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Full-field Flight Environments via a Hybrid Experimental-Analytical Method

Brian C. Owens, Brandon Zwink, Moheimin Khan,
D. Gregory Tipton, and Randall Mayes
Sandia National Laboratories[1]
P.O. Box 5800 – MS0346
Albuquerque, NM, 87185

ABSTRACT

Flight testing provides an opportunity to characterize a system under realistic, combined environments. Unfortunately, the prospect of obtaining flight environments is often accompanied by restrictive instrumentation budgets, thereby limiting the information collected during flight testing. Instrumentation selection is often a result of bargaining to characterize environments at key locations/sub-systems but may be inadequate to characterize the overall environments or performance of a system. This work seeks to provide an improved method for flight environment characterization through a hybrid experimental-analytical method, modal extraction, and model expansion.

This work will discuss the design of a flight experiment including hardware design, instrumentation, and data acquisition. The role of ground testing for model validation will be discussed as well as ground trials of the hybrid method. Finally, the results of fielding the experiment on a flight test will be presented. The work demonstrates a significant leap in our understanding of flight environments. Specifically, the ability to obtain full-field flight response predictions from limited measurements including non-measured quantities such as stress and strain.

INTRODUCTION

Flight testing of aerospace systems allows for qualification under the most realistic flight environments, including combined flight environments. While this is a great opportunity, characterization of environments and responses during these tests is prone to severe limitations on instrumentation. A system is often instrumented at a few locations of interest, without enough fidelity to characterize the response of the system in detail. As will be discussed, hybrid experimental-analytical methods using informed instrumentation sets and credible models allow flight data to be significantly augmented for a greater understanding of flight environments and system performance.

This paper discusses the design of a flight experiment to predict responses at unmeasured locations from limited measurements. The experiment also demonstrates the ability to obtain full-field responses from fight measurements for additional insight into flight environments and system performance. First, the theory behind the expansion process is presented. Next, the overall process of the flight experiment design is outlined along with the flight hardware design

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and associated structural dynamics model. The use of analysis for instrumentation design is discussed, and the expansion process is demonstrated for actual flight environments.

THEORY

The theoretical basis for the modal extraction and model expansion employed in this work is known as the System Equivalent Reduction and Expansion Process (SEREP) and has been thoroughly documented in Reference 1. Herein, the theory is summarized and begins with modal superposition theory shown in Eq. (1).

$$\vec{x}(t) = [\Phi]\vec{q}(t) \qquad (1)$$

Here, *x(t)* is represents physical degrees of freedom (DOFs) and *q(t)* represents modal degrees of freedom (DOFs). These two are related through the structural dynamic mode shape matrix (Φ). Each column of Φ is a unique mode shape of the system. The rows of Φ represent the discretization of the mode shapes at specific physical DOFs. The mode shape can be obtained via analytical methods (i.e. finite element modeling) or via experimental testing. In this work, modes are obtained through eigen solution analysis using a structural dynamics finite element model.

For the hybrid method described in this work, experimental measurements at discrete locations (e.g. accelerometer response measurements) will be paired with the modes of the finite element model to extract modal acceleration responses. Consider re-writing Equation 1 for acceleration response at measurement DOF set called set "M" as shown in Equation (2).

$$\ddot{\vec{x}}_M(t) = [\Phi]_M\ddot{\vec{q}}(t) \qquad (2)$$

The modal acceleration DOFs can be extracted as shown in Equation (3). Where $[\Phi]^g$ is the generalized inverse since Φ will not necessarily be square.

$$\ddot{\vec{q}}(t) = [\Phi]_M^g\ddot{\vec{x}}_M(t) \qquad (3)$$

It is very important to note that use of Equation 3 requires selection of DOFs that uniquely identify the modes of interest. Furthermore, $[\Phi]_M^g$ should be well-conditioned to ensure numerical accuracy when employing the generalized inverse operation. To clarify, $[\Phi]_M$ is obtained from a finite element solution, but could also be obtained from laboratory testing. The mode shapes should be reasonably accurate to extract meaningful modal DOFs, although previous work has shown the method is tolerant of errors in the mode shapes [2]. $\ddot{\vec{x}}_M(t)$ are physical accelerations of an operational environment (e.g. a flight environment) obtained via accelerometer measurements. These measurements should be of sufficient quality to ensure meaningful environments are being employed in the method.

