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STRUCTURE

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MODEL VALIDATION FOR A COMPLEX JOINTED STRUCTURE

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ABSTRACT

An overview of the modeling and validation of a complex engineering simulation performed at Los Alamos National Laboratory is presented. The application discussed represents the highly transient response of an assembly with complex joints subjected to an impulse. The primary source of nonlinearity are the contact mechanics. Several tests are conducted to assess the degree of environmental uncertainty, the variability of the assembly and to provide reference data for model validation. After presenting the experiment and the corresponding numerical simulation, several issues of model validation are addressed. They include data reduction, feature extraction, design of computer experiments, statistical effect analysis and model updating. It is shown how these tools can help the analyst gain confidence regarding the predictive quality of the simulation.

NOMENCLATURE

1 INTRODUCTION

Quantifying shock transmission through complex, jointed structures has traditionally been possible only with experimental methods. These experiments are expensive and time-consuming and thus only a few cases can be studied. With the advent of large scale

computing capabilities estimation of the shock with numerical models has become a tractable problem. A primary advantage of these models is that, when validated, parametric studies can be efficiently performed to evaluate the effects of different input loads and variations to the structure's design or to load path changes caused by aging. The U.S. Department of Energy's Accelerated Strategic Computing Initiative (ASCI) is developing massively parallel hardware and software environments for modeling these types of problems.

The ASCI environment is being used at Los Alamos to study the transmission of shock through a complex, jointed structure that is similar to structures used in both conventional and non-conventional, defense applications. A three-dimensional explicit model has been developed that includes a detailed representation of the geometry and contact surfaces including preloading effects. A series of full-scale experiments has been performed to provide data for model updating and validation.

After describing the experiments, the data collected, and the finite element model, several issues of open research are addressed. First, large computer simulations tend to generate enormous amounts of output that must be synthesized into a small number of indicators for the analysis. This step is referred to as data reduction or feature extraction [1]. These features are typically used to define the test-analysis correlation

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metrics optimized to improve the predictive accuracy of the model. The main issue in feature extraction is to define indicators that provide meaningful insight regarding the ability of the model to capture the dynamics investigated. The features used for analyzing this nonlinear, transient data sets are presented.

Second, efficient numerical optimization requires that the correlation between the model's input variables and output features be assessed with good accuracy. Statistical meta-models must be generated to replace the expensive, large-scale simulations. One difficulty of fitting meta-models is efficient sampling, that is, the generation of sufficient information in regions where the feature's joint probability density function is maximum. Recent advances in the statistics community are evaluated using these data sets [2].

2 HARDWARE DESCRIPTION

The test article used for the experiments and subsequent analyses consists of several components fabricated from a variety of materials. A component designated the mount to which all other components are attached is shown in Fig. 1. Referring to this figure together with the finite element mesh shown in Fig. 4 in section 4 while describing the assembly of the test article makes the configuration more understandable. The upper payload mass simulator, which is fabricated from 6061-T6 aluminum is bolted to the three feet on the upper end of the mount. The lower payload mass simulator, which is fabricated from carbon steel is held up inside the mount using a tapered tape joint. The tape

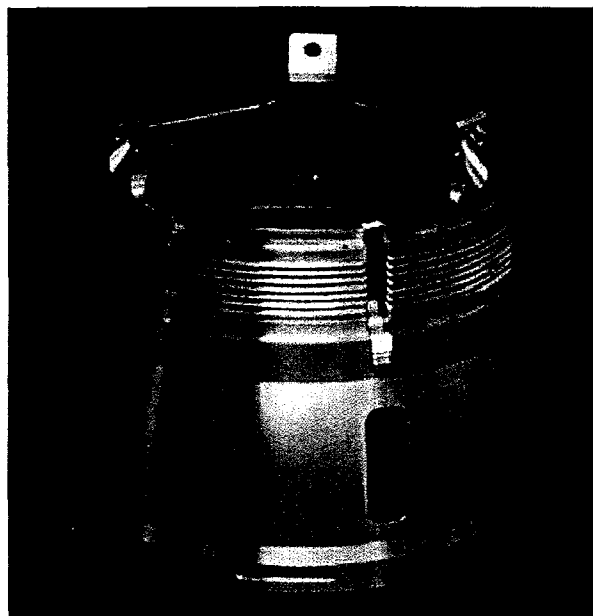


Figure 1: Titanium mount that connects all components of test article.

for this joint is fabricated from SS304 stainless steel. It is inserted through the thin slot near the base of the mount. Separate pieces of the tapered tape are driven in wedging the mass simulator against an inner retaining surface.

