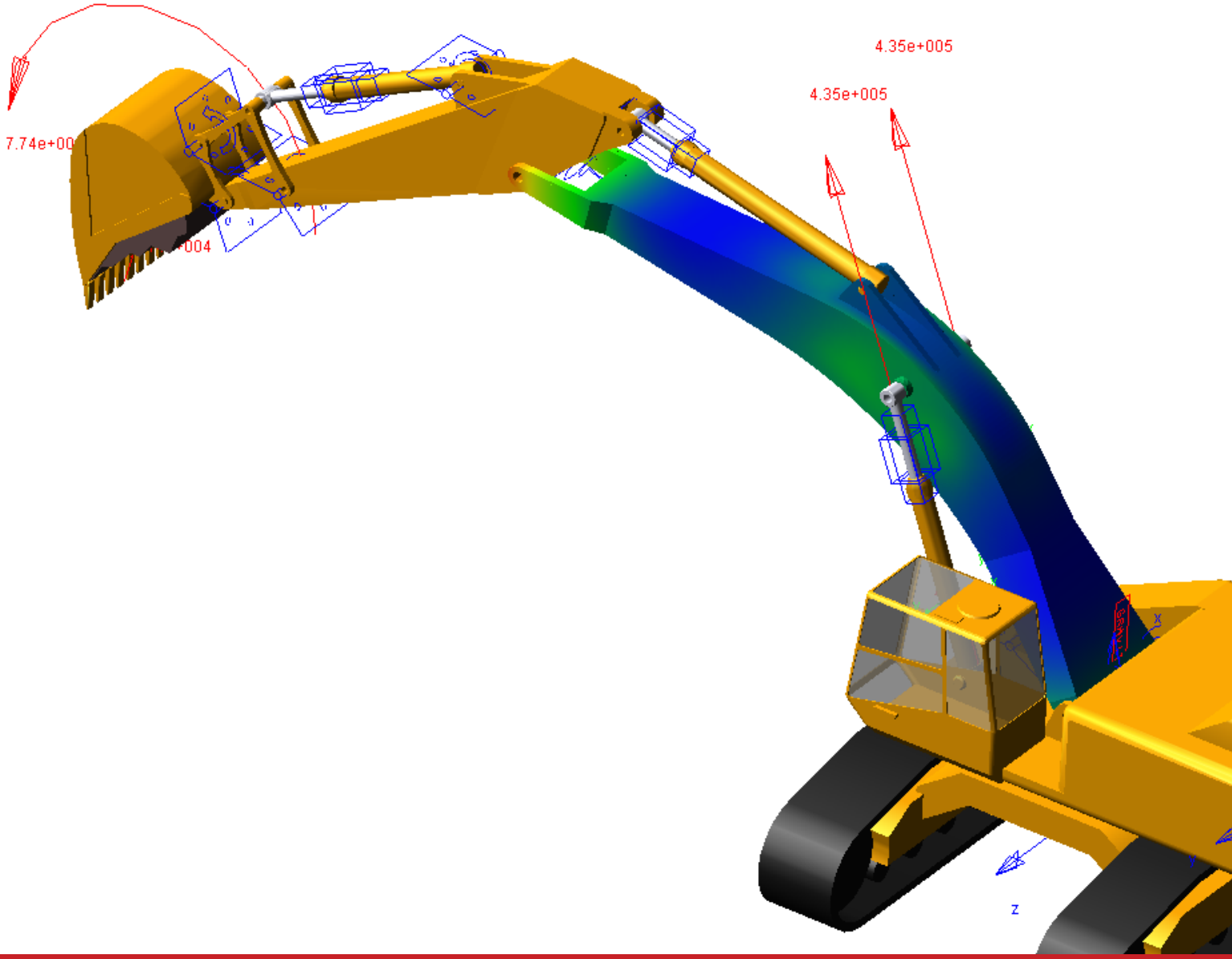
Introduction to

Mechanical System Simulation Using Adams™

James B. McConville



SDC PUBLICATIONS
Better Textbooks. Lower Prices.
www.SDCpublications.com
MSC Software

