

# DYNAMICS OF SPACE TETHER SYSTEMS

by

Vladimir V. Beletsky  
Evgenii M. Levin



Volume 83

ADVANCES IN THE ASTRONAUTICAL SCIENCES





# DYNAMICS OF SPACE TETHER SYSTEMS

**Volume 83  
ADVANCES IN THE ASTRONAUTICAL SCIENCES**

by  
**Vladimir V. Beletsky**  
**Evgenii M. Levin**

*The English language edition of this book is based on a Russian language version originally published in Moscow, Nauka, Main Editorial Board for Physical and Mathematical literature, 1990.*

*Published for the American Astronautical Society by  
Univelt, Incorporated, P.O. Box 28130, San Diego, California 92198*

# CONTENTS

Foreword . . . . .	iii
Historical . . . . .	7
The Concept of the Book . . . . .	9
Computer Aid . . . . .	13
Nomenclature . . . . .	15
<b>1. Tethers in Space . . . . .</b>	<b>19</b>
1.1. Space Tether Applications . . . . .	20
1.2. Science Fiction and Reality . . . . .	34
1.3. Mechanical Models . . . . .	42
1.3.1. <i>General Model</i> . . . . .	42
1.3.2. <i>Equations of Tether Motion</i> . . . . .	43
1.3.3. <i>Motion of the End-Bodies</i> . . . . .	45
1.3.4. <i>Simplified Models</i> . . . . .	47
1.3.5. <i>Tether Systems (TS)</i> . . . . .	48
1.4. Perturbations . . . . .	48
1.5. The Main Points . . . . .	59
<b>2. Dynamic Problems . . . . .</b>	<b>61</b>
2.1. Model with a Massless Tether . . . . .	62
2.2. Massive Tether: Motion of the Mass Center . . . . .	66
2.3. Pendular Motions . . . . .	71
2.4. Oscillations Against a Pendular Motion . . . . .	78
2.4.1. <i>Full Equations</i> . . . . .	78
2.4.2. <i>Linearization</i> . . . . .	80
2.4.3. <i>Decomposition</i> . . . . .	83
2.5. Stationary Motions . . . . .	83

2.6. Investigation of Stability . . . . .	87
2.6.1. <i>Variation Equations</i> . . . . .	87
2.6.2. <i>Eigenvalue Problem</i> . . . . .	88
2.6.3. <i>Eigenvalue Calculation Technique</i> . . . . .	91
2.7. Forced Oscillations . . . . .	95
2.8. Fast and Slow Components of Tether Motion . . . . .	98
2.8.1. <i>Difficulties of Numerical Simulation</i> . . . . .	98
2.8.2. <i>Modified Minakov's Equations</i> . . . . .	100
2.8.3. <i>Tether Compression</i> . . . . .	103
2.8.4. <i>Gradient of External Forces</i> . . . . .	106
2.8.5. <i>Boundary Conditions</i> . . . . .	107
2.8.6. <i>Concluding Relations</i> . . . . .	109
2.9. The Main Points . . . . .	111
<b>3. Tether in the Newtonian Field</b> . . . . .	115
3.1. Classification of Motions with a Massless Tether . . . . .	116
3.2. Equilibria of a Massive Tether . . . . .	120
3.2.1. <i>Equilibrium Equations</i> . . . . .	120
3.2.2. <i>Integrating Tether Equilibrium Equations</i> . . . . .	122
3.2.3. <i>Tether Wave Shapes</i> . . . . .	125
3.2.4. <i>Out-of-Plane Configurations</i> . . . . .	128
3.2.5. <i>Tapered Constant-Stress Tether</i> . . . . .	131
3.3. Conditions at the Tether Ends . . . . .	132
3.4. Bifurcations of Equilibria and Stability . . . . .	137
3.4.1. <i>Out-of-Plane Oscillations</i> . . . . .	138
3.4.2. <i>Instability of Wave-Like Configurations</i> . . . . .	139
3.4.3. <i>Stability of Monotonous Configurations</i> . . . . .	142
3.4.4. <i>Analogy to Euler's Problem</i> . . . . .	147
3.5. Radial Configurations . . . . .	148
3.6. Stability of Radial Configurations . . . . .	153
3.6.1. <i>Inextensible Tether</i> . . . . .	153
3.6.2. <i>Extensible Tether</i> . . . . .	157
3.6.3. <i>Super-Long Tether</i> . . . . .	160
3.6.4. <i>Tether Twisting</i> . . . . .	162
3.7. Natural Frequencies and Modes of Oscillations . . . . .	164
3.7.1. <i>Eigenvalue Problem</i> . . . . .	164
3.7.2. <i>Longitudinal Oscillations</i> . . . . .	166
3.7.3. <i>Transverse Oscillations</i> . . . . .	167
3.7.4. <i>Coupled Longitudinal-Transverse Oscillations</i> . . . . .	173
3.8. Nonlinear Oscillations . . . . .	176
3.8.1. <i>Galerkin's Formulation</i> . . . . .	176

