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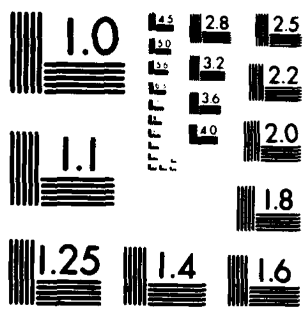

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DISTRIBUTION THEORETIC METHODS FOR DYNAMIC ANALYSIS AND OPTIMIZATION OF MECHANISMS WITH INTERMITTENT MOTION

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FINAL REPORT

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U.S. ARMY RESEARCH OFFICE
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intermittent motion dynamics, dynamic design sensitivity analysis, computer aided dynamic analysis

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A computer aided dynamic and design sensitivity analysis technique for planar dynamic systems undergoing intermittent motion is developed and applied. Planar dynamic systems made up of multiple rigid bodies connected by joints and force elements are modeled. A constrained dynamic system approach that accounts for discontinuous velocities associated with impulsive loading and impact between bodies is developed. A new numerical integration technique for mixed differential and algebraic equations that automatically defines and

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integrates for independent generalized coordinates has been developed. It has demonstrated an order of magnitude improvement in computing efficiency compared to preceding techniques. Intermittent motion dynamic effects due to impulsive loading or impact have been incorporated into the dynamic simulation, using a pieced interval dynamic analysis technique in which momentum balance relations are used to determine discontinuities in velocity at logical event times. This technique has been demonstrated on multibody, multiple contact point applications in mechanisms and automatic weapons. To assist in design optimization of mechanical system dynamics an adjoint variable design sensitivity analysis technique has been developed for calculation of first and second order derivatives of dynamic response with respect to design. Numerical calculations have demonstrated that accurate first and second derivatives can be obtained for moderate scale dynamic systems.

OBJECTIVE OF THE RESEARCH

The objective of the research carried out in this project was to develop a computer aided analysis technique that can be used to represent intermittent motion dynamics and to predict the effect of design variations, for optimal design of mechanisms and machines with intermittent motion. In order to obtain a meaningful capability, the focus of the research was on large scale systems that can be analyzed through computer generation and automatic integration of equations of motion. In addition, techniques are needed that require a minimum of ad hoc computer programming to carry out dynamic and design sensitivity analysis of realistic mechanical systems.

INTERMITTENT MOTION DYNAMIC ANALYSIS

As an initial step in the research, two basically different and potentially complementary, methods for analysis of mechanisms with intermittent motion were considered. The first is the "pieced interval" method, where logical times separate intervals in which different forms of the equations of motion are valid. Discontinuities in velocities across logical times may occur due to impact, cam action, or other sudden events that commonly occur in weapon mechanism and machine operation. Digital computer simulation of such systems is common and design sensitivity analysis and optimization has been carried out [B1]* using an adjoint variable method of optimizaiton theory [B2]. For complex systems in which the ordering of logical times is unknown, technical difficulties in predicting jump discontinuities in the adjoint variables had previously limited application of this method to small scale systems or systems for which the ordering of the sequence of logical times is known.

These difficulties led to the recent development of a distribution theoretic method of approximating discontinuities with representative

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* [ ] denotes references given at the end of the report.

sequences or logical functions [B3, B4], which has somewhat alleviated the difficulties associated with the pieced interval method. Computer generated equations of motion and adjoint equations, coupled with efficient numerical integration methods, have been adapted to the distribution theoretic method [B5, B6] and provide a unified method of dynamic and design sensitivity analysis for large scale systems with intermittent motion.

The alternative distributional representative sequence technique (logical functions) [B3, B4] and pieced interval, logical time velocity discontinuity model of intermittent motion were first considered. Recent developments in computer generation of governing equations and the greater associated generality that can be achieved with such computer aided analysis techniques lead the research team to pursue the pieced interval approach.

A computer-based method for formulation and efficient solution of nonlinear, constrained differential equations of motion was developed for planar mechanical systems [A1, A2]. Nonlinear constraint equations and differential equations of motion are written in terms of a maximal set of Cartesian generalized coordinates, to facilitate the general formulation of constraints and forcing functions. A Gaussian elimination algorithm with full pivoting decomposes the constraint Jacobian matrix, identifies dependent variables, and constructs an influence coefficent matrix that relates variations in dependent and independent variables. This informaion is employed to numerically construct a reduced system of differential equations, whose solution yields the total system response. A numerical integration algorithm with positive error control, employing a predictor-corrector algorithm with variable order and step-size, was developed that integrates for only the independent variables.

The generalized coordinate partitioning technique, coupled with a general purpose computer code called the Dynamic Analysis and Design System (DADS) has demonstrated an order of magnitude improvement and computational efficiency, compared to earlier methods. Using this new computer formulation of equations, attention was focused on the intermitttent motion problem. A method was developed for dynamic analysis of systems with impulsive forces, impact, discontinuous constraints, and discontinuous velocities [A3, A4]. This class of systems includes discontinuous kinematic and geometric constraints that characterize backlash and impact within systems. A method of computer generation of the impulse-momentum relations that define jump discontinuities in system velocity for large scale systems was developed. An event predictor, employing functions of the system state and working in conjunction with the new numerical integration algorithm, efficiently controls its progress and allows for automatic equation reformulation.

Numerical applications have been presented for planar motion of a tracked articulated vehicle system with twenty-four degrees of freedom. A mechanism with discontinuous forces and velocities was simulated to demonstrate program generality and improved efficiency over previous modeling methods. An order of magnitude improvement in efficiency has been demonstrated.

DESIGN SENSITIVITY ANALYSIS AND OPTIMIZATION

A first order design sensitivity analysis technique has been developed for systems of nonlinear differential equations subject to highly nonlinear algebraic constraint equations [A5]. The formulation, while written with specific reference to constrained dynamic mechanical systems, is generally applicable to any type of constrained or unconstrained dynamic systems that are described by a system of differential and algebraic equations. For example, electrical, hydraulic, or elastic systems, or any combinaion thereof, can be analyzed for system dynamic response design sensitivity. The design sensitivity analysis algorithm has been incorporated into the DADS planar analysis code and preliminary test results with a linkage mechanism indicate that it efficiently and accurately determines design sensitivity coefficients. A complex hydraulically operated mechanical ammunition loader model is being developed for design sensitivity analysis, using the above program. A general first order design sensitivity analysis technique for nonlinear mechanical systems with intermittent motion has been developed and is being implemented into the DADS analysis program.

A second order design sensitivity analysis technique has been developed and successfully tested on model problems [A6]. A functional measure of dynamic response of a mechanical system is differentiated twice with respect to design variables, using two successive applications of the adjoint variable technique of design sensitivity analysis. The result of this formulation is a dual system of adjoint equations that are integrated backward in time for first derivatives and subsequently forward in time for generation of adjoint variables required for second design derivative computation. It is shown that a consistent form of these differential equations yields essential numerical efficiencies in computation of second design derivatives. Application to an elementary oscillator problem showed precise numerical agreement with analytical computations. Subsequent application to a three shot, salvo fired rifle accurately predicted the second design derivatives of dynamic response with respect to design. The second order Taylor approximation of dynamic response can be used to advantage in design optimizaiton or in enforcing bounds on system performance sensitivity to variations in uncontrollable parameters.

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