REFERENCES

1. Baumgarte, J., "Stabilization of Constraints and Integrals of Motion," *Concept. Methods Appl. Mech. Eng.*, Vol. 1, 1972.
2. Chua, L. O., and P. M. Lin, *Computer-Aided Analysis of Electronic Circuits: Algorithms and Computational Techniques*. Prentice-Hall, Englewood Cliffs, N.J., 1975.
3. Goffman, C., *Calculus of General Variables*. Harper and Row, New York, 1965.
4. Goldstein, H., *Classical Mechanics*. 2nd. ed., Addison-Wesley, Reading, Mass., 1980.
5. Greenwood, D. T., *Principles of Dynamics*. Prentice-Hall, Englewood Cliffs, N.J. 1965.
6. Hiller, M. H., "Analytical-Numerical Description of the Kinematical and Dynamical Behavior of Series-Connected Spatial Four-Bar Mechanisms and its Applications," *Proc. 6th World Cong. Theory of Machines and Mechanisms,* 1983.
7. Jerkovsky, W., "The Structure of Multibody Dynamics Equations," *J. Guidance and Control,* Vol. 1, No. 3, pp. 173–182, May–June 1978.
8. Kim, S. S., and M. J. Vanderploeg, "QR Decomposition for State Space Representation of Constrained Mechanical Dynamic Systems," *ASME J. Mech., Trans., and Auto. in Design,* Vol. 108, No. 2, pp. 183–188, June 1986.
9. Kim, S. S., and M. J. Vanderploeg, "A General and Efficient Method for Dynamic Analysis of Mechanical Systems Using Velocity Transformations," *ASME J. Mech., Trans., and Auto. in Design,* Vol. 108, No. 2, pp. 176–182, June 1986.
10. Liang, C. G., and G. M. Lance, "A Differentiable Null Space Method for Constrained Dynamic Analysis," *ASME Paper 85-DET-86*.
11. Mani, N. K., E. J. Haug, and K. E. Atkinson, "Application of Singular Value Decomposition for Analysis of Mechanical System Dynamics," *ASME J. Mech., Trans., and Auto. in Design,* Vol. 107, No. 1, pp. 82–87, March 1986.
12. Nikravesh, P. E., and I. S. Chung, "Application of Euler Parameters to the Dynamic Analysis of Three Dimensional Constrained Mechanical Systems," *ASME J. Mech. Design,* Vol. 104, No. 4, pp. 785–791, October 1982.
13. Nikravesh, P. E., O. K. Kwon, and R. A. Wehage, "Euler Parameters in Computational Kinematics and Dynamics, Part 2," *ASME J. Mech., Trans., and Auto. in Design,* Vol. 107, No. 3, pp. 366–369, September 1985.
14. Nikravesh, P. E., and M. Srinivasan, "Generalized Coordinate Partitioning in Static Equilibrium Analysis of Large-Scale Mechanical Systems," *Int. J. Numerical Methods in Engineering,* Vol. 21, pp. 451–464, 1985.
15. Nikravesh, P. E., R. A. Wehave, and O. K. Kwon, "Euler Parameters in Computational Kinematics and Dynamics, Part 1," *ASME J. Mech., Trans., and Auto. in Design,* Vol. 107, No. 3, pp. 358–365, September 1985.
16. Orlandea, N., M. A. Chace, and D. A. Calahan, "A Sparsity-Oriented Approach to Dynamic Analysis and Design of Mechanical Systems," *ASME J. Engineering for Industry,* Vol. 99, pp. 773–784, August 1977.
17. Paul, B., *Kinematics and Dynamics of Planar Machinery*. Prentice-Hall, Englewood Cliffs, N.J., 1979.

18. Wehage, R. A., and E. J. Haug, "Generalized Coordinate Partitioning of Dimension Reduction in Analysis of Constrained Dynamic Systems," *ASME J. Mech. Design,* Vol. 104, pp. 247–255, January 1982.

19. Wittenburg, J., *Dynamics of Systems of Rigid Bodies.* Teubner, Stuttgart, 1977.

20. Wittenburg, J., "A New Correction Formula for Euler-Rodriguez Parameters," *ZAMM,* Vol. 62, pp. 495–497, 1982.

BIBLIOGRAPHY

ANDREWS, G. C., and H. K. KESAVAN, "The Vector Network Model: A New Approach to Vector Dynamics," *Mechanism and Machine Theory,* Vol. 10, pp. 509–519, 1975.

BARMAN, N. C., "Design Sensitivity Analysis and Optimization of Constrained Dynamic Systems." Ph.D. Thesis, The University of Iowa, 1979.

