
TABLE OF CONTENTS

Preface	xiii
Nomenclature	xv
Chapter 1 Introduction	1
1.1 Drillstrings	2
1.1.1 Drill Pipe	2
1.1.2 Drill Collars	3
1.1.3 Rotary Shouldered Connections	3
1.2 Static Analysis	3
1.2.1 Neutral Point	4
1.2.2 Drill Collar Buckling	7
1.2.3 Stabilized Drill Collars	9
1.2.4 Drill Pipe Buckling	10
1.3 Dynamic Analysis	11
1.3.1 Drillstring Vibrations	11
1.3.2 Downhole Measurements of Drill Bit Forces and Motion	12
1.4 Directional Drilling	14
1.4.1 Stabilized Bottom Hole Assemblies	14
1.4.2 Directional Control Using Downhole Motors	14
1.4.2.1 <i>Positive Displacement Motors (PDM)</i>	16
1.4.2.2 <i>Downhole Drilling Turbines</i>	16
1.5 Marine Drilling And Production Risers	17
1.5.1 Hydrodynamic Forces on Cylinders	18
1.5.2 Vortex Shedding	19
1.5.3 Boundary Conditions	20
1.5.4 Marine Risers Response Prediction	21

1.5.4.1	<i>Closed Form Method of Solutions</i>	22
1.5.4.2	<i>Riser Displacement due to Rig Offset</i>	23
1.5.5	Dynamic Response	26
1.6	Maturity of Drilling and Production Technology	26
	References	27
Chapter 2	Mechanics of Long Beam Columns	31
2.1	Buckling Due to Weight of Vertical Column	31
2.2	Oscillation of a Hanging Chain	34
2.2.1	Natural Frequency of a Freely Hanging Chain	34
2.2.2	Natural Frequencies of a Hanging Chain Constrained at the Lower End	36
2.3	Short Beams Under Uniform Tension	38
2.3.1	Constant Inside and Outside Pressure with Uniform Tension	39
2.3.2	Static Analysis of Short Pipe	41
2.3.2.1	<i>Buckling of Short Pipe</i>	41
2.3.2.2	<i>Buckling from Internal Pressure</i>	43
2.3.2.3	<i>Uniformly Distributed Side Load</i>	43
2.3.2.4	<i>Non-Uniformly Distributed Side Load</i>	48
2.3.3	Dynamic Analysis of Short Pipe	49
2.3.3.1	<i>Natural Frequencies and Mode Shapes</i>	49
2.3.3.2	<i>Instability of Rotating Shafts with End Loads</i>	50
2.3.3.3	<i>Modal Analysis of Short Pipe</i>	52
2.4	Bending Equation for Long Beam-Columns	53
2.4.1	Hydrostatic Effects of Surrounding Fluids of Equal Density	53
2.4.2	Hydrostatic Effects of Surrounding Fluids of Different Densities	54
2.4.3	Unique Features of the Differential Equation of Bending	54

2.4.3.1	<i>Effective Tension</i>	56
2.4.3.2	<i>Closed Form Solution</i>	57
2.5	Buckling and Frequencies of Long Vertical Pipe	59
2.5.1	Pipes Completely Supported at the Top	63
2.5.2	Synchronous Whirl of Long Pipe	63
2.5.3	Fluid Density Greater than Pipe Density	67
2.5.4	Pipe Completely Supported at the Lower End	67
2.5.5	Stability of Pipe Stands (Case 11)	69
2.5.6	Comparison of Pipe and Chain Solutions (Case 12)	69
2.5.7	Natural Frequencies of Steel Catenaries with Buoyancy	70
2.5.8	Comparison of Steel Catenary with Elastic Pipe Solutions	72
2.6	Torsion Buckling of Vertical Pipe	74
2.6.1	Torsion Buckling of Short Pipe	74
2.6.2	Torsion Buckling of Long Vertical Pipe	78
2.6.2.1	<i>Both Top and Bottom Ends Pinned</i>	80
2.6.2.2	<i>Simply Supported at Both Ends with no End Thrust</i>	84
2.6.2.3	<i>Top End Pinned and Bottom End Fixed</i>	85
2.7	Rotational Stability and Whirl of Vertical Pipe	88
2.7.1	Stability of Long Vertical Pipe due to Torque, Rotation, and Damping	88
2.7.2	Lower End Subjected to a Direct Pull Force	88
2.7.3	Lower End Opened to Hydrostatic Pressure	90
2.7.3.1	<i>Mathematical Solution</i>	91
2.7.3.2	<i>Stability Analysis</i>	93
2.7.4	Relative Whirl versus Absolute Whirl	99
2.8	Parametric Resonance	100
	References	102

