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Parameter Gradient-Based Optimization Case Study: the Medium Weight Shock Machine

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1 Introduction

Generating a multibody model from a physical model is a complex process involving numerous assumptions and simplifications. These uncertainties stem from various sources, such as the material properties of the bodies, their dimensions, the forces acting on them, or the presence of clearances or friction. Depending on the multibody model and the purpose of the analysis, these uncertainties may corrupt the outcome and conclusions. Therefore, adjusting parameters is a crucial part of any multibody model.

Frequently, the modeling engineer does not have direct measurements of all magnitudes but rather a set of complementary measurements that are not directly correlated with the former. In these cases, parameter adjustment can be approached as an optimization problem, where the objective is to minimize the error between the simulated and measured magnitudes, with the parameters as the sources of uncertainty.

This work studies the parameter optimization of a Medium Weight Shock Machine using gradient-based optimization algorithms. The objective function gradient is obtained using analytical sensitivity analysis methods, which are generally more efficient than numerical or automatic differentiation methods [3]. A sensitivity analysis of a flexible floating frame of reference (FFR) Augmented Lagrangian formulation in natural coordinates is performed at each optimization iteration.

2 Model

The Medium Weight Shock Machine (MWSM) is used for the evaluation of equipment mounted on warship vessels. It consists of a 90000-lb concrete foundation which lays over a sprung bed, a massive hammer in the configuration of a pendulum and an anvil table which describes a small translation after the hammer impact. All the listed elements can be modeled as rigid bodies without a notable error. The uncertainties at this point are concentrated in the contact model used to reproduce the hammer-anvil table contact and the top and bottom stops of the anvil table.

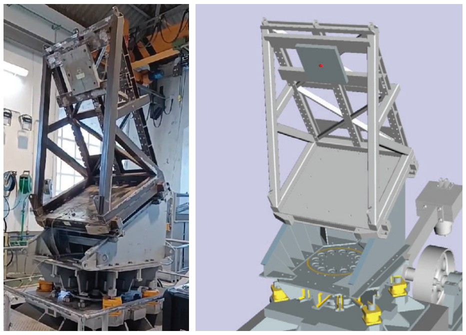

Figure 1: Real (left) and simulated (right) MWSM shock test.

The MIL-DTL901E specification establishes a set of auxiliary structures that must be used in a shock test. A set of supporting channels, which are C-shaped beams used to mimic the filtering of accelerations along the ship structure, must be mounted between the testing item and the anvil table. The dynamics of the testing item after the hammer impact is strongly related to the elastic deformation of these channels, thus they are modeled as flexible bodies. These elements are linked to other bodies via clamps that permit slight displacements and local rotations. These connections are modeled as 3D linear spring-damper forces with uncertain values. The structural damping of the flexible elements is also unknown. The list of uncertainties is completed with the structural damping of the load fixture (for hull-mounted equipment only) and the properties of its connection with the testing item.

3 Sensitivity analysis and Optimization

The machine is modeled in natural coordinates with modal amplitudes accounting for flexibility in the framework of the FFR method. The index-3 Augmented Lagrangian formulation with projections (ALI3-P) described in [1] is considered with the mass matrix as projection matrix. All derivatives involved in the sensitivity analysis of this formulation are computed analytically taking advantage of multidimensional matrix algebra. Both dynamics and sensitivities have been programmed in the multibody library MBSLIM [2] as general formulations. Due to the large amount of experimental tests executed in the real MWSM and the number of measurements per test, the objective function is build as a sum of errors:

$$\psi = \sum_{i=1}^{n_t} \left\{ \int_{f_0}^{f_F} \left[\sum_{j=1}^{n_{sens}} \left(\mathbf{s}_{exp}^{i,j} - \mathbf{s}_{sim}^{i,j} \right)^{\mathrm{T}} \left(\mathbf{s}_{exp}^{i,j} - \mathbf{s}_{sim}^{i,j} \right) \right] \mathrm{d}f \right\} \tag{1}$$

wherein $\mathbf{s}_{exp}^{i,j}$ and $\mathbf{s}_{sim}^{i,j}$ are the acceleration shock response spectra (SRS) of the experimental and simulated measurements of sensor j in test i, being n_t the number of shock tests, n_{sens} the number of sensors and f the frequency. The gradient of (1) is computed by meas of a forward sensitivity analysis as:

$$\nabla \psi = -2 \sum_{i=1}^{n_t} \left\{ \int_{f_0}^{f_F} \left[\sum_{j=1}^{n_{sens}} \left(\mathbf{s}_{exp}^{i,j} - \mathbf{s}_{sim}^{i,j} \right)^{\mathrm{T}} \left(\mathbf{s}_{sim}^{i,j} \right)' \right] \mathrm{d}f \right\} \tag{2}$$

with $\left(\mathbf{s}_{sim}^{i,j}\right)'$ obtained from $\left(\ddot{\mathbf{r}}_{sim}^{i,j}\right)'$. Executing several simulations each gradient evaluation involves a high computational effort per optimization step. This computational time is minimized by the use of analytical differentiation. In the optimization process, an Augmented Lagrangian and an LBFGs [4] algorithms are compared for identical initial parameters with parameter bounds as the set of optimization constraints. Results show that both optimization algorithms convey to a significant improvement in the convergence between experimental measurements and simulation, and evidence the advantages of analytical sensitivity for tackling the uncertainties of multibody modeling.

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