Visit the following websites to learn more about this book:

Introduction

The Significance of Large Motion

Multibody Dynamics (hereafter referred to using the acronym MBD) is typified most of all by its ability to efficiently deal with appreciable motion. Such motion, and especially rotational motion, tends to be highly non-linear in the spatial sense. Compounding this are effects which vary non-linearly with time. Thus, all aspects of an MBD problem are usually mathematically very non-linear. This is where Adams shines. It is specifically designed to deal efficiently with these nonlinearities. However, there is a price to be paid for this capability. A reader who is familiar with Finite Element Analysis (FEA) may be used to dealing with structural systems possessing hundreds of thousands of points of interest (e.g., "nodes" or "grids"), perhaps even millions of such points. While such models are extremely valuable, they are very often limited by the assumption of linearity if they are to remain computationally tractable. In other words, the assumption is made that the motion of all the points of interest is so limited that it doesn't have to be tracked during the analysis, and the starting point positions are all that is needed. As we shall see later in this book, that is a serious restriction on what kinds of analysis can validly be performed. Because it is basic to the Adams MBD approach, the motion of the points of interest ***must*** be tracked, which limits the number of points of interest which can be considered if the Adams analysis is to remain tractable. As we shall see, however, there are methods which permit the direct use of linear FEA structures in Adams MBD models. Currently, extension of the Adams MBD capability to include complex structural nonlinearity is accomplished using co-simulation methods, which are beyond the scope of this book. Methods to efficiently include structural non-linearity directly in Adams, without resort to co-simulation, are under development as this book is published.

The Intent and Scope of This Book

This book is intended to familiarize the reader with the basics of theory and practice in Adams MBD modeling. The content has been developed to be beneficial to readers who are students or practicing engineers who are either completely new to MBD modeling or have some experience with MBD modeling. While this book is neither software user documentation nor a training guide, the author's lengthy experience using the Adams software adds a practical and, occasionally, humorous complement to standard documentation and training materials, intended to benefit the reader learning Adams. The book features relatively small examples which can be readily built and executed by the reader. This book contains an introduction to Adams theory which provides the basics on how Adams models are formulated and then numerically solved. These sections are deliberately limited and make no claim to comprehensiveness. Finally, this book concludes with some "success stories" taken from industry.

Acknowledgements

The Adams (**A**utomatic **D**ynamic **A**nalysis of **M**echanical **S**ystems) program has its origins in the brilliant PhD thesis written at the University of Michigan in 1973 by Dr. Nicolae Orlandea (reference [5]). Using this thesis as a foundation, 3 University of Michigan pioneering software entrepreneurs (Dr. Milt Chace, Mike Korybalski, and John Angell) founded Mechanical Dynamics, Inc. (MDI) in 1976. The rest is history.

The author would also like to thank Dr. Frank Owen and Dr. Xi Wu, both of Cal Poly, for their critiques and assistance in generating this book. Further thanks go also to Leslie Bodnar of MSC for getting the ball rolling and to John Janevic of MSC for his skill and perseverance in editing the text. Finally, a *very* special thanks is due to Dominic Gallello, President and CEO of MSC Software, without whose vision, inspiration, encouragement, and support this book would not have happened.

An Example to Come

The figure below gives the reader a brief foretaste of the kind of analyses possible with Adams MBD analysis. The backhoe excavator shown is one of the sample problems examined in great detail later in this book.