BAUMGARTE, J., "Stabilisierumg Von Bindungen im Lagraneshen Formalismo," *ZAMM 58,* T360-T361, 1978.

BOTTEMA, O., and B. ROTH, *Theoretical Kinematics.* North-Holland, 1979.

BRYSON, A. E., and W. F. DENHAM, "A Steepest-Ascent Method for Solving Optimum Programming Problems," *ASME J. Applied Mechanics,* pp. 247–257, 1962.

CALAHAN, D. A., *Computer-Aided Network Design.* New York, McGraw-Hill, 1962.

CHACE, M. A., and P. M. SHETH, "Adaptation of Computer Techniques to the Design of Mechanical Dynamic Machinery," *ASME Paper 73-DET-58,* 1973.

CHACE, M. A. and D. A. SMITH, "DAMN-A Digital Computer Program for the Dynamic Analysis of Generalized Mechanical Systems," *SAE paper 710244,* January 1971.

CHANG, C. O., and P. E. NIKRAVESH, "An Adaptive Constraint Violation Stabilization Method for Dynamic Analysis of Mechanical Systems," *ASME J. Mech., Trans., and Auto. in Design,* Vol. 107, No. 4, pp. 488–492, 1985.

CHANG, C. O., and P. E. NIKRAVESH, "Optimal Design of Mechanical Systems with Constraint Violation Stabilization Method," *ASME J. Mech., Trans., and Auto. in Design,* Vol. 107, No. 4, pp. 493–498, 1985.

CLIFFORD, W, "Preliminary Sketch of Biquaternions," *Proc. London Math. Soc.,* Vol. IV, 1873.

CONTE, S. D., and C. D. BOOR, *Elementary Numerical Analysis,* 3rd. ed., New York: McGraw-Hill, 1980.

DENAVIT, J., *Displacement Analysis of Mechanisms Based on (2 ×2)-Matrices of Dual Numbers.* VDI-Berichte, 1958.

DEO, N., *Graph Theory with Applications in Engineering and Computer Science.* Englewood Cliffs, N.J.: Prentice-Hall, 1974.

DIJKSTRA, E. W., "A Note on Two Problems in Connection with Graphs," *Numerische Mathematik,* Vol. 1, 1959.

DIMENTBERG, *The Screw Calculus and its Applications in Mechanics.* Moscow: Nauka, 1965.

DUFFY, J., *Analysis of Mechanisms and Robot Manipulator.* London: Arnold, 1980.

GEAR, C. W., "Numerical Solution of Differential-Algebraic Equations," *IEEE Transaction on Circuit Theory,* Vol. CT-18, pp. 89–95, January 1981.

GUPTA, G. K., R. SACKS-DAVIS, and P. E. TISCHER, "A Review of Recent Developments in Solving ODEs," *Computing Surveys,* Vol. 17, No. 1, pp. 5–47, March 1985.

HAMAD, B. M., "Optimal Design of Vibratory Systems." Ph.D. Thesis, The University of Wisconsin, 1968.

HAUG, E. J., V. N. SOHONI, S. S. KIM, and H. G. SEONG, "Vehicle Suspension Dynamics Optimization," *Proc. Int. Conf. on Vehicle Design Analysis,* London, June 21–24, 1983.

HAUG, E. J., R. A. WEHAGE, and N. C. BARMAN, "Design Sensitivity Analysis of Planar Mechanisms and Machine Dynamics," *ASME J. Mechanical Design,* Vol. 103, pp. 560–570, 1981.

HEMAMI, H., "Some Aspects of Euler-Newton Equation of Motion," *Ingenieur-Archiv,* Vol. 52, pp. 167–176, 1982.

HILLER, M., "The Dynamics of Spatial Multi-Bar Mechanisms," German-Japanese Seminar on *Nonlinear Problems in Dynamical Systems—Theory and Applications,* ed. M. Hiller and H. Sorg, Stuttgart, Germany, 1984.

HILLER, M., and C. WOERNLE, "A Unified Representation of Spatial Displacements," *J. Mech. and Machine Theory,* Vol. 19, No. 6, pp. 477–486, 1984.

HUSTON, R. L., and J. W. KAMAN, A Discussion on Constraint Equations in Multibody Dynamics," *Mechanics Research Communications,* Vol. 9(4), pp. 251–256, 1982.

HUSTON, R. L., and C. E. PASSERELLO, "On Multi-Rigid Body System Dynamics," *Computers and Structures,* Vol. 19, pp. 439–446, 1979.

HUSTON, R. L., and C. E. PASSERELLO, "Multibody Structural Dynamics Including Translation Between the Bodies," *Computers and Structures,* Vol. 11, pp. 715–720, 1980.

