
Contents

Preface	v
Summary	vii
Nomenclature	xv
1 Introduction	1
1.1 Some illustrative examples	3
1.2 Factors in biodynamic feedthrough	5
1.3 The complexities of biodynamic feedthrough	9
1.4 Previous biodynamic feedthrough studies	11
1.5 Motivation, goal and approach	17
1.5.1 Measuring biodynamic feedthrough	19
1.5.2 Modeling biodynamic feedthrough	20
1.5.3 Mitigating biodynamic feedthrough	20
1.6 Scope of thesis	20
1.7 Guidelines for the reader	21
1.8 Outline of the thesis	22
1.8.1 A method to measure biodynamic feedthrough dynamics and admittance	23
1.8.2 A framework to analyze BDFT	24
1.8.3 A physical BDFT model	24
1.8.4 A mathematical BDFT model	24

1.8.5	New insights regarding BDFT mitigation . . .	25
1.8.6	A new approach to BDFT mitigation	25
I	Measuring and analyzing biodynamic feedthrough	27
2	Measuring biodynamic feedthrough	29
2.1	Introduction	31
2.2	Biodynamic feedthrough system model	32
2.2.1	An introduction to the biodynamic feedthrough system model	32
2.2.2	The occurrence of biodynamic feedthrough	35
2.2.3	Scope of research	36
2.3	Disturbance signal design	37
2.3.1	Frequency separation of the disturbance signals	37
2.3.2	Reduced power method	38
2.3.3	Design	39
2.4	Experiment	40
2.4.1	Hypotheses	41
2.4.2	Apparatus	42
2.4.3	Subjects	44
2.4.4	Task and task instruction	44
2.4.5	Disturbance signal scaling	46
2.4.6	Independent variables	47
2.4.7	Dependent measures	47
2.5	Results	50
2.5.1	Admittance and biodynamic feedthrough	50
2.5.2	Frequency decomposition	54
2.6	Conclusions	59
3	A framework for biodynamic feedthrough analysis	61
3.1	Introduction	63
3.2	The BDFT system model	65
3.3	BDFT signals and dynamics	71
3.3.1	Signals	71
3.3.2	Response to force disturbances	73
3.3.3	Response to motion disturbances	76

3.4	Obtaining BDFT dynamics from measurements . . .	82
3.4.1	The disturbance signals	82
3.4.2	Neuromuscular admittance	83
3.4.3	Force disturbance feedthrough	85
3.4.4	Biodynamic feedthrough to positions	86
3.4.5	Biodynamic feedthrough to forces in closed-loop	86
3.4.6	Biodynamic feedthrough to forces in open-loop	87
3.5	BDFT relationships	90
3.5.1	Force disturbance feedthrough relationships	91
3.5.2	Relationship between B2P and B2FCL	91
3.5.3	Relationship between B2P and B2FOL	92
3.5.4	Relationship between B2FCL and B2FOL	92
3.6	Neglecting control device feedthrough	94
3.7	Validating the framework	96
3.7.1	Validating the relationships	97
3.7.2	Validating the approach to calculate B2FOL dynamics	100
3.8	Interpreting BDFT dynamics	102
3.8.1	FDFT, admittance and control device dynamics	102
3.8.2	B2FOL, FDFT and B2P dynamics	105
3.8.3	The effects of changing the control device dynamics	107
3.8.4	Neglecting CDFT dynamics	110
3.9	Applying framework knowledge: an example	113
3.10	Applying the framework to literature	116
3.10.1	Case study I: mitigating B2FOL dynamics	116
3.10.2	Case study II: a vertical BDFT model	117
3.10.3	Case study III: BDFT in rotorcraft	119
3.11	Conclusions	121

II Modeling biodynamic feedthrough 125

4	A physical biodynamic feedthrough model 127
4.1	Introduction 129
4.2	The biodynamic feedthrough system model 131

4.2.1	Force disturbance feedthrough model	133
4.2.2	Developing the BDFT model	135
4.3	Model transfer functions	137
4.3.1	The FDFT model	137
4.3.2	The BDFT model	140
4.4	Modeling considerations	142
4.4.1	Open- or closed-loop	142
4.4.2	Two-stage parameter estimation	142
4.4.3	Describing the output	144
4.5	Measuring neuromuscular admittance and biodynamic feedthrough	145
4.5.1	Apparatus	145
4.5.2	Subjects	147
4.5.3	Task instruction	147
4.5.4	Procedure	148
4.5.5	Perturbation signal design	149
4.5.6	Perturbation signal scaling	149
4.5.7	Non-parametric identification	150
4.5.8	Experimental data	151
4.6	Parameter estimation procedure	152
4.6.1	The admittance model	152
4.6.2	The BDFT model	154
4.7	Analysis in the time domain	157
4.8	Results	158
4.8.1	The admittance model	158
4.8.2	The BDFT model	161
4.8.3	Results across subjects	163
4.8.4	A sanity check: adapting control device dy- namics	165
4.9	Discussion	166
4.10	Conclusions	168
5	A mathematical BDFT model for rotorcraft	171
5.1	Introduction	173
5.2	Modeling biodynamic feedthrough	175
5.2.1	The biodynamic feedthrough system model .	175
5.2.2	Relevant dynamics from the BDFT sys. model	177

