Characterization of Load Uncertainty on Simulated Dynamic Responses

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Abstract

Finite Element Analysis (FEA) of complex systems such as aerospace structures are routinely being used to predict dynamic responses, generate environmental specifications, and qualify component designs. Uncertainties in model parameters cause model form error, which can lead to overdesign, overtesting, or component failure caused by inaccurate model predictions. Calibration to experimental modal tests address most of these uncertainties. One major source of uncertainty not addressed in system modeling is the uncertainty in the input force. Although accelerations are routinely measured with accelerometers in laboratory and flight testing, the actual input forces being imparted to the system are unknown. Use of the measured accelerations as input forces is known to cause large model form errors. This study characterizes causes of the load mismatch and quantifies the uncertainty in the resulting response predictions caused by the current methods. The Box Assembly, Removable Component (BARC) academic structure is used to perform the load uncertainty characterization. The results of this work are critical to reduce uncertainty in model predictions and enhance the credibility of FEA models.

Keywords: DET, force estimation, modeling and simulation

Background

Finite Element Analysis (FEA) models are universally used to predict a structure's response to a given excitation. For structural dynamic FEA, those predicted responses will be used to inform component design, supplement the generation of environmental specifications in the absence of test data, and even support component qualification. Uncertainties in model parameters lead to model form errors, which can contribute to overdesign, overtesting, and even component failure. Model calibration is routinely performed to reduce structural model form errors. Model calibration is traditionally performed by iteratively updating the mass, stiffness, and joint definitions in a model until the FEA mode shapes are representative of measured mode shapes of the structure. However, more complex model updating techniques exist that attempt to use advanced algorithms to identify model parameters that will reproduce measured modes, such as FEMtools [1] and FuSED [2].

Regardless of the model calibration approach, a calibrated model is only useful for predicting dynamic responses if the loads applied to the model are realistic. Model calibration is possible because the true dynamics of a structure can be experimentally measured. The true loads on a structure, however, are not possible to measure directly and must be derived from other measurements, usually from acceleration measurements. In some cases load estimation is straightforward; single degree of freedom (SDOF) shaker tests apply a measured excitation to a structure in a single direction. Assuming the shaker is rigid, applying the measured table acceleration as an enforced boundary condition to a calibrated model will accurately predict the structure's response.

In other cases, however, load estimation is difficult and the error in the estimated load is unknown. For example, a structure experiencing launch conditions will be subject to three-dimensional loads at the attachment locations to the launch vehicle, in addition to possible acoustic loads. Many techniques have been developed to reconstruct impact [3] and even acoustic [4] forces on a structure, but these techniques usually require more measurement locations than are actually captured, and can sometimes generate unrealistic and incorrect predicted loads. More commonly, measured accelerations near the base of the structure are used as applied accelerations in the model. The use of the measured accelerations assumes that the structure between the measurement location and the actual load locations is perfectly rigid, and that the measured location perfectly captures the loads imparted to the structure.

Finally, force reconstruction techniques are useful if the derived forces are reapplied to the structure under the same boundary conditions. In practice, however, forces are derived to define the environment on a specific component within a larger structural system. The boundary conditions of that component are almost never replicated in the lab testing. Reapplying the derived forces to the component with different boundary conditions is expected to produce different responses. However, the error of those responses is unknown.

This paper uses a simple academic structure to quantify how errors in the loads applied to the model can propagate to errors in the predicted response. First, we will quantify how error grows as the load path between the measured base excitation and the actual load location becomes more flexible. Next, we will show that reapplying derived forces to a dynamic structure with different boundary conditions produces different responses, and quantify those differences.

Modeling and Simulation Approach

The Box Assembly, Removable Component (BARC) academic structure was used to quantify how errors in the input forces propagate to predicted responses, and is shown in Figure 1. The BARC was chosen because it is dynamically active, familiar to the Structural Dynamics community, and not overly complex.