HUSTON, R. L., C. E. PASSERELLO, and M. W. HARLOW, "Dynamics of Multirigid Body Systems," *J. Applied Mechanics,* Vol. 45, No. 4, pp. 889–894, 1978.

KAMMAN, J. W., and R. L. HUSTON, "Dynamics of Constrained Multibody Systems," *J. Applied Mechanics,* Vol. 51, No. 4, pp. 387–904, 1984.

KAMMAN, J. W., and R. L. HUSTON, "Constrained Multibody System Dynamics," *Computers and Sructures,* Vol. 18, pp. 999–1003, 1984.

KANE, T. R., "Solution of Kinematical Differential Equations for a Rigid Body," *ASME J. Appl. Mech.,* Vol. 40, pp. 109–113, March 1973.

KANE, T. R., and D. A. LEVINSON, *Dynamics Theory and Applications.* New York: McGraw-Hill, 1985.

KANE, T. R., and C. F. WANG, "On The Derivation of Equations of Motion," *J. Soc. Indust. Appl. Math.,* Vol. 13, No. 2, June 1965.

KEAT, J., "Dynamics Equations of Multibody Systems with Applications to Space Structure Development." Ph.D. Dissertation, Massachusetts Institute of Technology, May, 1983.

KHULIEF Y. A., and A. A. SHABANA, "Dynamics of Multibody Systems With Variable Kinematic Structure," *ASME Paper 85-DET-83,* 1985.

KHULIEF Y. A., and A. A. SHABANA, "Impact Responses of Multibody Systems with Consistent and Lumped Masses," *J. Sound and Vibration,* Vol. 104 No. 2, pp. 187–208, 1986.

KIM, S. S., "State Space Formulation for Multibody Dynamic Systems." Ph.D. Dissertation, The University of Iowa, 1984.

KRISHNASWAMI, P., and M. A. BHATTI, "A General Approach for Design Sensitivity Analysis of Constrained Dynamic Systems," *ASME Paper 84-DET-132,* 1984.

KRUSKAL, J. B. JR., "On the Shortest Spanning Subtree of Graph and the Traveling Salesman Problems," *Proc. Am. Math. Soc.,* Vol. 7, 1956.

LIANG, C. G., and G. M. LANCE, "A Differentiable Null Space Method for Constrained Dynamic Analysis," *ASME Paper 85-DET-86,* 1985.

ORLANDEA, N. V., "Node Analogous Sparsity-Oriented Methods for Simulation of Mechanical Dynamic Systems." Ph.D. Thesis, University of Michigan, 1973.

ORTEGA, J. M., and W. G. POOLE, JR., *An Introduction to Numerical Methods for Differential Equations.* Pitman, Marshfield, M. A., 1981.

PARK, T., and E. J. HAUG, "A Hybrid Numerical Integration Method for Machine Dynamic Simulation," *ASME Paper 85-DET-59,* 1985.

PASSERELLO, C. E., and R. L. HUSTON, "An Analysis of General Chain Systems," NASA CR-127924, Report No. N72-30532, 1972.

PAUL, B., "Analytical Dynamics of Mechanisms: A Computer Oriented Overview," *Mechanism and Machine Theory,* Vol. 10, pp. 481–507, 1975.

PAUL, B., and D. KRAJCINOVIC, "Computer Analysis of Machines with Planar Motion—Part I: Kinematics; Part II: Dynamics," *J. Applied Mechanics,* Ser. E, Vol. 37, pp. 697–712, 1970.

RALSTON, A., and P. RABINOWITZ, *A First Course in Numerical Analysis,* 2nd ed., New York: McGraw-Hill, 1978.

SCHIELEN, W. O., "Dynamics of Complex Multibody Systems," *SM Archives,* Vol. 9, pp. 297–308, 1972.

SCHIELEN, W. O., "Computer Generation of Equations of Motion," *Computer Aided Analysis and Optimization of Mechanical Systems,* ed. E. J. Haug, Heidelburg: Springer-Verlag, 1984.

SCHIELEN, W. O. and E. J. DREUZER, "Symbolic Computerized Derivation of Equations of Motion," *Dynamics of Multibody Systems,* ed. K. Magnus. pp. 290–305, Heidelburg: Springer-Verlag, 1978.

SHABANA, A. A., "Automated Analysis of Constrained Systems of Rigid and Flexible Bodies," *ASME Paper 85-DET-29,* 1985.

SHABANA, A. A., and R. A. WEHAGE, "Variable Degree of Freedom Component Mode Analysis of Inertial Variant Flexible Mechanical Systems," *ASME J. Mechanical Design,* Vol. 105, no. 3, pp. 1193–1205, September, 1983.