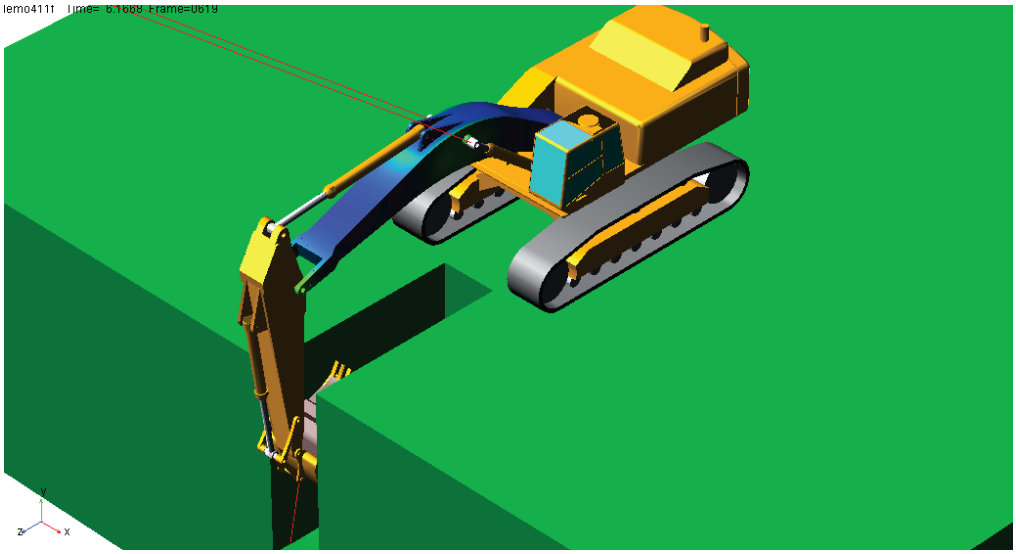


Figure 1 Excavator with Flexible Boom Arm Performing a Typical Duty Cycle

The reader will be shown how to represent articulating Adams parts defined by CAD geometry, how to connect and drive those parts so that the system moves correctly, how to load the system appropriately, and how to interrogate the model for results. Finally, the excavator boom, initially modeled as a rigid body, will be rendered flexible using MSC Nastran, and the effects of its flexibility on the modeling results will be demonstrated.

A brief note on conventions used throughout the examples and text in this book: capital letters (e.g. “PART”) are generally used to denote keywords and parameters in the Adams or MSC Nastran modeling languages; however, in practice capitalization is not necessary for these keywords and parameters. Every attempt is made to relate keywords to common terminology (e.g. “CBAR” is a beam element in the MSC Nastran modeling language), but where this has been missed or insufficiently explained, the reader is invited to refer to Adams and/or MSC Nastran documentation (details in the References section).

Finally, at various points in the book, it will be helpful if the reader has some familiarity with the traditional usage paradigm of MBD (and FEA) tools:

- The user builds models of the product to be analyzed in a “preprocessor” or “user interface” (e.g. Adams/View or Patran)
- The preprocessor generates a representation of the product and its relevant mechanical characteristics in the native modeling language of the “solver” (e.g. Adams or MSC Nastran)
- Input to the solver consists of the model definition as well as a set of instructions for what analysis to perform
- The solver generates and numerically solves the appropriate equations, generating (often large) amounts of numerical output
- The user will then load the numerical output files into the “postprocessor” (e.g. Adams/View or Patran) for convenience in interpreting the results (animations, plots, etc.)

MSC is at the forefront of innovations to this traditional usage paradigm as the steps in FEA and MBD become highly interactive, with exciting developments to come.

Elementary Adams Theory

Basic Formulations

As commented on in the introduction, there are some fundamental differences between the FEA (Finite Element Analysis) and MBD (Multibody Dynamics) approaches to the analysis of an articulating mechanical system. In this theory section, the basic contrasts between the two approaches will be examined initially. Subsequently, a pendulum example will be dissected in some detail, with the intent being to show the basics of MBD equation formulation and subsequent numerical solution.