3.8.2. <i>Integrating Equations of Oscillations</i>	. . . . .	179
3.8.3. <i>Amplitude-Frequency Relation</i>	. . . . .	182
3.9. Rotation of the End-Bodies	. . . . .	183
3.9.1. <i>Equations of Rotational Motion</i>	. . . . .	183
3.9.2. <i>Uniaxial Orientation along the Tether Line</i>	. . . . .	186
3.9.3. <i>Rotation about the Tether Line</i>	. . . . .	189
3.9.4. <i>Torsional Oscillations of a Tape</i>	. . . . .	194
3.10. The Main Points	. . . . .	195
<b>4. Tethered Atmospheric Probe</b>	. . . . .	199
4.1. Aerodynamic Forces	. . . . .	200
4.2. Classification of Motions with a Massless Tether	. . . . .	202
4.3. Equilibria of a Massive Tether	. . . . .	208
4.3.1. <i>Equilibrium Equations</i>	. . . . .	208
4.3.2. <i>Wave-Like Configurations</i>	. . . . .	209
4.3.3. <i>Monotonous Configurations</i>	. . . . .	212
4.3.4. <i>The Effect of the Atmospheric Rotation</i>	. . . . .	214
4.4. Stability of Stationary Motions	. . . . .	216
4.4.1. <i>Increments to the Aerodynamic Forces</i>	. . . . .	216
4.4.2. <i>Damping Out-of-Plane Oscillations</i>	. . . . .	216
4.4.3. <i>In-Plane Oscillations</i>	. . . . .	218
4.4.4. <i>Orbital Instability</i>	. . . . .	220
4.4.5. <i>Evolution of Eigenvalues</i>	. . . . .	222
4.5. Aerogradient Instability	. . . . .	226
4.5.1. <i>Massless Tether</i>	. . . . .	226
4.5.2. <i>Massive Tether</i>	. . . . .	229
4.5.3. <i>Stability Regions</i>	. . . . .	233
4.5.4. <i>Effective Longitudinal Stiffness of the Tether</i>	. . . . .	235
4.6. Sounding Feasibility Assessment	. . . . .	241
4.6.1. <i>Tether Strength Condition</i>	. . . . .	241
4.6.2. <i>Stability Condition</i>	. . . . .	243
4.6.3. <i>Thrusting</i>	. . . . .	248
4.6.4. <i>Heating</i>	. . . . .	248
4.6.5. <i>Conclusions</i>	. . . . .	253
4.7. Periodic Perturbations	. . . . .	253
4.7.1. <i>Rotation of the Atmosphere</i>	. . . . .	253
4.7.2. <i>Variations of the Air Density</i>	. . . . .	256
4.7.3. <i>Orbit Ellipticity</i>	. . . . .	258
4.7.4. <i>Resonance in Out-of-Plane Oscillations</i>	. . . . .	260
4.7.5. <i>Pendular Approximation</i>	. . . . .	262
4.8. The Main Points	. . . . .	264

