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Optimization and mechanical systems simulation

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Abstract

A seamless interface has been developed linking the ADAMS (Automatic Dynamic Analysis of Mechanical Systems) MSS (Mechanical Systems Simulation) tool with optimization libraries to form an integrated package for the optimum design of mechanical systems. These features enable the user to design models parametrically and visualize differences in product performance. With this parametric optimal design capability, manufacturers can quickly and easily develop, refine, and optimize a mechanical system design in the ADAMS virtual prototyping environment. The general approach taken to defining an optimization problem will enable designers to formulate design investigations that are more meaningful to specific industry and engineering challenges. The methods have been verified using classical examples from engineering and has been used for several automotive applications.

Introduction

Until recently, optimization has largely been applied to specific problems on a case by case basis.(Minen [10]) General purpose codes are emerging, but much of the previous work in this area has been broadly applicable within disciplines such as synthesis, design, or controls.(Haug, Sohoni [5]) While powerful and extremely functional, it still places a large programming burden on the user.

The evolution of ‘concurrent’ engineering and virtual prototyping give rise to the need for tools that cross even these disciplines and, perhaps more importantly, include state of the art ease of use features that remove the user several levels from the basic theory of optimization and mechanical simulation. Optimization has historically been the domain of senior analysts and researchers with advanced degrees. As optimization becomes more ingrained in the development cycle, the challenge is to provide broad optimization capabilities to users with less theoretical background or training.

The ADAMS virtual prototyping environment is commercially available from Mechanical Dynamics, Inc., in Ann Arbor, Michigan, USA. ADAMS 8.0

contains the DOT (Design Optimization Tools) package from Vanderplaats, Miura, and Associates, Colorado Springs, Colorado, USA. [1, 2] This paper shares early experiences and suggests some guidelines for future development.

This paper will discuss the three stages in the development of optimization and MSS. First, we will suggest some objectives, including a brief list of some applications of this technology. From this we can derive a concise set of software requirements and describe some of the available tools. Examples are included to demonstrate the successes of the technology seen so far. Finally, possibilities for future work is discussed.

Objectives

MSS makes virtual prototyping truly indispensable for manufacturers by providing parametric design optimization and design of experiments. [1] (Minen [10]) New features enable the user to design models parametrically, subject them to standard simulation "test suites," generate optimal design parameters based on user specified performance targets, and visualize differences in product performance. With this new parametric optimal design capability, manufacturers can quickly and easily develop, refine, and optimize a mechanical system design in the virtual prototyping environment.

MSS now offers embedded design optimization capabilities. Users can define design objectives, constraints, and variables to be modified, and then automatically iterate to the optimally performing configuration. [1] Importantly, the general approach taken to defining an optimization problem will enable them to formulate design investigations that are more meaningful to their specific industry and engineering challenges.

Requirements

Our experience has shown that there are three requirements of optimization and MSS. The tool must be easy to use. In other words, the software must fit comfortably into the work environment of engineers with little or experience with optimization. At the same time, it must also be a powerful tool for engineers with optimization expertise. Finally, the optimization must work well with a broad suite of analyses.

There are two crucial elements to constructing an optimization tool that is easy to use.(Spagnuolo [12]) The user should be able to define the optimization parameters within a familiar framework, but should not need to interact with the numerical algorithms.

MSS and optimization is targeted for design engineers.(1) An effective tool will not force the user to experiment with the parameters of the numerical algorithms. Numerical analysts seek to find a single algorithm that can solve all problems robustly. Computer scientists seek to find ways to automatically select the best method and parameters suited for each problem on a case by case basis. To that end, software must:

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1. Eliminate the effects of errors in the MSS analysis on the optimization, including
   a) failures at infeasible designs
   b) discontinuous objective or constraint function behavior due to approximation errors
2. Help the user specify tolerances in quantities that are meaningful to that organization
3. Provide diagnostics in the user's style so that results can be intelligently interpreted.
4. Adaptively change methods and solution parameters to provide a robust solution

   The solution to many of these issues involves interface customization bordering on artificial intelligence, which is the subject of future work.

While MSS and optimization is geared toward the design engineer, it must also be a tool for engineering analysts. They need a broad suite of methods, and almost complete control over methods and solution parameters. For them, the tool must provide access to all parameters, capabilities to control the process, and sufficient documentation and training for the analyst to comprehend the effects of the available choices.

