

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. Wehage, 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., "Stabilisierung Von Bindungen im Lagrange'schen Formalismus," *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 Structures*, 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. KRAJCIKOVIC, "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, Heidelberg: 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, Heidelberg: 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., "Quaternions and Euler Parameters—A Brief Exposition," *Comp. Aided Anal. and Opt. of Mech. Systems*, ed. E. J. Haug, Heidelberg: 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, Heidelberg: 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.

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COMPUTER-AIDED ANALYSIS ^{OF} MECHANICAL SYSTEMS

Parviz E. Nikravesh

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