The lower shell, fabricated from 7075-T4 aluminum and then anodized is placed over the mass simulator and its rim sits on a ledge just below the threaded portion of the mount. Next a titanium retaining nut threads onto the mount bearing against the upper surface of the lower shell rim. It is torqued to a specified value. Finally, the upper shell, also fabricated from 7075-T4 aluminum, is threaded onto the mount. As it is torqued to a specified value, the load between the retaining nut and lower shell is reduced.

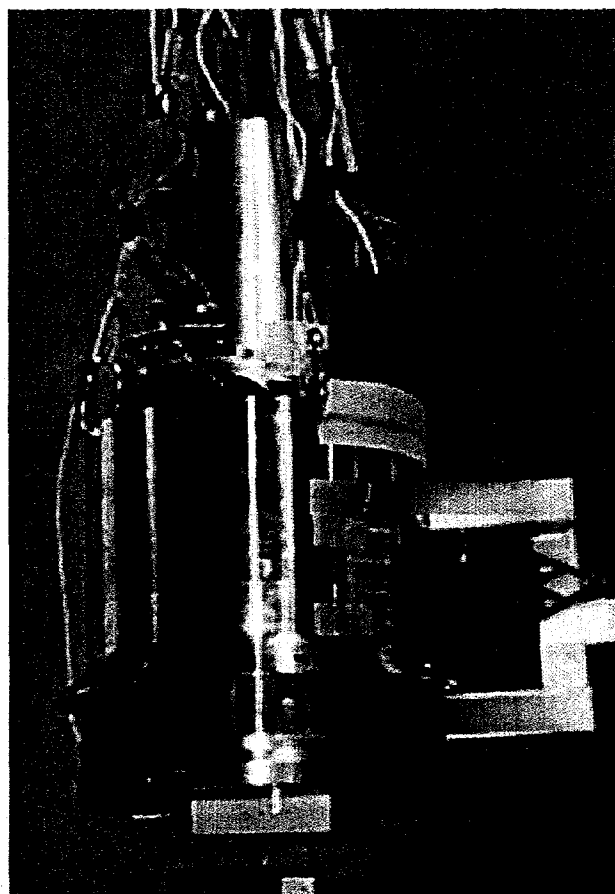


Figure 2: The test article is shown in the test configuration with the explosive source attached.

3 VALIDATION EXPERIMENTS

To date four experiments have been performed on the test article. These tests were performed by SRI International at their Menlo Park, California facility. For the experiments the test article was suspended using wire rope to creating a pendulum with a length of about 1

meter (Fig 2). Pendulum motion was monitored to determine the total impulse delivered to the tests article.

For each experiment new upper and lower aluminum shells were used to ensure that accumulated damage did not affect test results. For three of these tests the shells were manufactured with "loose" tolerances. In other words, the shells were fabricated as nearly as possible to the upper end of the tolerance specification. For the fourth test the shells were fabricated with "tight" tolerances. During assembly of the test article for the first, second, and fourth tests the lower shell was forced to be tight against the mount on the loaded side of the test article. For the fourth test the lower shell was forced to be tight against the mount on the side opposite the load. That is, it had the maximum possible gap between the shell and mount directly behind the explosive source. The resulting test matrix is shown in Table 1.

	Loose assembly	Tight assembly
Loose Tolerance	Test no. 3	Test nos. 1, 2
Tight Tolerance		Test no. 4

Table 1: Test matrix for explosively driven shock tests.