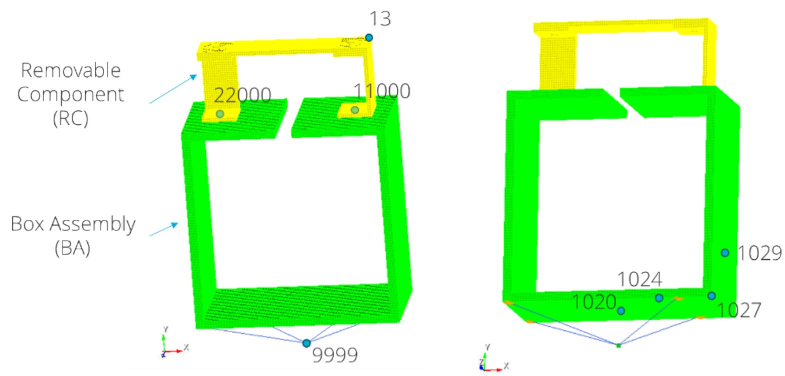

Figure 1. Box Assembly, Removable Component (BARC) academic structure

The RC connection to the BA was simulated with a full rigid set on the base of each RC leg connected to a small rigid patch on the tops of the BA sides with a stiff spring element for each leg connected to the nodesets 11000 and 22000 shown in Figure 1. The rigid sets are free to move and rotate, but the surfaces in the set must move together rigidly. Each stiff spring element has spring components in all six DOFs. Forces in the spring element can be computed to pull the true force applied to the component at the connection location. The three components of the RC (the top plate and two C-channels) are "bolted" together by tying rigid spiders in the bolt holes together with stiff spring elements. The base of the BA is attached to a concentrated mass (conmass) at four small rigid patches. A conmass was used to represent the structure as if it were bolted to something large and stiff like a shaker table.

The Sierra SD finite element analysis (FEA) code [5] developed at Sandia National Labs was used to simulate the BARC responses. Within Sierra SD, connection forces can be extracted from linear elements, including the spring elements. These forces describe the force imparted at that connection location and will be used as the "truth" forces on the component. The forces can be directly reapplied to the structure. Accelerations, however, cannot be directly applied as defined inputs. Acceleration responses will be converted to force inputs using the equation F=M*a, in which a desired acceleration scaled by the mass of a conmass can be applied to a conmass boundary to produce the desired acceleration at that boundary.

Results: Reapplied Acceleration Measurements

The first study used accelerations at points systematically farther away from the true excitation location as inputs to the BARC conmass, Nodeset 9999, to quantify how inputs derived from measurements that only approximate the input acceleration will propagate error to the predicted responses. A single point, Nodeset 13, identified in Figure 1 at the top corner of the RC was used to compare responses between reapplied acceleration case studies. Only one point was used to reduce the complexity of the comparison and to represent expected comparisons between test series with limited measurement locations. Four locations were used to represent the measured input acceleration locations, shown in Figure 1. Three input locations were selected on the bottom of the BA: 1020 in the center, 1024 on the edge near the rigid connection to the conmass, and 1027 on the corner. One input location, 1029, was taken near the base on the side of the BA to represent instances where measurement sensors cannot be placed on the base of a structure of interest.

First, a haversine pulse signal with a pulse width of 1e-3 seconds was applied to the conmass of the BARC assembly in the X direction (the direction along the long side of the BA base, shown in Figure 1) and the response of the structure was recorded. The excitation pulse was applied in just one direction to simplify the analysis and to represent single-axis shocks that are common in testing. Next, the simulated accelerations at the four chosen locations were recorded and the X-direction accelerations were converted to the equivalent force to be applied to the BARC conmass. Y and Z accelerations were not included to replicate the case where the direction of excitation is known. The moments were not included, because moments are generally not measured during tests. The acceleration response was predicted using a modal transient simulation with 500 modes of the BARC assembly capturing responses up to 74 kHz, which fully captures the response of the structure in the 2 kHz frequency range of interest. The computed forces from the acceleration measurements at the four chosen locations were then independently applied to the assembly conmass, and the responses of the BARC assembly were recorded. Finally, the maximum percent error of the response at Nodeset 13 was computed.

Figures 2 and 3 show the time and frequency comparisons, respectively, of the acceleration at the conmass boundary condition. Nodesets 1020, 1024, and 1027 on the base of the BA closely replicated the true input pulse, although with some additional inputs that are observed as small perturbations about zero after the initial pulse. Nodeset 1029 on the side of the BA underpredicted the initial pulse acceleration but continued to significantly excite the boundary condition after the true pulse event, which can be seen as peaks in the frequency plot below 2 kHz. The RMS error between the input derived from Nodeset 1029 and the true input was about 30%.