<b>5. Electrodynamic Tether</b>	267
5.1. Physical Description	268
5.2. Analysis of Motion with a Massless Tether	272
5.2.1. <i>Equations of Motion</i>	272
5.2.2. <i>Equilibrium Positions</i>	274
5.2.3. <i>Instability under a Constant Current</i>	276
5.3. Equilibria of a Massive Tether	281
5.3.1. <i>Equilibrium Equations</i>	281
5.3.2. <i>Integrating Tether Equilibrium Equations</i>	283
5.3.3. <i>Conditions at the Tether Ends</i>	286
5.3.4. <i>Current Limitation</i>	287
5.3.5. <i>Tether Shape</i>	289
5.4. Stability of Stationary Motions	291
5.4.1. <i>Out-of-Plane and In-Plane Oscillations</i>	291
5.4.2. <i>Instability under a Constant Current</i>	292
5.4.3. <i>Current Control</i>	294
5.4.4. <i>Calculation of Eigenvalues</i>	295
5.4.5. <i>Asymptotic Stability Conditions</i>	297
5.4.6. <i>Effective Longitudinal Stiffness of the Tether</i>	299
5.4.7. <i>Stability Regions</i>	303
5.5. Generation and Propulsion Feasibility Assessment	304
5.5.1. <i>Stability Limitations</i>	304
5.5.2. <i>Ohmic Losses</i>	308
5.5.3. <i>Conclusions</i>	309
5.6. Forced Oscillations and Orbit Evolution	310
5.7. Petal-Like Configurations	314
5.7.1. <i>Equilibrium Shapes</i>	314
5.7.2. <i>Stability Proof</i>	316
5.7.3. <i>Forced Oscillations</i>	320
5.8. The Main Points	321
<b>6. Traveling Tether</b>	323
6.1. Equations of Motion with a Traveling Tether	324
6.1.1. <i>General Equations</i>	324
6.1.2. <i>Integrating Tether Equilibrium Equations</i>	325
6.1.3. <i>Out-of-Plane Configurations</i>	328
6.2. The Loops of a Traveling Tether	332
6.2.1. <i>“Right” and “Left” Loops</i>	332
6.2.2. <i>Stability of the “Right” Loops</i>	336
6.3. The Main Points	337

<b>7. Damping Oscillations . . . . .</b>	339
7.1. Possible Ways of Damping . . . . .	340
7.1.1. <i>Internal Friction in the Tether</i> . . . . .	340
7.1.2. <i>Active Longitudinal Damper</i> . . . . .	342
7.1.3. <i>Nonlinear Damping of Out-of-Plane Oscillations</i> . . . . .	344
7.1.4. <i>Other Strategies</i> . . . . .	346
7.2. Decrments for a Massive Tether . . . . .	348
7.3. Damping with a Movable Boom . . . . .	353
7.4. The Main Points . . . . .	358
<b>8. Rotation and Libration . . . . .</b>	361
8.1. Classification of Motions with a Massless Tether . . . . .	362
8.1.1. <i>Equations of Motion</i> . . . . .	362
8.1.2. <i>Circular Orbit</i> . . . . .	362
8.1.3. <i>Elliptic Orbit</i> . . . . .	366
8.2. Motions with a Slack Tether . . . . .	369
8.2.1. <i>Tether Bounces</i> . . . . .	369
8.2.2. <i>Evolution of Motion</i> . . . . .	371
8.2.3. <i>Final Motions</i> . . . . .	378
8.3. Pendular Motions with a Massive Tether . . . . .	378
8.4. Modal Decomposition . . . . .	383
8.4.1. <i>Transverse Oscillations</i> . . . . .	383
8.4.2. <i>Parametric Resonances</i> . . . . .	386
8.4.3. <i>Oscillations of Tension</i> . . . . .	391
8.5. The Main Points . . . . .	395
<b>9. Deployment and Retrieval . . . . .</b>	397
9.1. Exponential Deployment and Retrieval . . . . .	398
9.2. Uniform Deployment and Retrieval . . . . .	401
9.2.1. <i>Nearly Uniform Tether Length Variation</i> . . . . .	402
9.2.2. <i>Natural Tether Tension Control</i> . . . . .	407
9.2.3. <i>Adjusted Tension Control</i> . . . . .	412
9.3. Some General Limitations . . . . .	415
9.4. Tether Configuration During Deployment and Retrieval . . . . .	420
9.4.1. <i>Quasi-Stationary Tether Shapes</i> . . . . .	420
9.4.2. <i>Deployment from the Main Satellite</i> . . . . .	423
9.4.3. <i>Deployment from the Subsatellite</i> . . . . .	424
9.4.4. <i>Deployment from Both Ends</i> . . . . .	426
9.5. Modal Expansion and Analysis of Transient Processes . . . . .	427
9.5.1. <i>Transverse Oscillations</i> . . . . .	427
9.5.2. <i>Longitudinal Oscillations</i> . . . . .	432
9.5.3. <i>Numerical Simulation</i> . . . . .	433

9.6. Motion after Tether Release or Failure . . . . .	435
9.7. The Main Points . . . . .	440
<b>10. Anchored Tether . . . . .</b>	<b>443</b>
10.1. Motions of a Lunar Tethered Satellite . . . . .	444
10.1.1 <i>Equations of Motion</i> . . . . .	444
10.1.2. <i>Approximation of a Circular Orbit</i> . . . . .	446
10.1.3. <i>Elliptic Orbit</i> . . . . .	450
10.2. Stationary Configurations . . . . .	451
10.3. Stability of Radial Configurations . . . . .	457
10.4. Motion of a Phobos Anchored String . . . . .	461
10.5. The Main Points . . . . .	463
<b>11. Satellite Ring . . . . .</b>	<b>465</b>
11.1. Discrete and Continuum Models . . . . .	466
11.2. Stability of a Continuum Ring . . . . .	468
11.3. Stability of a Discrete Ring . . . . .	476
11.4. Analogy to Planet Rings . . . . .	479
11.5. The Main Points . . . . .	482
References . . . . .	485
Subject Index . . . . .	495
List of Tables . . . . .	499