3.1 Explosive Source

An explosive source was developed and characterized to apply an impulsive load to a portion of the outside surface of the test article. The source was fabricated from strips of thin explosive sheet material. Each strip was 0.48 mm thick and 1.27 mm wide. Spacing between strips was 6.86 mm. The pressure at the surface of the test article was moderated with a buffer material made from 3.18-mm-thick solid neoprene. The explosive strips were simultaneously initiated using an explosive lens. Characterization of the source involved using thick plates of aluminum target material containing plugs that could fly free. Measuring the velocity of these plugs and measuring the pressure with miniature piezoresistive sensors ensured that the desired impulse was realized. Additional verification of the impulse was obtained by measuring the change in velocity of the test article for each test. Figure 3 shows the pressure time histories of the pressure acting on the test article both directly under an explosive strip and half way between two strips.

The final geometry of the explosive source was 38 mm high by 102 mm long (circumferential direction). It was placed vertically such that 12.7 mm was below the intersection between the upper and lower shells and 25.4 mm was above the intersection. The portion on the upper shell was directly outside the threaded intersection between the shell and the titanium mount.

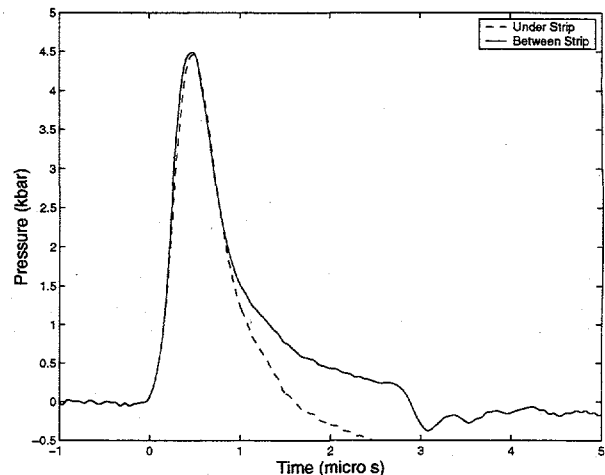


Figure 3: Pressure histories measured on surface of aluminum substrate under neoprene buffer.

3.2 Instrumentation

The test article was instrumented with 33 strain gages and 6 accelerometers. The strain gages were attached to the inside surface of the titanium mount and had an active length of 0.8 mm to obtain localized effects. The six accelerometers were Endevco Model 7270A-200k and were located on either end of both payload mass simulators. Four were oriented laterally in the direction of the delivered impulse and two were oriented along the axis of the structure. The conditioned strain signals had a frequency response of 100 kHz and the accelerometer signals had a frequency response of 500 kHz.

3.3 Experimental Results

Measured strains ranged up to approximately 0.01 and peak accelerations after filtering to 50 kHz ranged up to about 10 000 gs. Changes in rigid body velocity for the tests verified the total impulse measured during the characterization experiments. Test results are discussed further in following sections

4 NUMERICAL MODEL

The explicit finite element model (FEM) of the test article was developed using the ParaDyn finite element code^{xx}. The resulting model had approximately 1.4 million 8-node hex elements, 56 000 4-node shell elements, and 1.8 million node points. Contact among the various test article components was modeled with 480 contact pairs. This large number of pairs was required because each individual surface, usually circumferential in nature, had to be broken in to several individual surfaces to accommodate efficient partitioning for the parallel code. Automatic contact

features that are currently under development in ParaDyn will obviate the need to break the contact into so many surfaces. Figure 4 shows a cross-section of the finite element model that illustrates the mesh density at most of the contact interfaces.

All material models were elastic since the loads for the first four experiments were low enough to keep all components in the elastic range. The only source of nonlinearity was, therefore, motion at the contact surfaces. The nonlinearity at these interfaces can be quite severe as shown in Figs. 5 and 6 where the predicted contact forces across two interfaces are shown. The first case shown is a segment of a thread between the upper shell and mount directly under the explosive charge. Note that when the force goes to zero the threads have actually momentarily separated. The second case shown is the vertical interface between the upper shell and mount directly above the threaded region. Here the opening and closing of the gap is very obvious.

Because the contact involved interfaces among stainless steel, carbon steel, anodized 7075-T4 aluminum, 6061-T6 aluminum, and titanium, precise selection of static and kinetic coefficients of friction was not possible. Some of the variables that contribute to the coefficient of friction include surface finish and hardness and the presence of lubricants. Since these were not known, these coefficients of friction were estimated by bounds and allowed to vary between specified limits among different runs as described in later sections.