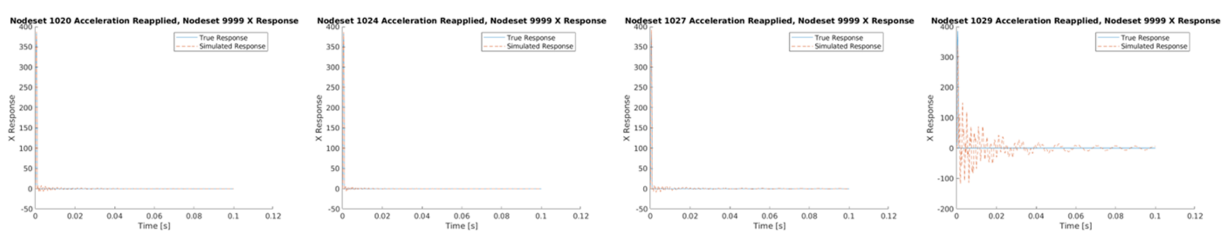

Figure 2. Acceleration response at forcing location

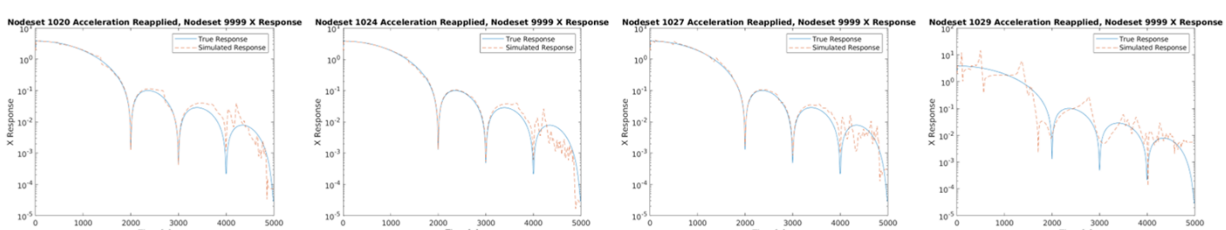

Figure 3. Acceleration frequency response at forcing location

Figures 4 and 5 illustrate the time and frequency responses, respectively, at Nodeset 13 on the top corner of the RA. Due to the similarities between the true pulse and the applied pulse, responses from inputs derived from nodesets 1020, 1024, and 1027 were very similar to the true responses with rms errors below 5%. The input derived from Nodeset 1029 on the side of the BA, however, produced a response with rms error of 164% in the X direction, 244% in the Y direction, and 23% in the Z direction. The predicted response errors were significantly higher than the input error of 30%. The frequency domain plot in the X direction shows that even though the Nodeset 1029 input excitation under-excites at some frequencies, peaks in the input frequency domain translate to peaks in the structural response that overall produce a response that is much higher than the true structural response. In practice, the use of an excitation location like Nodeset 1029 that does not correctly capture the input forces may result in severe overtesting.