The MBD Approach

Based on the principles of Lagrangian Dynamics, Adams numerically constructs and solves the system equations as functions of time. These equations are usually both algebraic and differential as well as highly nonlinear. The basic approach employed by Adams uses Lagrange's formulation of the 2nd form:

$$1) \quad \mathbf{F}_j = \frac{d}{dt}\left(\frac{\partial \mathrm{L}}{\partial \dot{\mathbf{q}}_j}\right) - \frac{\partial \mathrm{L}}{\partial \mathbf{q}_j} + \sum_{i=1}^{m} \frac{\partial \Phi_{\mathrm{q}}^{\mathrm{T}}}{\partial \mathbf{q}_j}\lambda_i - \mathbf{Q}_j = 0 \qquad \text{for } \mathrm{j} = 1, \ldots \mathrm{n}$$

$$2) \quad \mathbf{\Phi}_i = 0$$

Where:

q	= generalized coordinate
F	= the equilibrium equation in the direction of generalized coordinate q
L	= the Lagrangian (T-V) where T → kinetic energy; V → potential energy
Φ	= algebraic constraint equations
λ	= Lagrange multiplier
Q	= generalized Force
n	= # of generalized coordinates
m	= # of constraint equations (< or = n)

In the general case, the *Q*'s can be functions of *q* and time. The Φ's are either constant (scleronomic) or continuous, time-varying (holonomic) algebraic constraints. In general, the Adams solution is *always* iterative. If *m* = *n*, all motion is pre-determined (i.e., the system has zero Degrees of Freedom, or "DOFs"), and the constraint equations alone are adequate to solve the problem, with any resulting forces being back-calculated. If the problem is time-invariant, but *n* is greater than *m*, the solution, if feasible, is an iterated, quasi-static result with time-invariant *Q*'s playing a role in the solution.

The FEA Approach

The FEA equations are Newtonian in form and employ coordinates which are spatially orthogonal

$$3) \quad \{\mathbf{F}\} = [\mathbf{M}]\{\ddot{\mathbf{x}}\} + [\mathbf{C}]\{\dot{\mathbf{x}}\} + [\mathbf{K}]\{\mathbf{x}\}$$

Where:

x	= coordinate
F	= the equilibrium forces in the orthogonal (Cartesian) coordinates
M	= the mass matrix
C	= the damping matrix
K	= the stiffness matrix

In the general case, F, M, C, and K can be functions of *x* and time. In the simplest case, when *x* is time invariant, *K* is constant, and the problem is not otherwise ill-posed, equation 3 submits to a single step solution.

If the problem at hand is linear, both the FEA and MBD methods can produce valid, frequency domain solutions. If equation 3 is time-invariant and the coefficient matrices are constant, an eigenvalue solution is directly obtainable. In Adams, equation set 1 must first be linearized about some bona fide equilibrium point.

In what follows, the frequency domain will not be further considered, and attention will be limited to time-varying, dynamic solutions only. Suffice it to say that "Physics is Physics" and, to be correct, both FEA and MBD must give the same results when applied to the same engineering problem. The deciding factor as to which method is employed must be based on which solution is most tractable and practical.

Elementary Overview of Solution Approaches

FEA Transient Response Analysis – Explicit Integration

The direct transient response analysis in MSC Nastran (known in shorthand as "SOLUTION 109" or "SOL109") is typical of the MSC Nastran FEA time-domain approach to the FEA solution of dynamical problems (for a more detailed description of the MSC Nastran approach, the reader is directed to reference [2]). In brief, the equations are solved using a modified Newmark-Beta approach. In its most efficient form, the time step size is fixed, and the coefficient matrices in equation 3 are constant. The instantaneous velocities and accelerations are derived from central divided differences which divide consecutive displacements by the time step for velocities and divide consecutive displacements by the square of the time step for accelerations. In effect, this converts the problem into a pseudo-static form at each new point in time, permitting the use of standard matrix inversion coding. This solution is

explicit, meaning that each advance in time is determined from past, converged time steps only. This has important implications, as will be discussed in the examples to follow.