Preloading due to assembly of the threaded joints and the tape joint was accomplished in the model by implementing an orthotropic thermal coefficient of expansion in specific layers of elements. At the start of each analysis the temperature was increased using a half-cosine time history over 0.2 ms. The structure was then allowed to freely respond with no additional input for 0.1 ms before the explosive impulse was applied. Lacking a precise definition of the coefficient of friction also led to unknown levels of these preloads. Therefore, the preloads were also allowed to vary between specified limits among the different runs.

The impulse from the explosive source was applied over the appropriate region of the test article as a pressure time history. Since the explosive strips were center-detonated, the pressure pulse arrived at each circumferential position at a different point in time. This time delay was accommodated in the model by dividing the loaded region into vertical strips of elements and using the appropriate time of arrival for each element strip.

The finite element model was run on 504 processors on the Los Alamos Blue Mountain computer. Using this number of processors resulted in 1.3 cpu hours for each ms of the simulation.

5 MODEL UPDATING AND VALIDATION FEATURES

The first aspect in determining what features are appropriate for model updating and model validation is consideration of what the model will be used to predict. For instance, if the model will be used to predict only peak acceleration at a given point it is not necessary to consider the time of arrival of the peak or the frequency content of the acceleration data. In this case the feature is a single number representing the peak acceleration. If the designer or analyst is concerned not only with the peak level of acceleration, but also the frequency content of the acceleration history, the shock response spectrum (SRS) may be an appropriate measure of the systems response. However, in general, the SRS is ambiguous in that an infinite number of transients can lead to the same SRS. An alternative measure of frequency content is the Fourier transform of the acceleration history. Here the analyst has the freedom to choose the frequency range of interest and compare the transform only in those frequency bands. Other features of response that might make sense could include counting the number of times that a strain history exceeds certain levels. This feature may be appropriate for certain fatigue analyses.

A second aspect in determining the appropriate features is to select features that have a low enough dimensionality to make comparison tractable. Comparing two acceleration histories point by point is not a good choice. A choice such as this becomes even more impossible if the acceleration at several different points need to be compared. An obvious alternative of simply using the RMS level of acceleration, however, may not give sufficient information. Other options for reducing dimensionality that are frequently used are comparing mode shapes and frequencies or measures of their differences.

In the case of the test article being considered here the desire is to fully characterize the acceleration and strain responses at specific locations over a wide frequency range (0.5 – 30 kHz). The direct use of linear mode shapes and natural frequencies of vibration is not a viable alternative because of the systems inherent nonlinearities. As an alternative, the use of principal component analysis is being investigated. In this case information from 6 accelerometers or 33 strain gages can be reduced to one time history if only the first principal component is considered.