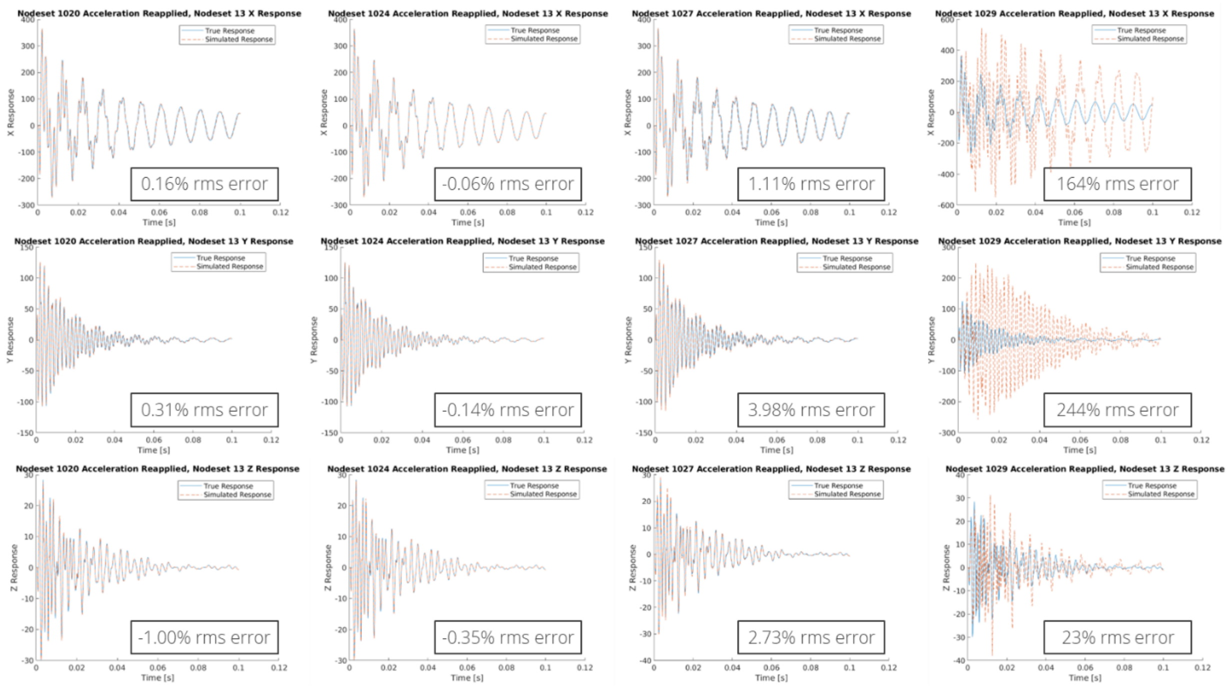

Figure 4. Reapplied acceleration response comparison at top corner of the RC with rms error noted

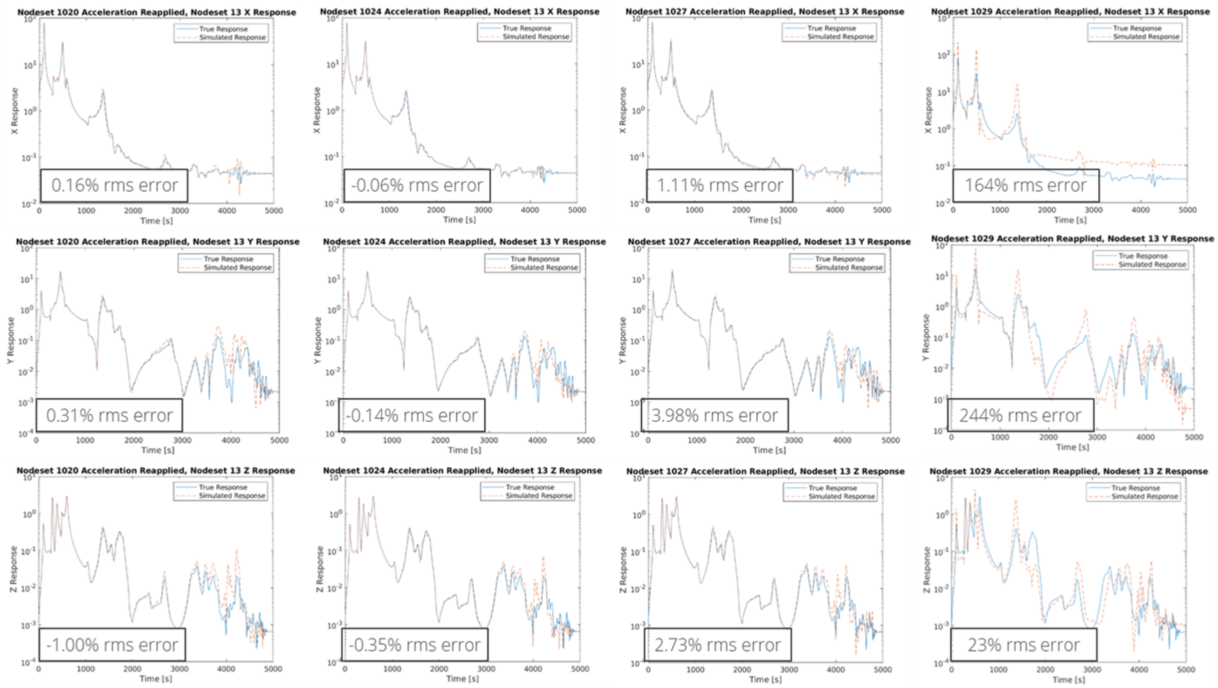

Figure 5. Reapplied acceleration response frequency comparison at top corner of the RC