# Chapter 1

## TETHERS IN SPACE

*Twenty six kinds of tether systems in space (20–33)*

*"The Fountains of Paradise" by A. Clarke and tethers (34–42)*

*Real restrictions on the tether strength and mass (34–37)*

*Modern tether materials (35)*

*An appropriate material for a space elevator (36)*

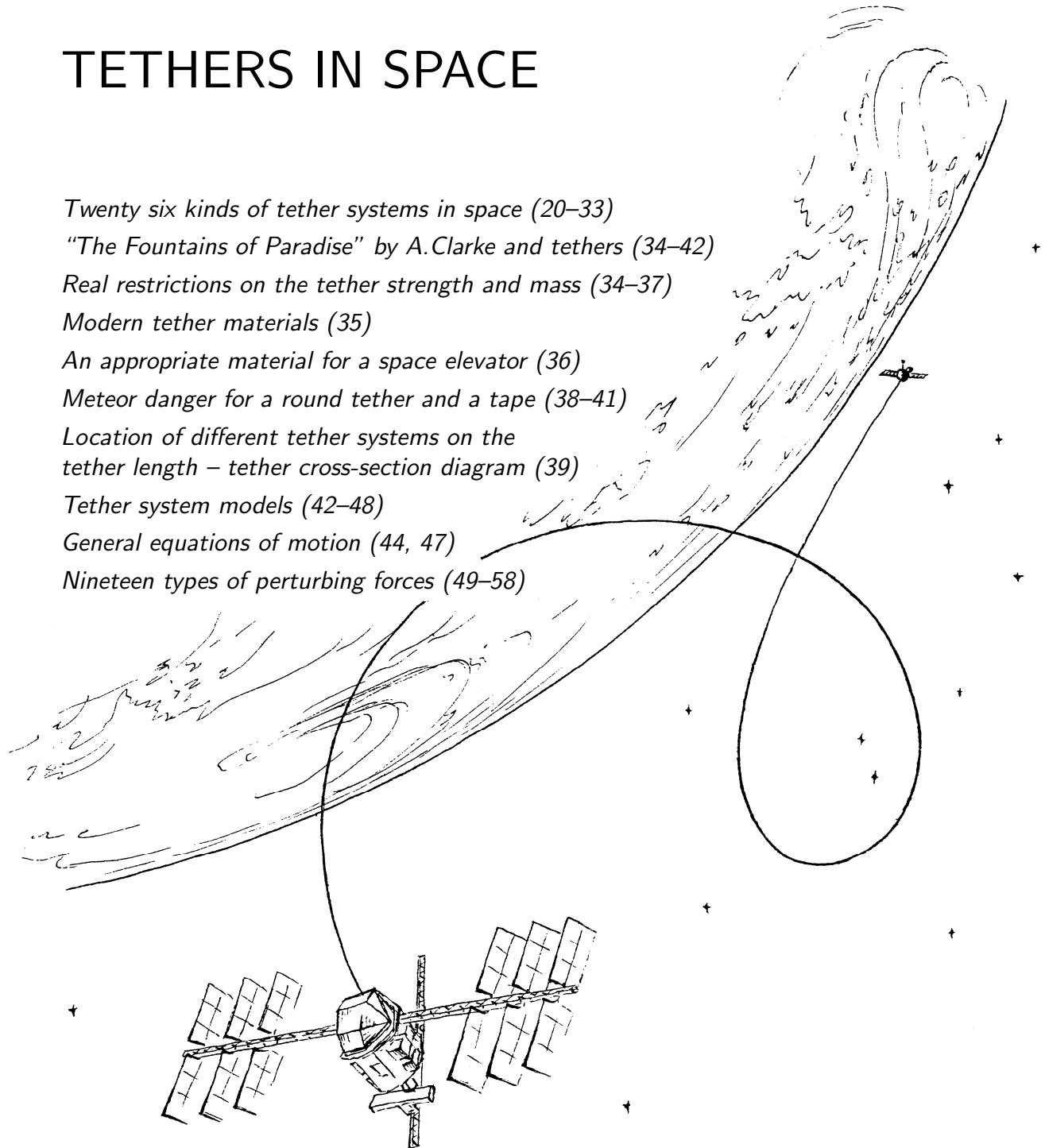
*Meteor danger for a round tether and a tape (38–41)*