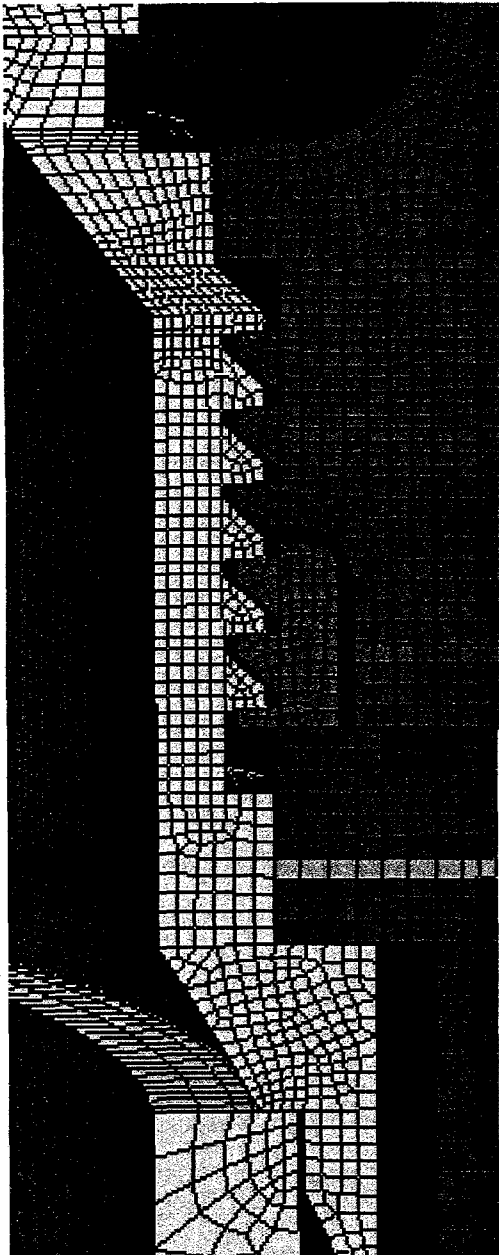


Figure 4: Closeup view of finite element mesh showing complex interfaces among components as they interface titanium mount.

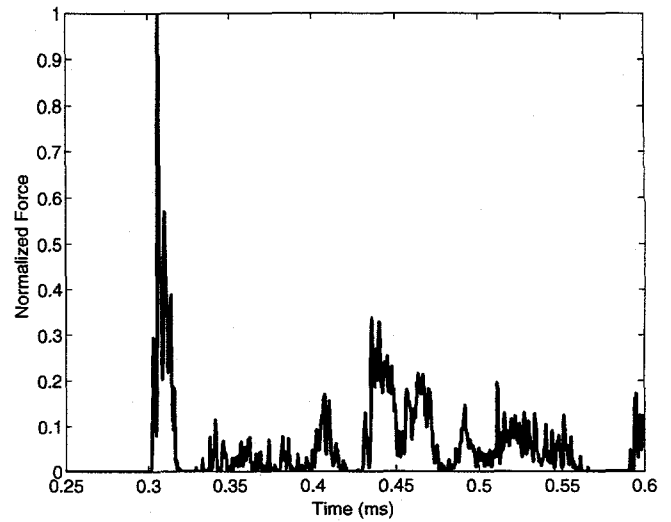


Figure 5: Normalized contact force between an individual thread on upper shell and the titanium mount. Impulse is applied at 0.3 ms.

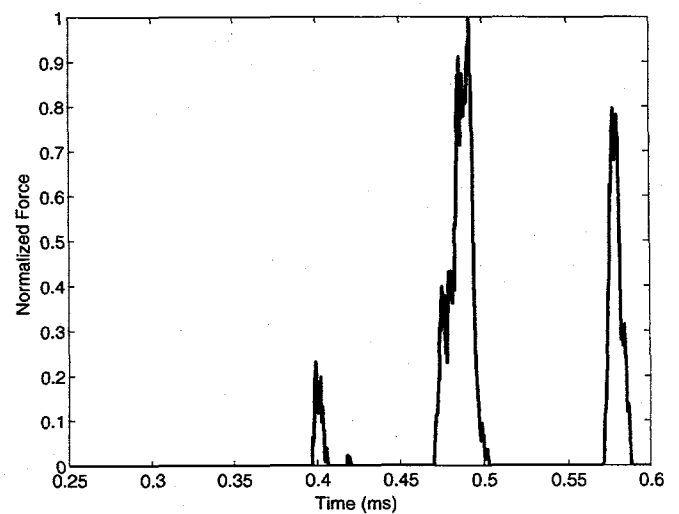


Figure 6: Normalized contact force between vertical surface of upper shell and titanium mount just above threaded region.

To further reduce the dimensionality of the data, an auto-regressive moving average (ARMA) model is fit to the first principal component derived from the test data. The time history predicted by this model is then compared to the FEM prediction. The variance between the two model predictions is a single number that is used as a primary model updating feature. In a similar manner an ARMA model is fit to the FEM prediction and this is compared to the test data.

The ARMA based feature does not give a measure of the RMS response so, in addition to this feature, the RMS value of a vector representing the differences of RMS values of individual acceleration or strain histories from the test and FEM predictions is used.

Additional features being considered but not yet implemented include a measure of the energy content distribution in the Fourier transform of the time history of the first principal component.