SHETH, P. N., "A Digital Computer Based Simulation Procedure for Multiple Degree of Freedom Mechanical Systems with Geometric Constraints," Ph.D. Thesis, University of Wisconsin, 1972.

SHETH, P. N., and J. J. UICKER JR., "IMP (Integrated Mechanisms Program), A Computer-Aided Design Analysis System for Mechanisms and Linkages," *J. Engrg. For Industry,* Vol. 94, p. 454, 1972.

SMITH, D. H., "Reaction Forces and Impact in Generalized Two-Dimensional Mechanical Dynamic Systems." Ph.D. Dissertation, The University of Michigan, 1973.

SONG, J. O., and E. J. HAUG, "Dynamic Analysis of Planar Flexible Mechanisms," *Computer Methods in Applied Mechanics and Engineering,* Vol. 24, pp. 359–381, 1976.

SRINIVASAN, M., "*Multi-Rate Numerical Integration in Design and Analysis of Flexible Mechanical Systems.*" Ph.D. Thesis, The University of Iowa, 1984.

SUNADA, A. A., and S. DUBOWSKY, "The Application of Finite Element Methods to the Dynamic Analysis of Flexible Spatial and Co-Planar Linkage Systems," *J. Mechanical Design,* Vol. 103, pp. 643–651, July 1981.

TONG, K. N., *Theory of Mechanical Vibration.* New York: John Wiley, 1960.

TSE, F. S., I. E. MORSE, and R. T. HINKLE, *Mechanical Vibration.* 2nd ed., Boston: Allyn and Bacon, 1978.

UICKER, J. J., JR., "Dynamic Behavior of Spatial Linkages," *J. Engrg. Indust., Trans. ASME,* Ser. B, Vol. 91, pp. 251–265, 1969.

WEHAGE, R. A., "Generalized Coordinate Partitioning in Dynamic Analysis of Mechanical Systems." Ph.D. Dissertation, The University of Iowa, 1980.

WEHAGE, R. A., "Quaterions and Euler Parameters—A Brief Exposition," *Comp. Aided Anal. and Opt. of Mech. Systems,* ed. E. J. Haug, Heidelburg: Springer-Verlag, 1984.

WILLMERT, K. D., and R. L. FOX, "Optimal Design of A Linear Multi-Degree of Freedom Shock Isolation System," *J. Engrg. For Indus.,* Vol. 96, pp. 465–471, 1972.

WINFREY, R. C., "Elastic Link Mechanism Dynamics," *ASME J. Engrg. for Industry,* Ser. B, Vol. 93, No. 1, pp. 268–272, February 1971.

WINFREY, R. C., "Dynamic Analysis of Elastic Link Mechanisms by Reduction of Coordinates," *ASME J. Engineering for Industry,* Ser. B, Vol. 94, No. 2, pp. 577–582, May, 1972.

WITTENBURG, J., "Dual Quaternions in the Kinematics of Spatial Mechanisms," *Comp. Aided Anal. and Opt. of Mech. Systems,* ed. E. J. Haug, Heidelburg: Springer-Verlag, 1984.

YANG, A. T., *Calculus of Screws: Basic Questions of Design Theory,* ed. W. R. Spiller, pp. 265–281, New York: American Elsevier Publishing Co., 1974.

YANG, A. T., and FREUDENSTEIN, F., "Application of Dual-Number Quaternion Algebra to the Analysis of Spatial Mechanisms," *J. Appl. Mech.* 86, pp. 300–308, 1964.

YUAN, M. S. C., and F. FREUDENSTEIN, "Kinematic Analysis of Spatial Mechanisms by Means of Screw Coordinates," *J. Engrg. in Industry,* pp. 61–73, 1971.

Index

A

G

H

I

J

K

W

COMPUTER-AIDED ANALYSIS OF MECHANICAL SYSTEMS

Parviz E. Nikravesh

This book introduces fundamental theories and numerical methods for use in computational mechanics. The theories and methods can be used to develop computer programs for analyzing the response of simple and complex multibody mechanical systems. Equations of motion are formulated systematically and then solved numerically.

Author Parviz Nikravesh emphasizes the use of Cartesian coordinates for formulating the equation of motion. Knowledge of this formulation serves as a stepping stone for reader understanding of the formulation of the equation of motion for other sets of coordinates.

Problem assignments conclude most chapters and are designed to clarify certain points and to prove ideas for program development and analysis techniques. Two FORTRAN programs for planar kinematic and dynamic analysis (KAP and DAP) are also developed in the book. A software disk is available from Prentice Hall.

PRENTICE HALL, Englewood Cliffs, NJ 07632

ISBN 0-13-164220-0