*Location of different tether systems on the  
tether length – tether cross-section diagram (39)*

*Tether system models (42–48)*

*General equations of motion (44, 47)*

*Nineteen types of perturbing forces (49–58)*



## Chapter 2

# DYNAMIC PROBLEMS

*Five types of subsatellite motion equations with a massless tether (62–65)*

*Equations of the mass center motion with a massive tether (66, 70)*

*Forces acting on a tether system: reactive, gravitational, aero- and electrodynamic (66–70)*

*The concept of a “gravicraft” (67–68)*

*Rotation of an imaginary rigid tether system (72–76)*

*Expressions for the external torques (75–76)*

*Nonlinear and linearized equations of oscillations about the imaginary rigid motion (78–82)*

*Tether equilibrium configurations with respect to the orbital frame (84–86)*

*Calculation of the eigenvalues of small oscillations about the equilibrium configurations (88–93)*

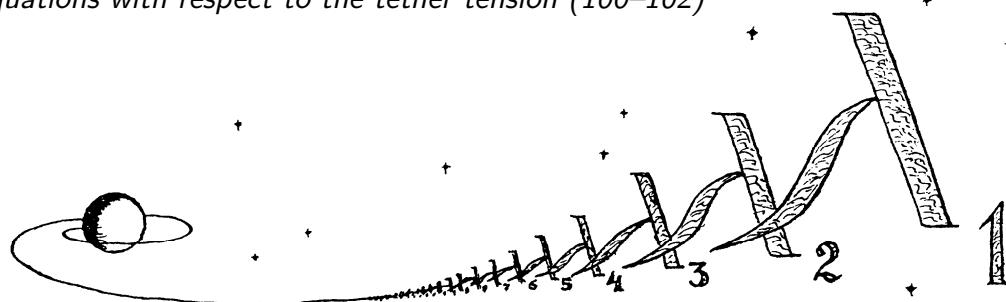
*Asymptotic calculation of the real parts of the eigenvalues (93–94)*

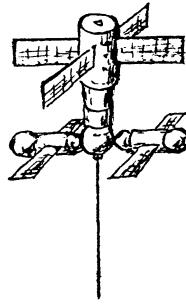
*The effect of perturbing forces having the orbital period (96–97)*

*Fast longitudinal and slow transverse waves in the tether (98–99)*

*Wave velocities for various tether materials (99)*

*Distinguishing “fast” and “slow” wave structures in second order equations with respect to the tether tension (100–102)*





## Chapter 3

# TETHER IN THE NEWTONIAN FIELD

*Six equilibrium positions of a subsatellite on a massless tether and their stability (116–118)*

*Regions of possible motion (119)*

*Wave-like configurations of tether described by quadratures (122–127)*

*Tether specific strength and characteristic length (126, 128)*

*The length of a uniformly stressed tapered tether can exceed the characteristic length (131–132)*

*Equilibria without thrust support (135)*

*The evolution of the eigenvalues in a set of wave-like configurations (141–142)*

*Features of monotonous configurations (143–146)*

*Stabilizing tether configurations along the orbit (147–148)*

*The diversity of radial configurations is described by only two parameters (149–152)*

*Lyapunov's functionals and Poincaré's stability coefficients (138, 143–146, 154–159)*

*A super-long tether system "falls" from the orbit (160–162)*

*A "pig-tail" shape of the tether (162–163)*

*Analytic expressions and low frequency maps for uniform and tapered tethers (166–174)*

*Frequencies of a super-long tether system (175–176)*

*Analytic results for nonlinear oscillations (178–182)*

*The attitude dynamics of a tethered subsatellite (183–195)*

## Chapter 4

# TETHERED ATMOSPHERIC PROBE

- Aerodynamic characteristics of the tether (200–201)*
- Inclined equilibria of a tethered subsatellite (203–207)*
- Aerodynamic stabilization tangent to the orbit (205–206)*
- Wave-like configurations with a “sailing” tether loop (209–210)*
- Generalized integral of the tether tension force moment (212, 214)*
- Drag-compensating thrust (214, 249)*
- The effect of the atmospheric rotation (215, 253–255)*
- Damping decrements for out-of-plane oscillations (217–218)*
- Instability of the wave-like configurations (223, 226)*
- Energy pumping through non-conservative components of the aerodynamic forces (228)*
- Stability conditions and the critical tether length and diameter (227–233)*
- Damping decrements for in-plane oscillations (231)*
- Location of the stability boundary and the effective longitudinal stiffness of the tether (234–240)*
- Comparison of different tether materials (243–252)*
- The orbital lifetime of an atmospheric tether system (248–249)*
- Periodic motions originating from the stationary motions (253–264)*