This simple exercise demonstrates that errors in inputs can dramatically change the response of a structure, and that the error in input does not predict the error in the response. In this example, three of the chosen input locations were similar enough to the true input to reasonably predict the BARC's response; those inputs were derived from locations that were essentially rigidly connected to the true excitation location. The nodeset that did not correctly capture the true input excitation was dynamically active, and therefore added additional excitation resulting in an overtest of the structure. The nodeset 1029 location used to derive the input excitation was more responsive at structural resonances, shown as peaks in the input spectra in Figure 3, and so the derived excitation also had peaks at those frequencies. Because those peak frequencies align with the resonances of the structure, the derived excitation will strongly excite those modes. Amplification of the structural resonances that were not strongly excited by the true input excitation amplifies the error in the simulated response, which is why the input error is not predictive of the response error.

The chosen location was reasonably close to the true excitation location, and hypothetically would be used to derive inputs to the system if the base measurements were unobtainable. The BARC structure is fairly flexible and the magnitude of the error is magnified by that flexibility. However, in practice, input measurements are often not rigidly connected to the true location of excitation and input error magnification likely occurs.

Results: Excitation Force Reapplied

The previous analysis showed that errors in inputs propagate to predicted responses, and that predicted responses can magnify those errors. However, the previous analysis assumes that the true boundary conditions of the system are known. In practice, true boundary conditions are rarely known. A second academic study was performed to demonstrate how the same forces applied to a component in different boundary conditions will produce significantly different responses.

The BARC model was again used, but now with a focus on only the RC component response. The same pulse input was applied to the conmass of the full BARC model and the connection forces between the RC legs and the BA top was computed for the connection location at each leg of the RC. Because there are no other forces applied to the BARC system besides the impulse at the conmass, the connection forces perfectly describe all forces acting on the RC. A hypothetical perfect force reconstruction technique performed on the RC would produce the calculated forces shown in Figure 6. However, reapplying those forces to the RC component alone does not produce the same response at Nodeset 13, as shown in Figure 7. The RC response to the same forces applied at the same locations is different because the boundary conditions have changed; the stiffness and mass at the applied force locations has changed.