MSS tools must be capable of providing several types of analysis. Kinematic analyses are frequently used at the beginning of the design cycle to determine range of motion, clearance tolerances, and interference. Static analyses provide initial estimates of reaction loads and removing numerical transients. Kinetostatics provides a a computationally inexpensive approximation to dynamic loads where inertial effects are considered neglible.

The eventual dynamic analysis must be available in both the rigid and and flexible body (elastodynamics) case. Computational elastodynamics involves some integration with finite element analysis. Mass, damping, and stiffness matrices can be imported in the 'discrete' approach, or modes shapes can be included using the 'modal' or component synthesis method. Similarly, linear dynamics can provide frequency analysis, mode shapes, and forced vibration information for rigid or flexible body models.

Tools, Applications, and Examples

Available Tools

ADAMS provides these optimization modeling capabilities and a general-purpose optimization algorithm, DOT, embedded in the full simulation package. Three options are available within DOT [2] (Moré and Wright [11]):

DOT1
  uses BFGS (Broyden-Fletcher-Goldfarb-Shanno) for unconstrained optimization
  uses MMFD(Method of Modified Feasible Directions) for constrained optimization
DOT2
  uses FR (Fletcher-Reeves) for unconstrained optimization
  uses SLP(Sequential Linear Programming) for constrained optimization

DOT3
uses FR (Fletcher-Reeves) for unconstrained optimization
uses SQP(Sequential Quadratic Programming) for constrained optimization

To fulfill the requirement of broad functionality, the tool must communicate well with complimentary technologies. Presently, this communication is accomplished either by constructing interfaces between MSS tools, or integrating the tool or tools under or within a custom design environment. Several interfaces and custom design environments couple with MSS to form a multidisciplinary design tool, all of which can provide optimization input.

The need for MSS analysis tools to interface with controls design and finite element analysis tools is well established. (Minen [10]) In addition, custom design environments are emerging to provide engineers with design and analysis tools that are represented by a paradigm they are immediately familiar with. Examples include environments for automobiles, wind turbines, railways and rail vehicles, and human body (android, crash dummy) modeling. Integrated optimization enhances the capabilities of such tools.

Applications

Of course, the potential applications of optimization and MSS are limitless, but some standard problems can be identified. Those that have been requested most often are listed here. Some are quite general, and are most naturally categorized by the classic statement of the optimization problem: design variables/functions, objectives and constraints. Some problems are so specific in nature that an interface can be customized to define the problem in a more meaningful context, removing a level of abstraction.

Any optimization problem can be stated in some form as: determine a set of design variables to minimize (maximize) an objective, subject to constrains on the design variables. These ingredients categorize optimization problems.

The nature of the variables identifies the problem as optimal design or optimal control. Examples of optimal design variables include:

a) Spring/Beam/Bushing Parameters
b) Joint Locations
c) Geometry, e. g., Link Lengths
d) Gain Constants

Examples of optimal control functions include:

a) Thrust Profile
b) Motor Torques
c) "Boundary" (Initial, Final) Conditions

Examples of optimization objectives include:

a) Path Tracing
b) Minimize Mass
c) Minimize Energy Requirements
d) Minimize Fuel Consumption
e) Maximum Strength
f) Control Natural Frequencies

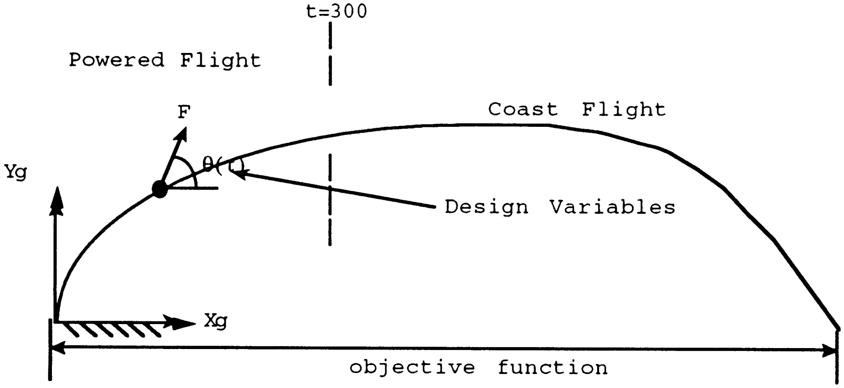
Examples of constraints include:
- a) Hitting a Target
- b) Workspaces, Interference
- c) Finish at Rest

Examples

The following three examples demonstrate two types of problems necessary to determine the validity of optimization and MSS. To determine the accuracy of the optimization, the optimization methods must be applied to MSS problems for which a closed form solution is known. To determine the usefulness of the entire tool set, existing industrial designs should be optimized to see how much the design can be improved.