## Chapter 5

# ELECTRODYNAMIC TETHER

*Operation of the electrodynamic tether system (268–271)*

*Subsatellite on a curved massless tether (272–276)*

*Energy pumping by non-conservative components  
of the Ampere forces (277–279)*

*Loop-like tether configurations described by quadratures (283–285)*

*The first critical current determined by  
equilibrium conditions (287–288)*

*Controlling oscillations through varying the current and  
the Ampere forces distributed along the tether (294–295)*

*Asymptotic calculation of the real parts of the eigenvalues (296–297)*

*Utilizing the energy dissipation due to  
the Foucault currents (299, 307, 318).*

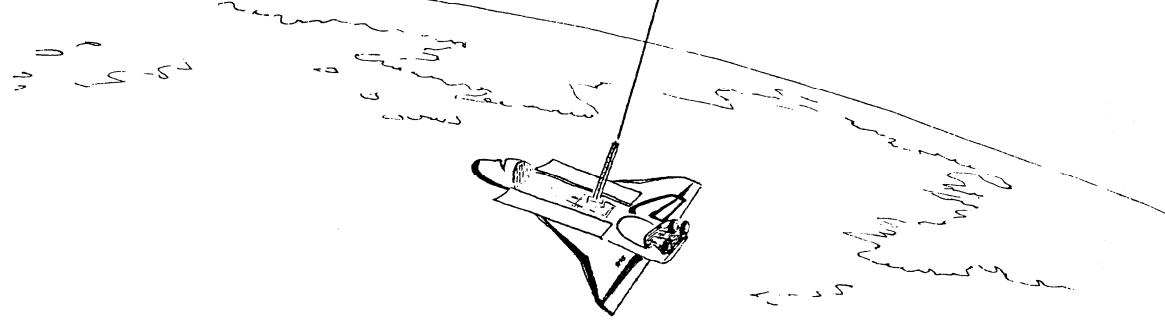
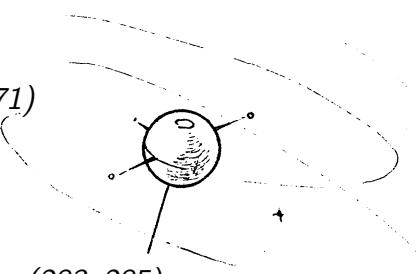
*Stability conditions and the second critical current (299, 305)*

*Behavior of the eigenvalues and the effective  
longitudinal stiffness of the tether (300–303)*

*Comparison of different tether materials (309)*

*Periodic perturbations and secular effects in the motion  
of the electrodynamic tether system (310–313)*

*Maintaining tether loops with the help  
of the Ampere forces (314–320)*



## Chapter 6

# TRAVELING TETHER

*Equations of motion of a tether system with a traveling tether and their first integrals (324–325)*

*Wave and loop-like configurations of a traveling tether described by quadratures (326–328)*

*Conditions of crossing surfaces of zero imaginary tension (329–331)*

*A traveling tether can create a repulsion force between the end bodies (332)*

*Keeping a traveling tether loop open by means of the Coriolis and centrifugal forces (332–335)*

*The “right” loops resemble the electrodynamic tether loops (332–333)*

*The “left” loops are unique (334–335)*

*Lyapunov’s functional and Poincaré’s stability coefficients for the “right” loops (336–337)*

## Chapter 7

# DAMPING OSCILLATIONS

*Damping due to the internal friction in the tether is efficient for longitudinal oscillations and inefficient for transverse oscillations (340–342)*

*Damping due to a tension control is efficient with a resonant tuning between longitudinal and transverse oscillations (343–346, 351)*

*Analytic expressions for all damping decrements for a massive tether (349–350)*

*The tether as a waveguide (353–354)*

*The maximum absorption of the energy of waves using a controllable boom (355–358)*

## Chapter 8

# ROTATION AND LIBRATION

*The regions of the prograde and retrograde rotation, libration and tether slackness (363–364)*