MBD Transient Response Analysis – Implicit Integration

Adams has several different solvers, including an explicit one similar to that employed by MSC Nastran SOL700. It is seldom used. Instead, implicit solvers, which use predicted states to advance in time, are employed. The use of implicit predictor-corrector solvers has profound implications for the solution of a broad class of dynamical problems.

To illustrate the Adams implicit solution approach, let us postulate a very simple, unconstrained dynamics problem in a single generalized coordinate **q**. The Adams equation set (equations 1 & 2) reduces to:

$$4) \quad \mathbf{F} = \mathbf{Q} - \mathbf{f(q)} = \mathbf{E} \Rightarrow \mathbf{0}$$

Where:

f(q) = some nonlinear function of **q**
E = equilibrium error (to be driven to zero)

Fig. 2 shows the initial prediction forward in time.

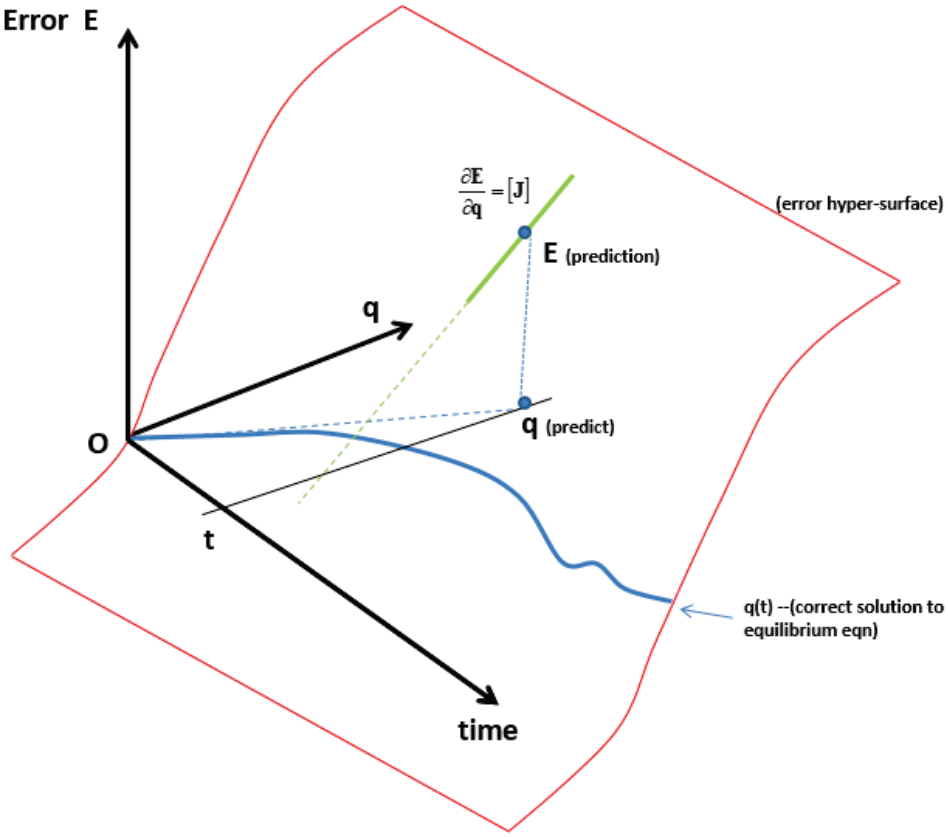


Figure 2 Predictor-Corrector Solution Space

The initial predictor equation is 1st order and uses a default time step to advance the solution to time *t*. The predicted value of **q** will, in general, not satisfy the equilibrium equation and will result in an error **E**. With time fixed at *t*, the equation set is numerically differenced around the predicted **q** to determine the error change with **q.** This determines the tangent to the *n*-dimensional error hyper-plane. This is called the Jacobian **[J]**. Note that, in our simplified example, *n*=1 and the Jacobian is a simple tangent line to the error hyper-surface at **q**. In general, *n* will be much larger than 1, and the Jacobian will be an n-dimensional, osculating hyper-plane to the *n*-dimensional error hyper-surface (just try to draw that on a 2-D piece of paper!).