Chapter 3 Drillstring Mechanics	105
3.1 Buckling and Lateral Vibrations of Drill Pipe	105
3.1.1 Differential Equation of Bending	105
3.1.2 Method of Solution	108
3.1.3 Use of Buckling Solution	109
3.1.4 Natural Frequencies of Drill Pipe (Lateral Modes)	112
3.2 Buckling of Drill Collars	116
3.2.1 Bending Equation	116
3.2.2 Lubinski's Solution	117
3.2.3 Helical Buckling Within Well Bore or Casing	122
3.3 Stabilizer Placement Analysis	123
3.3.1 Method of Solution	123
3.3.2 Example Calculation	128
3.4 Buckling on an Inclined Plane	130
3.4.1 Buckling of Drillstrings in Directional Wells	131
3.5 Drill Collar Dynamics	131
3.5.1 Whirling Motion in Drill Collars	131
3.5.1.1 <i>Differential Equations of Motion</i>	132
3.5.1.2 <i>Effective Tension</i>	132
3.5.1.3 <i>Mathematical Solution</i>	135
3.5.1.4 <i>Establishing R_γ and I_γ</i>	136
3.5.2 Criteria for Dynamic Stability	137
3.5.3 Relative Whirl versus Absolute Whirl	138
3.5.4 Synchronous Whirl Based on Zero Damping	139
3.5.5 Experimental Measurements of Drill Collar Whirl	140
3.5.6 Unbalanced Drill Collars	142
3.5.7 Excitation by Positive Displacement Motors (PDM)	142
3.5.8 Coupling of Axial and Lateral Vibrations	143
3.5.9 Stick-Slip-Induced Vibrations	143
3.6 Theories of Axial and Torsion Vibrations	144
3.6.1 Forced Vibrations	144
3.6.2 Roller Cone Drill Bits	144

3.6.2.1	<i>Axial and Torsion Vibration Model</i>	145
3.6.2.2	<i>Quantifying Damping for Axial Modes</i>	150
3.6.3	Natural Frequencies of Axial, Torsion, and Lateral Modes	152
3.6.3.1	<i>Natural Frequencies of Axial Modes</i>	153
3.6.3.2	<i>Natural Frequencies of Torsion Modes</i>	157
3.6.3.3	<i>Natural Frequencies of Lateral Modes</i>	159
3.6.4	Polycrystalline Diamond Compact (PDC) Drill Bits	160
3.6.4.1	<i>Self-Exciting Mechanism</i>	160
3.6.4.2	<i>Stability Analysis</i>	162
3.6.5	Experimental Verification of Theory	165
3.6.6	Backward Whirl of PDC Drill Bits	168
3.6.6.1	<i>Gear Tracking</i>	168
3.6.6.2	<i>Cutter Impulsive Force</i>	169
3.6.7	Accounting for Torsion Flexibility in Drill Collars	171
3.6.7.1	<i>Free Torsion Vibration Caused by Cutter Impulse</i>	172
3.7	Vibration Control	174
3.7.1	Roller Cone Drill Bits	175
3.7.1.1	<i>Shock Absorbers</i>	175
3.7.1.2	<i>Drill Collar Design</i>	176
3.7.2	PDC Rock Bit	178
3.7.2.1	<i>Operation and Design for Regions of Stability</i>	178
3.7.2.2	<i>Shock Absorber Design for PDC Drill Bit Applications</i>	178
3.7.2.3	<i>Drill Bit Design</i>	180
3.8	Friction in Directional Wells	180
3.8.1	Coefficient of Friction	180
3.8.2	Soft Pipe Model	181
3.8.3	Elastically Flexible Model	184
3.8.3.1	<i>Pulling out of Well Bore</i>	184
3.8.3.2	<i>Putting Pipe into Well Bore</i>	189