*The regions of possible and real motions (364–366)*

*The instability of periodic librations in elliptic orbit (367)*

*Tether bounces (369–371)*

*Mapping of the region of tether slackness and the evolution of motion with phases of tether slackness (372–378)*

*Pendular motions with a straight tether as exact solutions to the dynamic equations (378–380)*

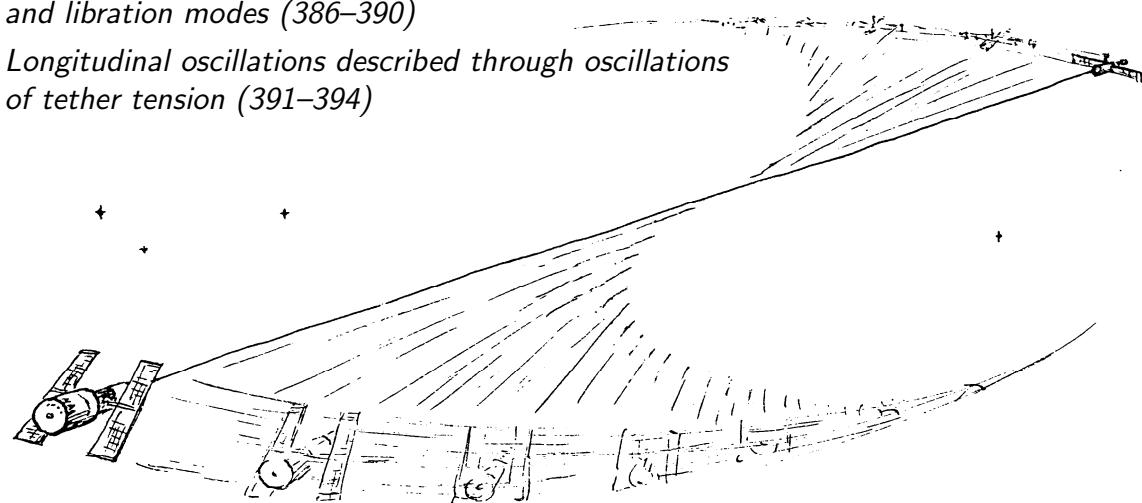
*The dynamic safety factor (380–381)*

*Maximum rotation velocities of the end-bodies for various tether materials (382)*

*Different modes of transverse oscillations are excited independently (383–385)*

*The regions of parametric resonances in the rotation and libration modes (386–390)*

*Longitudinal oscillations described through oscillations of tether tension (391–394)*



## Chapter 9

# DEPLOYMENT AND RETRIEVAL

*The exponential deployment with a velocity proportional to the deployed tether length (399–401)*

*Kinematic and dynamic versions of the uniform deployment and retrieval (402–414)*

*The vertical drift in elliptic orbit (408–410)*

*With a finite initial velocity of deployment the angular deviation from the vertical cannot be small (417–418)*

*Evaluation of the minimum deployment time (419)*

*Tether sag due to the Coriolis forces during deployment from one and both ends (422–426)*

*An analytical description of the excitation of the lower modes with a uniform deployment and retrieval (429–431)*