Finally, with the modes extracted, Equation 1 can be re-used with mode shapes at an alternative DOF set "A" for expansion to un-instrumented locations as shown in Equation 4. These mode shapes are most readily obtained from a finite element model, and could include discrete locations of interest within a system or even at all DOFs in the finite element model for visualization of full-field responses. Although the theory shown here has been developed for expansion of accelerometer responses, the model can also be used for expansion from displacement, velocity, stress, or strain responses.

$$\ddot{\vec{x}}_A(t) = [\Phi]_A\ddot{\vec{q}}(t) \qquad (4)$$

PROCESS

The underlying theory of the modal extraction and expansion process was described in the previous section. This section discusses the practical aspects of implementing the theory on a flight experiment to supplement the amount of data obtained through flight testing. A flow chart of the process is shown in Figure 1.

The process begins with identifying a system on which to employ the hybrid method and the development of a structural dynamics model for obtaining structural dynamic mode shapes. Although optional, it is desirable to perform some experimental modal testing of the system to characterize the structural modal frequencies and shapes of the system for model correlation and updating. This provides greater confidence in the structural dynamics model which is relied upon heavily in the hybrid method. The system under consideration and the associated finite element model will be discussed in a subsequent section.

Next, the instrumentation set (i.e. Set M) can be designed using the finite element model. Numerical studies can be performed considering various candidate locations for instrumentation, the mode shapes to be resolved with the instrumentation set, and the instrumentation budget allotted to the test. This step will also be discussed in a subsequent section.

With the instrumentation set designed, the hardware can be instrumented with accelerometers. It is advisable to validate the method and specific configuration on the ground before a flight test opportunity. This can be done through ground vibration testing with additional accelerometers installed for "truth" responses. The truth response DOF set are not be included in the modal extraction process and can serve as a verification of the expanded "un-instrumented" DOFs.

Finally, the instrumented hardware is fielded in a flight experiment, flight response data is collected and processed, and the hybrid method is employed. If additional "truth" accelerometers are fielded on the flight experiment there is an opportunity for validation of the expanded responses.