6 Sampling Methods

Efficient model updating and validation requires that the correlation between the model's input variables and output features be assessed with good accuracy. Statistical meta-models must be generated to replace the expensive, large-scale simulations. One difficulty of fitting meta-models is efficient sampling, that is, the generation of sufficient information in regions where the feature's joint probability density function is at its maximum. The approach used here was to first use a sparse sampling to determine what the main effects are and then to down select on the number of input parameters considered. A denser sampling is then performed over the reduced set of parameters.

The design-of-experiments method [3] was used to select the computer simulations that would be most efficient for determining which parameters were the main effects. This set of simulations is called the design matrix. In establishing the design matrix care must be taken to use enough simulations to avoid aliasing that may bias the subsequent statistical analysis. Aliasing in statistical modeling is caused by using sparse sampling of the input space that is too sparse. The result can be contamination of main effects by secondary effects.

If the design matrix is based on orthogonal variable arrays the columns of the input space are linearly independent. This independence results in the ability to distinguish the variance associated with the linear aspect (main effect) of a variable from the other variables. It does not imply that it is not confounded/aliased with second order or higher effects. However, if the design matrix is based on the Taguchi method the columns not correlated with other

columns and, in addition, they are free of interaction with second-order effects. This makes for very good linear screening ability with a limited set of simulations.

After the design matrix is established, the finite element package is run at the corresponding combinations of input parameters and results are gathered for feature extraction. Then, statistical tests are implemented to assess the global contribution of each input parameter to the total variability observed from the computer simulations. A popular example is the R-square (R^2) statistics that estimates Pierson's correlation ratio. It is defined as the ratio between the variance that can be attributed to a given effect and the total variance of the data.

7. RESULTS

As described in the previous section, the first step in the development of a parameter set to be used for model updating and response surface construction is the screening of the main effects of the candidate variables. This assesses the amount of variation of the model that can be explained by the different variables. Ideally the variables that have significant effect on the model will have also have significant contribution to the variance of the selected feature. As described in Section 5, the primary feature that has been applied to date is the comparison of the simulation's prediction to an ARMA model fit to the experimental data.

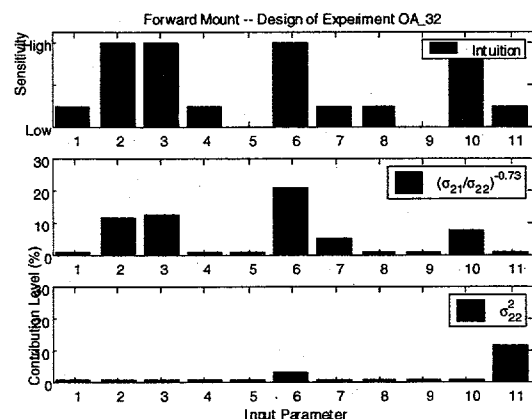


Figure 7: Results of preliminary main effects analysis using ARMA-based features and a Taguchi design matrix.

The design matrix for extracting main effects was developed based on 11 variables (input parameters) varied over 32 simulations. Figure 7 shows the results of the analysis. The first graph in the figure shows the analyst's expected results based on engineering judgement and a thorough knowledge of the test article. The second and third graphs show the results using two

different features; both based on the ARMA modeling technique. It is clear from the figure that variables 2, 3, 6, 7, 10 are significant for the feature shown in the middle plot. Only variable 6 and 11 have significant effect on the second feature.

Also from the figure, it is clear that the first feature matches well with analyst predictions. This partially confirms that the feature is extracting information that is reasonable. A current effort will lead to selection of a second, independent, feature that will be used to confirm that the indicated variables are the indeed the ones that should be used for the more detailed analysis to rigorously define the statistical meta-model.

8. CONCLUSIONS

Even though the results are preliminary at this point, analyses to date have shown that a very large FEM can be efficiently validated and updated if modern statistical methods are applied. In addition, early indications are that a large model that has to simulate significant nonlinearities can simulate response to a highly impulsive load throughout the frequency range of interest.

Further work is needed to develop additional features for use in both model updating and validation. Also, additional experiments are required since the four available at this time are probably not different enough to fully validate the model over the load ranges of interest.

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