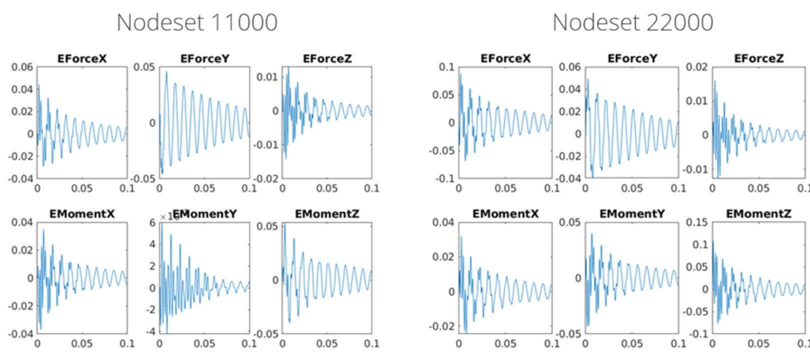

Figure 6. Applied force computed at the RC leg connections

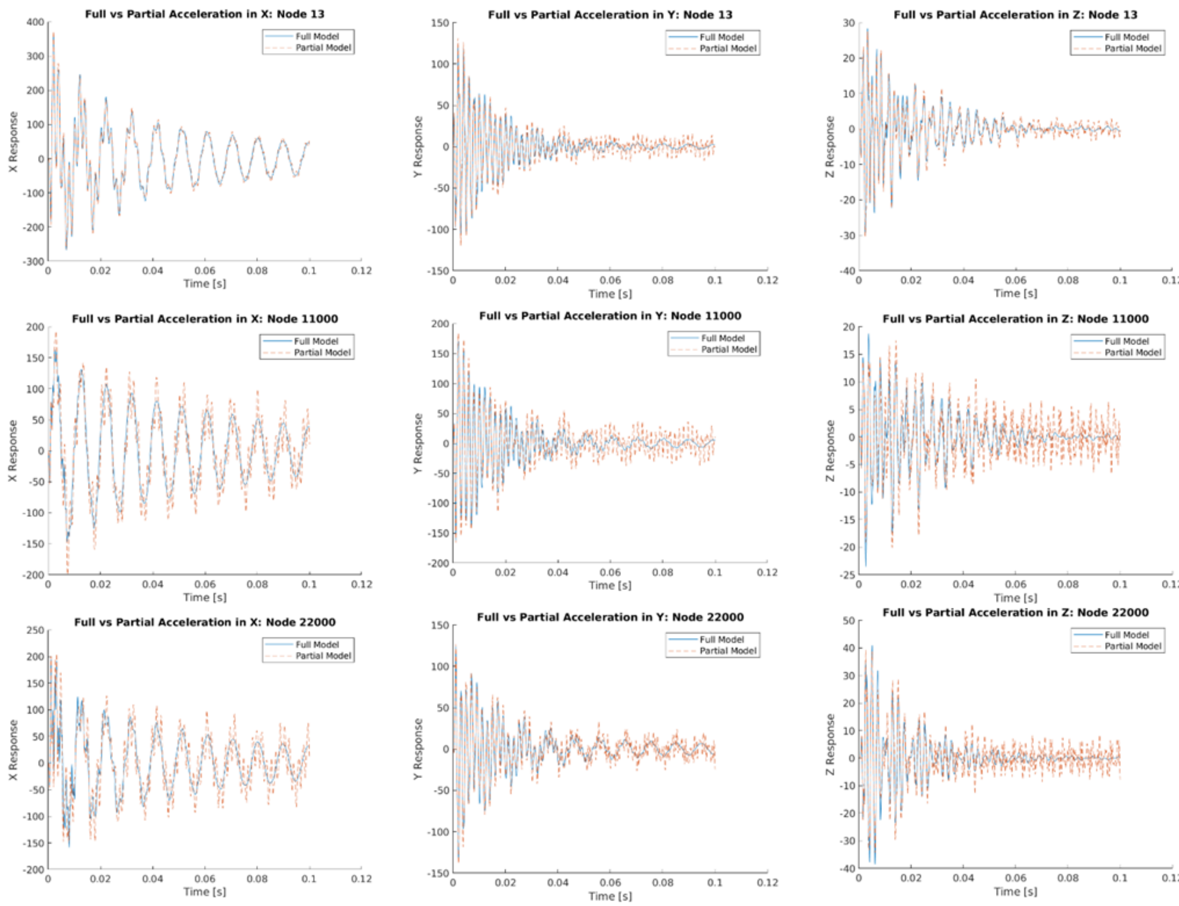

Figure 7. Reapplied force response comparison at top corner of the RC

The fact that the same forces applied to a system with different boundary conditions produces different responses is known. However, this example illustrates that force reconstruction techniques are limited when the boundary conditions of a component is unknown, which is often the case in practice. For example, the response of a specific component in a flight vehicle might be desired to qualify the component. However, force reconstruction will not help predict the response of that component if the dynamics of the connection to the flight vehicle is not also quantified. Error in the defined boundary conditions of a component will also propagate to the component's response.

Conclusions

This work investigated how errors in applied loads to FEA models propagates to the predicted responses. First, the BARC model was used to quantify how errors in applied loads propagate to the predicted response using a common force estimation technique. The exercise showed that the error in response can be significantly larger than the error in the input, and that even reasonable estimates of input force can produce huge response errors. Next, the same BARC model was used to illustrate how uncertainties in the boundary conditions of a component of interest will also propagate to errors in the predicted response, even if the force reconstruction is perfect. Future work should focus on developing techniques and promoting best practices for analysts to characterize errors in both applied forces and boundary conditions.

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