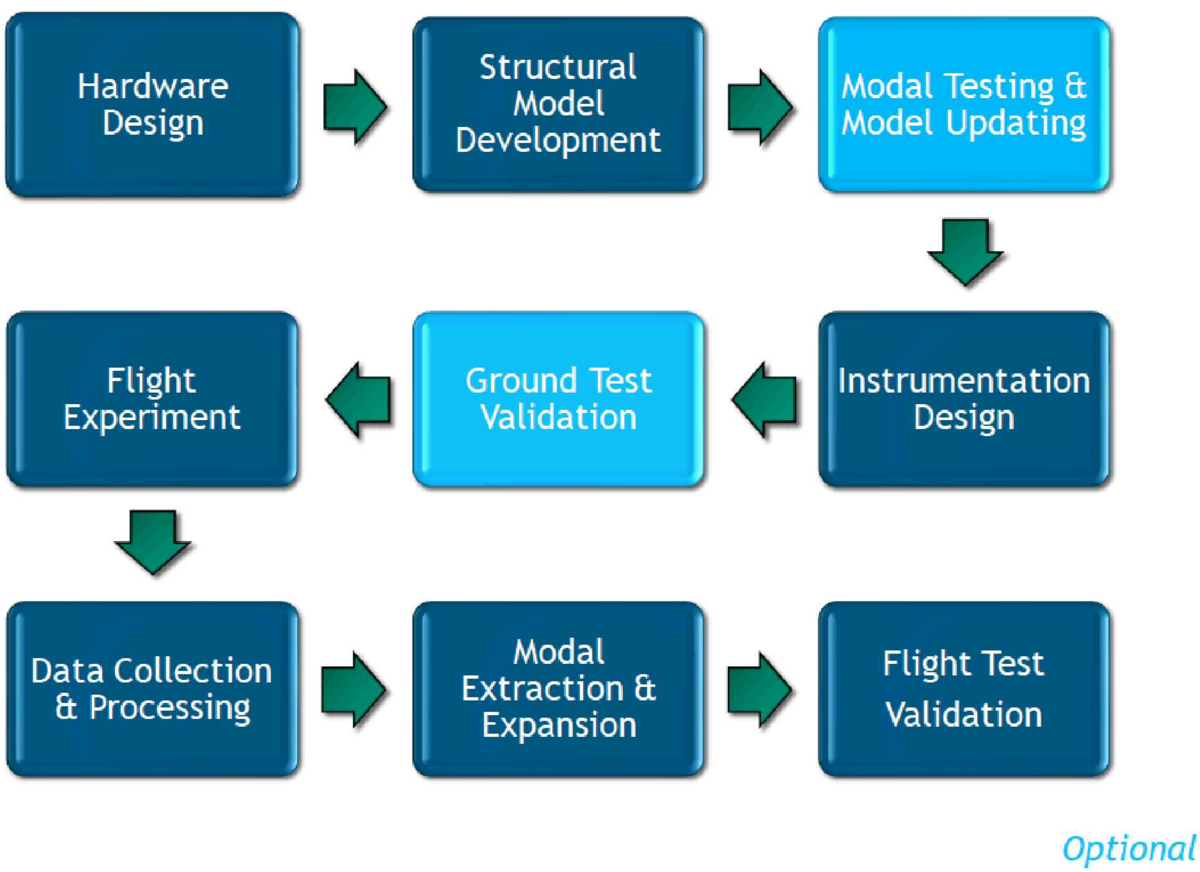


Figure 1. Flow chart of the process for employing the hybrid expansion process on a flight experiment

HARDWARE DESIGN AND STRUCTURAL DYNAMICS MODEL

The flight experiment hardware/system of interest is a sounding rocket payload section shown in Figure 2. The payload section is modular to support various flight experiments and has an exposed design for accessibility during instrumentation and cable routing. The design features two topology optimized, additively manufactured spars and two conventionally machined spars. The payload section is a good demonstration candidate for the hybrid expansion method. It is of moderate complexity, but relatively simple to model. The payload section has modes that are typical of aerospace structures (i.e. bending, torsion, and axial modes) and has about 30 structural modes below 1 kHz in frequency.

The structural dynamics model of the payload section was developed using Sandia's Sierra/SD finite element software [5, 6] and is shown in Figure 3. The model is linear elastic with nominal joint stiffness properties. Experiment payloads were modeled as concentrated masses to allow for modularity and flexibility in assessments for different payload configurations. Complex topology optimized geometry was modeled using advanced meshing algorithms in Sandia's CUBIT [6,7] meshing software. The mesh of the topology optimized geometry is also shown in Figure 3. In this work, the primary use of this structural dynamics model is for instrumentation design, and to supply the mode shapes for the expansion process. However, the model was also extensively used for technical basis in design assessments of structural integrity at ground qualification and flight shock & vibration environments. The first few elastic mode shapes of the payload section are shown in Figure 4. Modal testing of the payload section was performed, and the analytical mode shapes were in good agreement with the experimentally observed mode shapes. For brevity, model correlation to modal test data will not be presented in this paper.