References	191
Appendix 3A: Computer Model of Drill Collar Bending Between Multiple Stabilizers	195
Chapter 4 Mechanics of Marine Risers	201
4.1 Static Analysis of Marine Risers	201
4.1.1 Buckling of Marine Risers	201
4.1.2 Static Displacement of Riser in One Plane	205
4.1.2.1 <i>Differential Equation of Bending</i>	205
4.1.2.2 <i>Boundary Conditions</i>	206
4.1.3 Deflection Caused by Rig Offset	206
4.1.3.1 <i>Ball Joint at Lower End</i>	207
4.1.3.2 <i>Flex/Ball Joint</i>	210
4.1.3.3 <i>Fixed Lower End</i>	213
4.1.4 Deflections Caused by Uniform Current Loading	216
4.1.4.1 <i>Differential Equation of Bending</i>	217
4.1.4.2 <i>Method of Solution</i>	218
4.1.4.3 <i>Effective Tension vs Average Effective Tension</i>	222
4.1.5 Tapered Flex Joints	225
4.1.5.1 <i>Equation of Bending</i>	226
4.1.5.2 <i>Parabolic Approximation to Moment of Inertia</i>	226
4.1.5.3 <i>Solution to Differential Equation</i>	227
4.1.5.4 <i>Example Calculation</i>	230
4.1.5.5 <i>Hydrostatic Effects</i>	232
4.1.6 Interfacing Tapered Flex Joints with Uniform Riser Pipe	232
4.1.6.1 <i>Boundary Conditions</i>	233
4.1.6.2 <i>Tapered Flex Joint Section</i>	234
4.1.6.3 <i>Uniform Riser Pipe Section</i>	234
4.1.6.4 <i>Merging the Two Solutions</i>	236
4.1.6.5 <i>Example Calculation</i>	239
4.1.7 Broader Applications of the Closed Form Solution	241
4.1.7.1 <i>Combining Two or Multiple Sections</i>	241

4.1.7.2	<i>Intermediate Buoys in Riser Pipe</i>	248
4.1.8	Method of Segments	252
4.1.9	Ultra Deep Risers	254
4.1.9.1	<i>Tapered Flex Joint, Short Riser Pipe, Steel Catenary</i>	255
4.1.9.2	<i>Tapered Flex Joint Section</i>	255
4.1.9.3	<i>Short Riser Pipe Section</i>	256
4.1.9.4	<i>Steel Catenary Section</i>	256
4.1.9.5	<i>Boundary Conditions</i>	257
4.2	Dynamic Analysis — Natural Frequencies	260
4.2.1	Differential Equation of Motion	260
4.2.1.1	<i>Ball Joint Attachment</i>	261
4.2.1.2	<i>Structurally Fixed at BOP</i>	264
4.2.2	Natural Frequencies Based on Steel Catenary Model	265
4.2.3	Alternate Methods for Determining Natural Frequencies	265
4.2.3.1	<i>Uniform Tension</i>	265
4.2.3.2	<i>Iteration on Lateral Mode</i>	267
4.3	Dynamic Analysis — Forced Vibration	269
4.3.1	In-Line Vibration Caused by Ocean Currents and Waves	269
4.3.1.1	<i>Formulation of Equation of Motion</i>	271
4.3.1.1.1	<i>Current Loading</i>	272
4.3.1.1.2	<i>Rig Offset</i>	273
4.3.1.1.3	<i>Forced Vibration</i>	273
4.3.1.2	<i>Example Calculation</i>	274
4.3.2	Vortex-Induced Vibration	275
4.3.2.1	<i>Self Exciting Mechanism</i>	277
4.3.2.2	<i>Modal Analysis</i>	278
	Appendix 4A: Cables Suspended in Air	281
	Appendix 4B: Comparison of Steel Catenary Approximation with Elastic Riser	284
	References	286

