
Contents

1	Introduction	1
1.1	Why Fusion?	1
1.2	What is Fusion?	2
1.3	What is a Plasma?	3
1.3.1	Fusion Energy Production and the Lawson Criterion	6
1.4	What is a Tokamak?	9
1.5	Feedback Control in Tokamaks	14
1.6	Electromagnetic Control	15
1.6.1	Modelling for Control	15
1.6.2	Plasma Boundary Estimation	16
1.6.3	Vertical Position Control	16
1.6.4	Plasma Radial Position and Current Control	18
1.6.5	Plasma Shape Control	19
1.6.6	Other Magnetic Control Problems	20

Part I Plasma Modelling

2	Plasma Modelling for Magnetic Control	25
2.1	The Ideal Magnetohydrodynamics Theory	25
2.2	Magnetohydrodynamics in Axisymmetric Toroidal Geometry	26
2.3	A Plasmaless Model	30
2.4	The Plasma Equilibrium	35
2.5	A Linearized Model for Plasma Behaviour	40
3	The Plasma Boundary and its Identification	43
3.1	Plasma Boundary Definition	43
3.2	The Plasma Boundary Descriptors	46
3.3	Tokamak Magnetic Diagnostics for Plasma Shape Identification	50
3.4	Plasma Shape Identification	53
3.5	An Algorithm for Plasma Shape Identification	55

3.5.1	Choice of the Eigenfunctions for the Fourier Expansion	56
3.5.2	Choice of the Singular Point for the Toroidal Harmonics	57
3.5.3	Numerical Results	60
3.6	Taking into Account the Eddy Currents	60

Part II Plasma Control

4	Plasma Magnetic Control Problem	65
4.1	Model for Controller Design	66
4.1.1	Simulation Model	68
4.2	Requirements for the Controller Design	68
4.2.1	Gap Control Approach	69
4.2.2	Typical Requirements and Constraints	71
4.3	Plasma Vertical Stabilization Problem	72
4.4	Control of the Currents in the Active Coils	73
4.5	Possible Different Solutions	75
5	Plasma Position and Current Control at FTU	79
5.1	The FTU Simulation Model	80
5.1.1	Plasma Model	81
5.1.2	Plasma Shape Identification Block	83
5.1.3	The Radial and Plasma Current Controllers	84
5.1.4	The F and T Circuit Converter Models	85
5.2	Choice of the Controller Gains	86
6	Plasma Vertical Stabilization	89
6.1	Vertical Stabilization Problem in the ITER Tokamak	89
6.2	Vertical Stabilization Problem for the TCV Tokamak	93
6.2.1	Design of the Vertical Position Controller	96
7	Plasma Shape Control for ITER	99
7.1	Singular Perturbation Decomposition for the ITER Tokamak	100
7.1.1	Current and Shape Controller	103
7.2	Simulation Results	105
8	Plasma Shape Control at TCV	111
8.1	Description of the TCV	111
8.1.1	Magnetic Diagnostics	112
8.1.2	Description of the Controlled Variables	114
8.2	Design Specifications	115
8.2.1	Controller Robustness	115
8.2.2	Quantization Errors in the Measurements	116
8.3	A Solution Based on the H_∞ theory	117
8.3.1	Choice of the Plant for the Design	118
8.3.2	Description of the Weighting Functions	118

8.3.3	Robust Stability	120
8.3.4	Current and Shape Controller Synthesis	121
8.4	Simulation Results	121
9	Plasma Shape Control at JET	125
9.1	Control Requirements and Simplified Plasma Modelling	125
9.2	The Controller Design	131
9.2.1	Requirements and Motivations	131
9.2.2	Optimal Output Regulation	132
9.2.3	Design of PI Controllers	137
9.3	Simulation Results	139
A	Some Mathematical Background	143
A.1	Green's Functions for the Homogeneous Grad-Shafranov Equation	143
A.2	Solutions of the Homogeneous Grad–Shafranov Equation	144
A.2.1	Green's Functions	145
A.2.2	Toroidal Harmonics	145
A.3	Ill-posedness and Plasma Shape Identification Problem	147
B	Units Used in Plasma Physics	151
References		153
Index		159