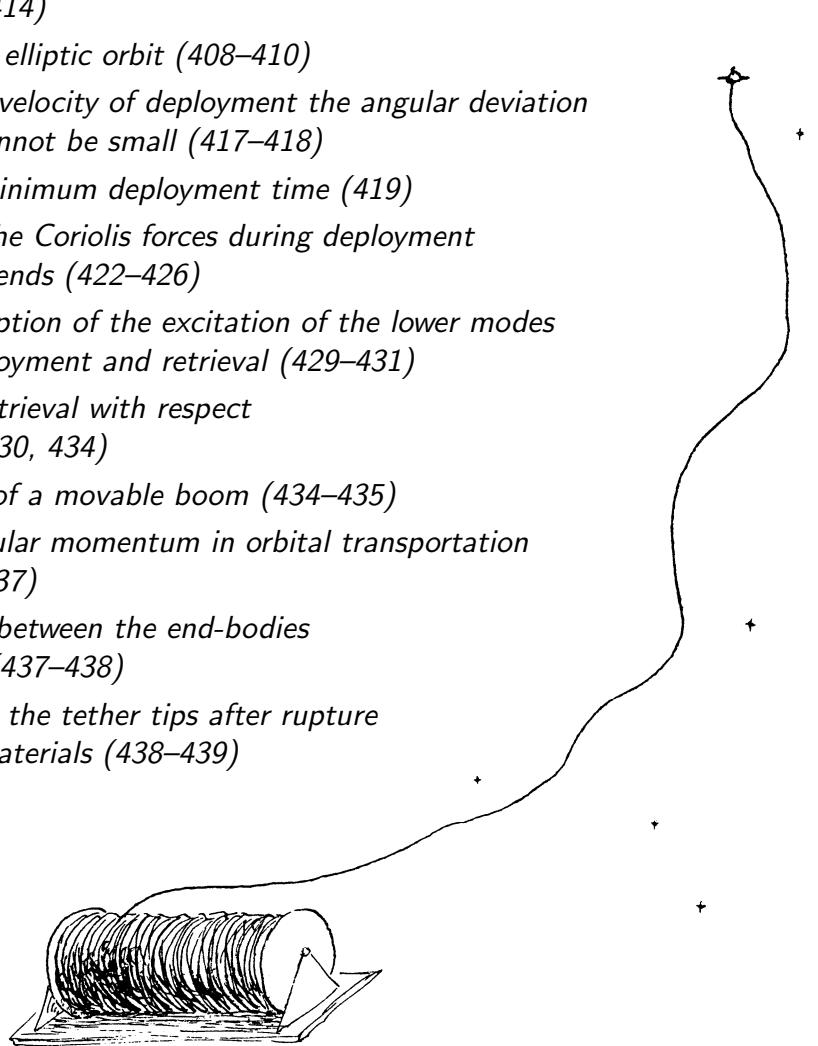
*The instability of retrieval with respect to the tether sag (430, 434)*

*A stabilizing effect of a movable boom (434–435)*

*Transfer of the angular momentum in orbital transportation applications (435–437)*

*A possible collision between the end-bodies after tether failure (437–438)*

*Velocities gained by the tether tips after rupture for various tether materials (438–439)*



## Chapter 10

# ANCHORED TETHER

*Five families of equilibrium positions and their stability (446–447)*

*Regions of librations with a taut tether (447–449)*

*Regions of possible motion (449–450)*

*The minimum tether length in circular and elliptic orbits (446, 451)*

*The integral of the tether tension (452–453)*

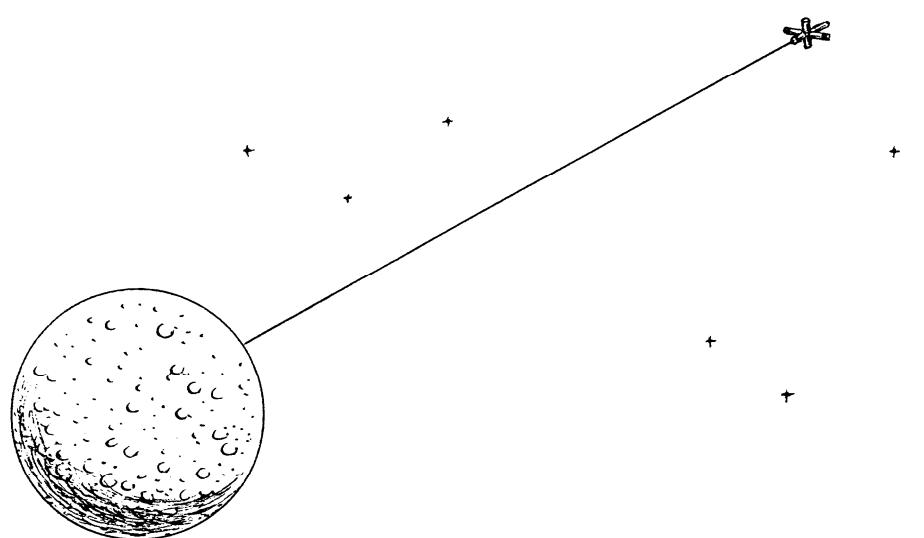
*The required specific strength of a uniform tether (455)*

*Parameters of uniformly stressed tapered tethers from various materials (455–456)*

*Stability conditions and the minimum tether length (458–459)*

*Lyapunov's functional and Poincaré's stability coefficients (459–460)*

*Deployment of a string of tethered sensors from a landing module on Phobos (461–463)*



# Chapter 11

## SATELLITE RING

*Models of a tethered satellite ring (466–467)*

*An extensible ring governed by Hooke's law is unstable with respect to the lower modes (469–472)*

*A ring with dropping tension is unstable with respect to the higher modes (472)*

*A narrow band of gyroscopic stabilization (472–473)*

*Stabilizing conditions for a ring of a large number of tethered satellites (477–479)*

*A ring of an equivalent thread as a model of a meteor ring (480–482)*