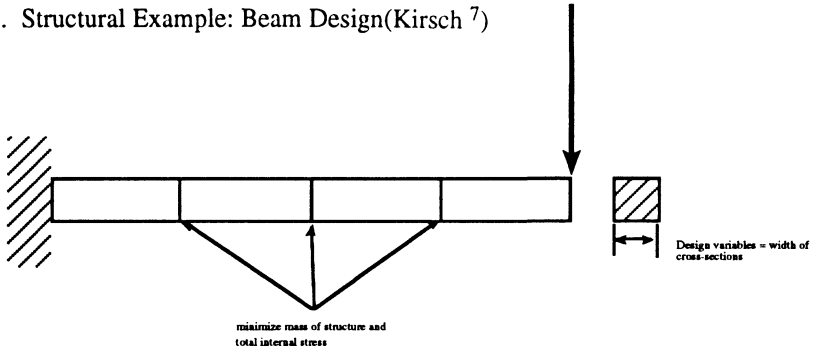
For each of the verification problems (for which the solution is known) and others, the numerical solution can easily be made to match the known solution to virtually arbitrary accuracy. For most industrial problems, the design improvement was nearly 100%.

1. Verification: Projectile Range (Vinh [15])



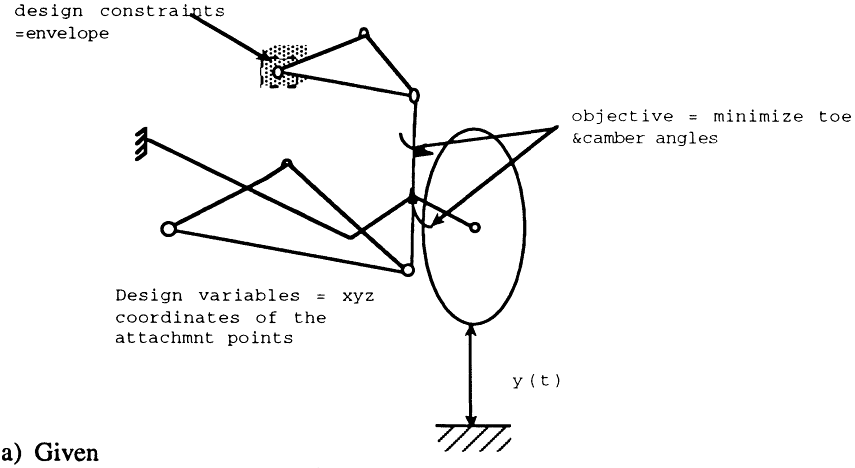
a) Given
(1) a rocket missile is fired at time t=0 from ground. Assume the following:
  (a) The missile may be treated as a particle of initial mass M=100 Kg.
  (b) Acceleration due to gravity is a constant at $g=-9.81\ m/s^2\ \mathbf{j}$
  (c) The propulsion system is of the the constant ejection velocity type with specific impulse duration of 300s.
  (d) The thrust program **F**(t) is such that acceleration (force/mass) is constant.
  (e) At the end of the burn program, the mass of the missile is 50 Kg
  (f) The rocket initial conditions at : t=0 are x = 0 y = 0 x' = 0y' = 0
b) Determine the design function:
(1) the time history of the thrust angle q(t),
c) Such that
(1) the total range of the rocket is maximized.
d) Results
(1) the optimal trajectory is a constant, q(t) = 1.4 radians

2. Structural Example: Beam Design(Kirsch [7])



a) Given
(1) a cantilever beam model with 4 square sections modeled as 4 rigid bodies connected by 3 ADAMS beams.
b) Determine
(1) 4 design variables representing the width of the sections,
c) Such that
(1) the mass and the maximum stress in beam for given loads is minimized
d) Subject to
(1) maximum deflection at tip for a constant load should not exceed 1 mm.
(2) lowest frequency of the cantilever beam should be greater than 5 Hz.
e) Results
(1) The original design did not have sufficient mass to support the required load. Minimum mass was added to reduce the dip deflection from 1.6 to 0.2 mm. Fundamental frequency = 21 Hz.