Chapter 5	Applied Drilling Mechanics	289
5.1	Developing a Drilling Program	289
5.1.2	Operational Requirements	289
5.1.3	Design Specifications	290
5.1.4	Creating Design Alternatives	290
5.1.5	Evaluating Alternatives	290
5.1.6	Drillstring Design	291
5.1.6.1	<i>Drill Bits</i>	292
5.1.6.2	<i>Roller Cone Drill Bits</i>	292
5.1.6.3	<i>Polycrystalline Diamond Compact (PDC) Bits</i>	292
5.1.6.4	<i>Natural Diamond Bits</i>	292
5.1.6.5	<i>Cost Analysis</i>	293
5.1.6.6	<i>Bottom Hole Assemblies</i>	296
5.1.6.7	<i>Positive Displacement Motors</i>	296
5.1.6.8	<i>Downhole Drilling Turbines</i>	302
5.1.6.9	<i>Measurement While Drilling Tools</i>	306
5.1.6.9.1	<i>Directional Drilling</i>	307
5.1.6.9.2	<i>Vibration Monitoring</i>	309
5.1.6.10	<i>Stabilized Assemblies</i>	309
5.1.6.10.1	<i>Building Assemblies</i>	309
5.1.6.10.2	<i>Holding Assemblies</i>	310
5.1.6.10.3	<i>Dropping Assemblies</i>	310
5.1.6.11	<i>Drill Collars</i>	312
5.1.6.12	<i>Drill Pipe</i>	314
5.1.6.12.1	<i>Drill Pipe Stress Components</i>	314
5.1.6.12.2	<i>Bending at Drill Pipe/Drill Collar Interface</i>	316
5.1.6.12.3	<i>Effect of Dog Legs on Bending Stress</i>	317
5.1.6.12.4	<i>Tool Joints and Make-up Torque</i>	322

5.2	Hydraulics of Rotary Drilling	323
5.2.1	Mud Pumps	324
5.2.2	Parasitic Losses	325
5.2.3	Nozzle Selection	328
5.2.4	Annular Velocity Requirements	329
5.2.5	Available Hydraulic Horsepower	330
5.2.6	Power Demands of Downhole Motors	331
5.3	Optimum Drilling Practices	333
5.3.1	Drill Bit Selection	333
5.3.2	Bit Weight and Rotation Speed	334
5.3.3	Optimum Hydraulics for Drill Bit Cleaning	335
5.3.4	Impact Force	336
5.3.5	Pressure Balance	338
5.3.6	Drilling Mud Properties	338
5.3.7	Bottom Hole Assembly Design	339
	References	339
Chapter 6	Selected Topics in Marine Riser Design	341
6.1	Marine Drilling Risers	341
6.1.1	Drilling Mode	341
6.1.1.1	<i>Effective Tension and Riser Buckling</i>	342
6.1.1.2	<i>Rotation Across Flex/Ball Joint</i>	342
6.1.2	Non-Drilling Mode	345
6.1.2.1	<i>Replacing Drilling Mud with Sea Water</i>	345
6.1.2.2	<i>Replacing Drilling Mud with Sea Water</i>	347
6.1.3	Disconnect Mode	348
6.2	Marine Production Risers	348
6.2.1	Top-Mounted Tapered Flex Joint	348
6.2.2	Optimizing Tapered Flex Joints	354
6.3	Bending of Bundled Tubulars Attached To Production Risers	355
6.3.1	Method of Solution	356
6.3.2	Example Calculation	361

xii • Table of Contents

Appendix 6A: Bop Suspended at Lower End of Drilling Riser	364
Appendix 6B: Drill Pipe Whirl Within Drilling Risers	367
References	372