.2.4. Comparison of identified linear process models 34
3.3. Identification of nonlinear part of process model 35
3.3.1. Limp-home nonlinearity 35
3.3.2. Friction 36
4. DESIGN OF LINEAR CONTROL SYSTEM 43
4.1. Control system structure 43
4.2. Damping optimum criterion 45
4.3. Control system optimization 46
4.3.1. Optimization based on second-order lag process model 46
4.3.2. Optimization based on integral+lag process model 48
4.3.3. Correlation between optimization methods based on second-order and integral+lag process model 49
4.4. Influence of sampling time and optimization of feedforward controller 50
4.5. PID controller gain scheduling and saturation 51
4.5.1. Gain scheduling 51
4.5.2. Controller saturation 52
4.6. Simulation and experimental results 53
4.6.1. Simulation results 53
4.6.2. Experimental results 56

5. ANALYSIS OF FRICTION AND LIMP-HOME EFFECTS 59
5.1. Limp-home effects 59
5.2. Friction effects 60
5.2.1. Static friction effects 60
5.2.2. Dynamic friction effects 63
5.3. Hybrid friction model 67
6. COMPENSATION OF FRICTION AND LIMP-HOME EFFECTS 71
6.1. An overview of friction compensation methods 71
6.1.1. Model-based methods 71
6.1.2. Non-model-based methods 73
6.2. Compensation of friction and limp-home effects 74
6.3. Simulation and experimental results 79
7. AUTOMATIC TUNING OF CONTROL STRATEGY 85
7.1. Problem formulation 85
7.1.1. Assumptions on the process model structure 85
7.1.2. Requirements on auto-tuner performance 86
7.1.3. Auto-tuner specification 86
7.2. Auto-tuner outline 87
7.3. On-line identification of process model 89
7.3.1. Phase 0 – Limp-home position estimation 89
7.3.2. Phase 1 – Breakaway from limp-home position 90
7.3.3. Phase 2 - Identification of linear process dynamics 91
7.3.4. Phase 4 - Identification of process static curve 92
7.4. Calculation of controller parameters 94
7.4.1. Phase 3 – Calculation of basic set of controller parameters 94
7.4.2. Phase 5 – Calculation of other control strategy parameters 95
7.5. Experimental results 96
8. ANALYSIS OF INFLUENCE OF PROCESS PARAMETERS VARIATIONS 97
8.1. Short discussion on influence of process parameters variations 97
8.2. Analysis of influence of armature resistance variations 98
8.2.1. Linear part of control system 99
8.2.2. Nonlinear part of control system 101
8.3. Analysis of influence of limp-home position variations and choice of limp-home compensation threshold 103
9. SELF-TUNING OF CONTROL STRATEGY 107
9.1. Problem formulation 107

9.2. Adaptation to armature resistance variations 108
9.2.1. Direct estimation of relative armature resistance R_a / R_{a0} 109
9.2.2. Indirect estimation of relative armature resistance R_a / R_{a0} 110
9.2.3. Estimation of limp-home voltage U_{LH} only 112
9.3. Adaptation to limp-home position variations 113
9.4. Experimental results 115
9.4.1. Real-time simulator of process parameters variations 115
9.4.2. Adaptation with respect to variations of armature resistance 117
9.4.3. Adaptation with respect to variations of limp-home position 122
10. APPLICATION TO SI ENGINE IDLE SPEED CONTROL 123
10.1. SI engine process model 123
10.1.1. Nonlinear mean-value engine model 123
10.1.2. Linearized engine model 125
10.2. Idle speed control 126
10.2.1. Control system structure 126
10.2.2. Feedback controller optimization 127
10.2.3. Design of load torque compensator lead-lag filter 128
10.3. Experimental results 129
11. CONCLUSION 133
APPENDIX A: ANALOGY OF INTEGRAL+LAG PROCESS MODEL AND PROCESS MODEL IN DC-DRIVE CONTROL 137
APPENDIX B: TUNING OF PI SPEED CONTROLLER 141
APPENDIX C: ANALYSIS OF LIMP-HOME OPERATING MODE 142
APPENDIX D: ANALYSIS OF PRESLIDING DISPLACEMENT BEHAVIOR 145
APPENDIX E: INFLUENCE OF ARMATURE RESISTANCE VARIATIONS IN PRESENCE OF FEEDFORWARD CONTROLLER 146
APPENDIX F: SELF-TUNING OF PID CONTROLLER TO ARMATURE RESISTANCE VARIATIONS 150
APPENDIX G: CHOICE OF POSITION REFERENCE 152
APPENDIX H: CHOICE OF DATA LENGTH FOR LIMP-HOME STANDSTILL DETECTION 153
APPENDIX I: NONLINEAR CONTROL SYSTEM STABILITY ANALYSIS 155
REFERENCES 159