Since the predicted solution results in error, it must be modified, if it can be, to reduce the error to within the requested error tolerance. To accomplish this, modified Newton-Raphson iteration is employed. The corrections to the predicted **q** are determined from:

$$\mathbf{E} + \left[\frac{\partial \mathbf{E}}{\partial \mathbf{q}}\right]\Delta\mathbf{q} = \mathbf{E} + [\mathbf{J}]\Delta\mathbf{q} = \mathbf{0} \quad (5)$$

$$\Delta\mathbf{q} = -[\mathbf{J}]^{-1}\mathbf{E} \quad (6)$$

This process is repeated as shown schematically in Fig. 3.

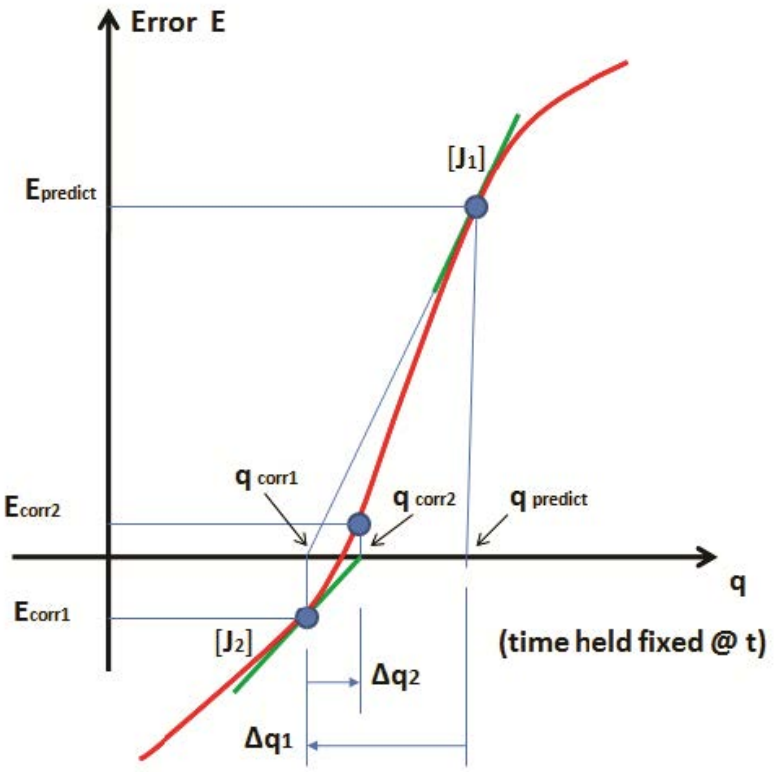


Figure 3 Newton-Raphson Iteration

If the error criterion cannot be met, the time step is reduced, and the process is repeated. Even if the corrector converges, the change in **q** must satisfy the remainder limit of the Taylor series expansion of the predicting polynomial. If this criterion is not met, the converged time step is discarded, the integrator "back-steps" in time, returning to the previously-converged time step (or back to the starting initial conditions if the analysis is just beginning), and starts the process again with a less aggressive predictor time step.

As the time solution progresses, more converged history is available for all the **q**'s, and, in order to minimize solution time, the solver will try, based on numerical criteria, to increase the time step size (the output step size is the upper limit) and will also try to increase the order of the predicting polynomial (maximum order used in Adams is 6).