3. Automotive Examples: Suspension Design(Haug, Sohoni, Kim [6])



a) Given
(1) an SLA (Short-Long Arm) suspension is one of the most frequently used automotive suspension types in existence. This suspension is characterized as a "four bar" mechanism in the front profile with the steering axis that rotates about the axis of the "idler link" and a wheel rotation axis that emanates from the idler link. See the figure. We wish to inspect the effects

that certain variables have on a desired toe curve throughout the wheel's vertical range of motion (i.e., full jounce to full rebound). The objective is the average toe curve deviation between the desired and the actual response.

(2) Determine design variables
  (a) 2 ball joint locations & 4 bushing locations,
(3) Such that
  (a) the toe angle vs. ride height profile matches a specified target curve
(4) Results
  (a) Design improvement = 100%. The area between the desired and actual design curves was reduced to << 1 from an initial design whose performance measure exceeded 1E4.

Conclusions

1. With optimization and MSS, manufacturers can quickly develop and optimize a design in the virtual prototyping environment.

2. This approach enables them to perform investigations that are meaningful to their specific industry .

3. A useful tool requires ease of use, power and open architecture, and broad functionality.

Future Work

The priority in future work is to facilitate improving engineering design, not squeezing out the last 2% of the Kuhn-Tucker conditions. The two issues that have the greatest impact on the user are robustness and efficiency, which has an indirect effect on the size of the problem.

If the methods are not robust, the user must frequently re-select methods and solution parameters. If they are not efficient, optimization may not be practical, or the user must reduce the size of the problem, which can increase the likelihood of missing a good design.(Adeli [3])

Robustness is sensitive to
1. the coarseness of finite differencing mesh,
2. the scale/range of the variables and functions, and
3. how the finite differencing is performed.

Robustness can be improved by automation (Adeli [3]):
1. using design of experiments techniques to select a good initial design,
2. automatic method selection,
3. adaptive finite differencing schemes, and
4. randomized initial design can provide an approximation to global optimization

Greater efficiency can be achieved through
1. the use of analytic gradients, where available, and
2. reanalysis methods.

References

[1] ___, *Optimization Guide,* Mechanical Dynamics, Ann Arbor MI, 1994

[2] ___, *DOT User's Manual,* VMA Engineering, Goleta CA, 1993

[3] H. Adeli, *Robustness in Design Optimization Software,* Reliability and Robustness of Engineering Software. Edited by C. A. Brebbia and G. A. Kerimidas, Elsevier and Computational Mechanics Publications, 1987

[4] M. A. Chace, *Methods and Experience in Computer Aided Design of Large-Displacement Mechanical Systems*, Computer Aided Analysis and Optimization of Mechanical System Dynamics. Edited by E. J. Haug, Springer Verlag, 1984

[5] E. J. Haug and V. N. Sohoni, *Design Sensitivity Analysis and Optimization of Kinematically Driven Systems*, Computer Aided Analysis and Optimization of Mechanical System Dynamics. Edited by E. J. Haug, Springer Verlag, 1984

[6] E. J. Haug, V. Sohoni, Sang S. Kim, Hwal-G. Seong, *Vehicle Suspension Dynamic Optimization,* IAVD, London, 1983

[7] U. Kirsch, *Optimum Structural Design*, McGraw-Hill, 1981

[8] D. F. Lawden, *Optimal Trajectories for Space Navigation,* Butterworths, London, 1962

[9] J. P. Marec, *Optimal Space Trajectories,* Elsevier Scientific Publishing, Amsterdam, 1979

[10] D. Minen, *New Strategy for Choosing Optimal Design Parameters via Xmath and ADAMS Interconnected Simulations,* Mechanical Dynamics Italy srl, Tavagnacco Italy, 1993

[11] J. J. Moré and S. J. Wright, *Optimization Software Guide*, SIAM, Philadelphia, 1993

[12] R. Spagnuolo, *Intelligent Interfaces for Software Reliability,* Reliability and Robustness of Engineering Software II. Edited by C. A. Brebbia and A. J. Ferrante, Elsevier and Computational Mechanics Publications, 1987

[13] W. Stuecklshwaiger and A. Ronacher, *Opitmisation of Engine Mount Parameters by Simulation and Statistic Techniques,* 1994 European ADAMS User Conference, Mechanical Dynamics GmbH, Marburg Germany, 1994

[14] G. N. Vanderplaats, *Numerical Optimization Techniques for Engineering Design with Applciations,* McGraw Hill, New York, 1984

[15] N. X. Vinh, *Optimal Trajectories in Atmospheric Flight,* Elsevier, Amsterdam, 1981