5.2.3	BDFT to forces and positions	178
5.2.4	Physical, black box and mathematical models	179
5.3	Obtaining experimental data	181
5.3.1	Experimental design	181
5.3.2	Analysis	185
5.3.3	Results	186
5.4	Model development	189
5.4.1	Asymptote modeling	189
5.4.2	The base functions	190
5.4.3	Combining base functions	191
5.4.4	Determining the orders	192
5.4.5	Determining the natural frequency and damp- ing	193
5.4.6	Results	195
5.5	Model Validation	197
5.5.1	The global scope model	197
5.5.2	The partial scope model: based on subject subgroup	203
5.5.3	A comparison with other BDFT models	204
5.6	Conclusions and recommendations	206

III Mitigating biodynamic feedthrough 209

6	Biodynamic feedthrough mitigation techniques	211
6.1	Introduction	213
6.2	Potential mitigation approaches	214
6.2.1	Minimizing platform accelerations	216
6.2.2	PLF-HO interface design	216
6.2.3	Neuromuscular adaptation	219
6.2.4	HO-CD interface design	220
6.2.5	Control device design	221
6.2.6	Signal filtering	223
6.2.7	Model-based cancellation	225
6.3	Selection of promising approaches	227
6.4	Potential of armrest in BDFT mitigation	230
6.5	Potential of model-based cancellation	232

6.5.1	Method of evaluation: Optimal Signal Cancellation	232
6.5.2	Experiment: measuring BDFT	233
6.5.3	Results: biodynamic feedthrough data	235
6.5.4	Methods: optimal signal cancellation	237
6.5.5	Results	239
6.6	Conclusions	243
7	Mitigating biodynamic feedthrough with an armrest	245
7.1	Introduction	247
7.2	Experiment	248
7.2.1	Apparatus	250
7.2.2	Subjects	251
7.2.3	Task and task instruction	251
7.2.4	Independent variables	252
7.2.5	Perturbation signal design	253
7.2.6	Perturbation signal scaling	253
7.3	Analysis	254
7.3.1	Calculating the dynamics	254
7.3.2	Effect of the armrest	256
7.3.3	Expected results	257
7.4	Results	258
7.4.1	Force disturbance responses	258
7.4.2	Motion disturbance responses	263
7.5	Conclusions	271
8	Admittance-adaptive model-based BDFT cancellation	275
8.1	Introduction	277
8.2	Biodynamic feedthrough system model	278
8.3	Mitigation considerations	280
8.3.1	Between- and within-subject variability	281
8.3.2	Types of biodynamic feedthrough	282
8.3.3	Neuromuscular admittance	283
8.3.4	The role of cognitive corrective inputs	284
8.4	Mitigation approach	285
8.4.1	Challenges and opportunities	286
8.4.2	Highway-in-the-sky	286

8.4.3	Neuromuscular adaptation	287
8.4.4	Model development step 1: Identification measurements	287
8.4.5	Model development step 2: Parameter estimation	289
8.4.6	Model development step 3: Implementation	290
8.4.7	The cancellation experiment: conditions	291
8.4.8	The cancellation experiment: metrics	292
8.5	Experiment description	293
8.5.1	Hypotheses	293
8.5.2	Apparatus	293
8.5.3	Subjects	294
8.5.4	Task instruction	294
8.5.5	Experiment execution	295
8.5.6	Vehicle dynamics	296
8.5.7	HITS configuration	297
8.5.8	Disturbance signals	298
8.5.9	Calculating B2P and B2FCL	300
8.5.10	Performance metrics	301
8.6	Results	302
8.6.1	Identification measurements and parameter estimation	303
8.6.2	Cancellation metric	305
8.6.3	Tracking error metric	309
8.6.4	Effort metric	311
8.6.5	Performance-effort balance	312
8.6.6	Straight HITS sections	314
8.6.7	The closed-loop case	316
8.7	Conclusions	317
9	Discussion	321
9.1	General discussion of the results	321
9.1.1	Measuring biodynamic feedthrough	321
9.1.2	Analyzing biodynamic feedthrough	326
9.1.3	Modeling biodynamic feedthrough	327
9.1.4	Mitigating biodynamic feedthrough	332
9.2	Relationship to previous works	335

9.3	Remaining challenges	342
9.3.1	Biodynamic feedthrough in actual vehicles . . .	343
9.3.2	The effect of cognitive corrective control . . .	343
9.3.3	The effect of preview	344
9.3.4	Model-based force cancellation	344
9.3.5	Operator state observation	345
9.4	A review of the research goal	345
10	Conclusions and recommendations	349
10.1	Introduction	349
10.2	Measuring biodynamic feedthrough	350
10.3	Analyzing biodynamic feedthrough	351
10.4	Modeling biodynamic feedthrough	352
10.5	Mitigating biodynamic feedthrough	354
10.6	General conclusions	358
10.7	Recommendations	359
	Bibliography	361
	Appendices	375
A	Fundamentals of biodynamic feedthrough	377
B	Practical guidelines for biodynamic feedthrough mitigation	383
B.1	Step 1: Identifying the BDFT problem	383
B.2	Step 2: Indexing the possible mitigation approaches .	384
B.3	Step 3: Performing the approach trade-off	385
B.4	Step 4: Implementing the mitigation approach	389
	Samenvatting	391
	Acknowledgments	399
	Curriculum Vitae	403
	Publications	405