The term "modified" is applied to the iteration scheme because, to speed the solution, it is not always necessary to update the system Jacobian at each iteration. A major computational cost in Adams is associated with the computation of the Jacobian inverse. For this reason the inverse of the Jacobian is "mapped" so that it can be quickly updated. Further, the inverse selected is a compromise chosen between maintenance of system equation set sparsity and retention of adequate equation set numerical conditioning. Sparsity is critical to fast solution speed, and system matrices that are only 3-5% populated are not uncommon. However, if upon updating during the solution, the Jacobian should sufficiently degrade (one or more of the terms being used as pivot for solution purposes approaches zero), it is "re-factorized" (e.g. re-mapped) and new pivots are chosen to restore equation set health. Problems which continually re-factorize are generally poorly defined and/or ill-posed.

Numerical "Stiffness"

A numerically "stiff" system is one possessing widely split eigenvalues. Fig. 4 depicts a 2 DOF spring/mass/damper system in which the masses are constrained to move vertically. Assume that K_1 and C_1 are large, that K_2 and C_2 are small, and that the resulting undamped system eigenfrequencies are 5 kHz and 5 Hz. Assume further that at least 10 output steps are necessary to track a complete

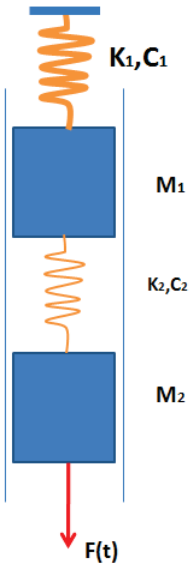


Figure 4 Excited 2 DOF Spring/Mass/Damper System

deformation cycle. This implies that the maximum permissible time step is 2.0e-5 seconds as long as the 5 kHz motion is present. An explicit solver always assumes the highest potential frequency in the system may be active, thus the integrator step is "maxed" at 2.0e-5. An implicit integrator, on the other hand, "senses" the highest, *currently-active* system frequency and opens the time stepping accordingly. Assume for the moment that **F(t)** initially excites the 5 kHz motion but that the damping factor $\mathbf{C_1}$ quickly drives this motion to zero. The implicit solver can now, since it is now dealing with a 5 Hz problem, increase the step size to 2.0e-2 second, resulting in a thousand-fold improvement in execution speed, and the time step will stay there unless *F(t)* should, again, excite the high frequency. Even if *F(t)* is not a source of high frequency excitation, the numerical solution itself of the system equations can result in solver "noise," leading to spurious system frequency excitation. This points out the importance of *always* including damping, however small it may be, in a simulation. It is always present when materials dynamically deform, except, perhaps, for those esoteric cases where the temperature of the deforming material approaches absolute zero.

There are potential issues with use of an implicit solver. A successful (i.e., converging) explicit solution will, in general, also be numerically accurate. A converging implicit solution may not be, unless the error control is sufficiently tight. A "rule of thumb" associated with implicit solvers is that the solution is not truly accurate unless the results stop changing with successive reductions in error tolerance. This consideration is often overlooked in practice.

In addition to MSC Nastran SOL109, other capabilities in the MSC Nastran FEA solution suite are SOLUTION 400 (implicit nonlinear analysis, based on MSC's Marc solver) and SOLUTION 700 (explicit nonlinear analysis, based on LSTC's LS-DYNA solver). SOL700 is limited to explicit numerical solution. MSC Nastran SOL109 and SOL400, like Adams, solve implicitly (at least by preference). The decision as to which solution to employ depends in large part on the importance of certain problem attributes.

Problem Attributes

The decision as to which solution to employ for an engineering problem depends on, in addition to explicit/implicit solver considerations, other factors, some principle ones of which are:

1) Constitutive Considerations
2) Degree-of-Freedom (DOF) Count – Structural vs. Mechanism
3) Event Motion/ Duration

Constitutive Considerations – Deformable vs. Non-Deformable

Rigid Components

If the structural deformation of the system components can be ignored (i.e., the components are considered rigid), MBD is the automatic choice. Even if the connections between the components are functionally complex, FEA cannot hope to compete in computational efficiency, completeness, and ease of use. MBD, with its algebraic constraint capability and its use of convecting reference frames (see below) is specifically designed to deal very efficiently with this type of problem.