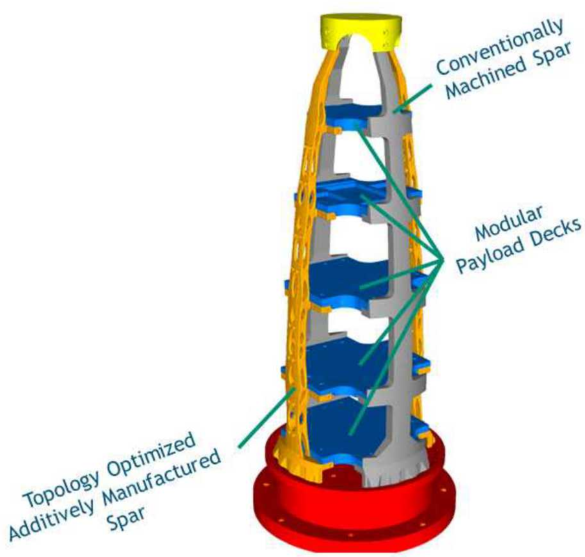


Figure 2 – Sounding rocket payload section design

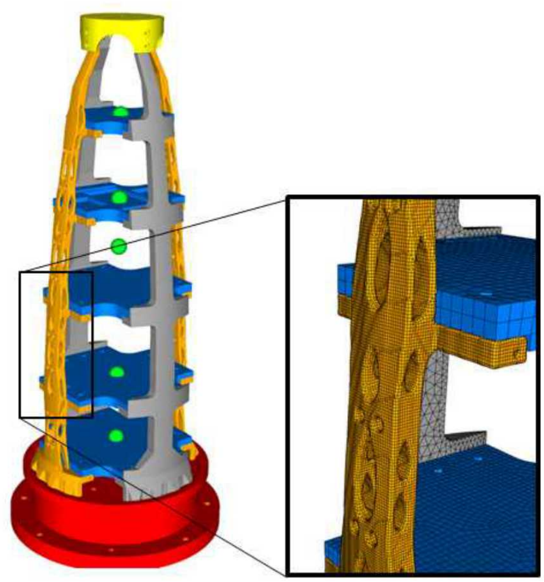


Figure 3 – Sounding rocket payload section structural dynamics model and mesh

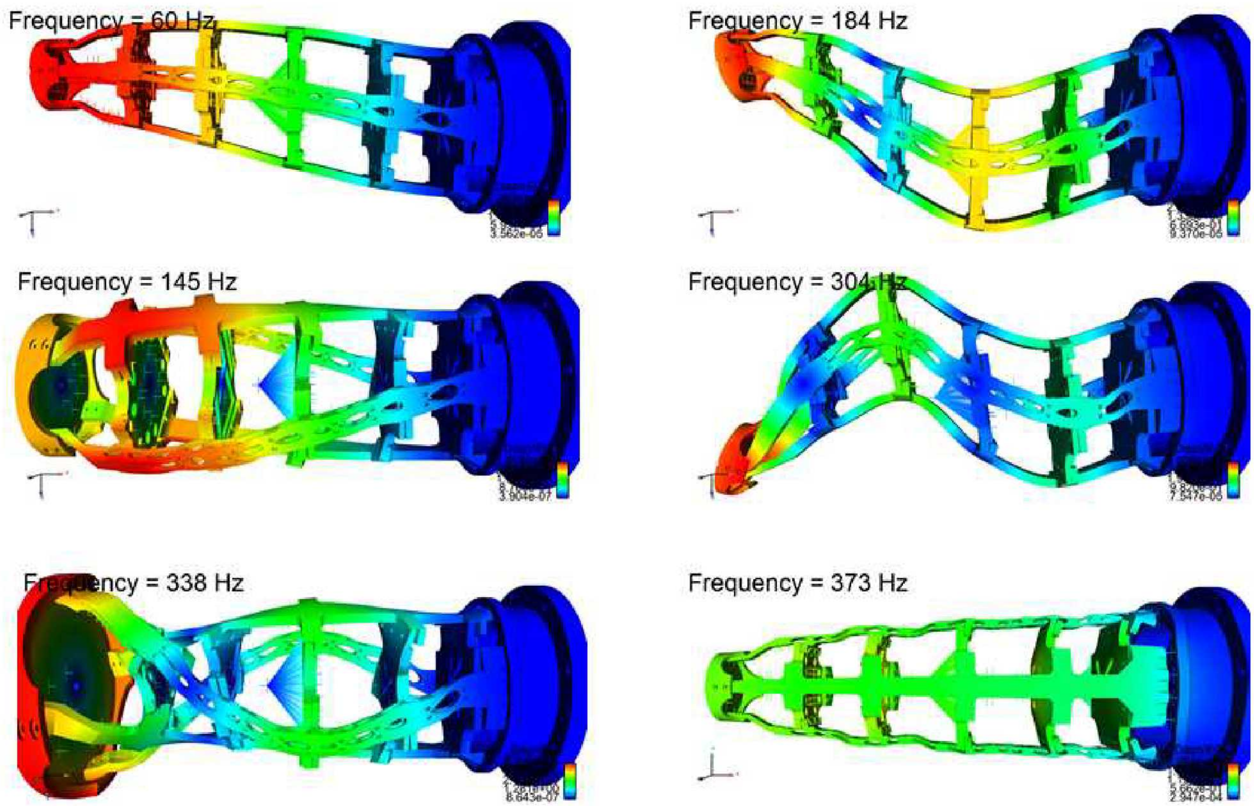


Figure 4 – Lower elastic modes of the payload section

INSTRUMENTATION DESIGN

Accelerometer instrumentation for this flight experiment was designed considering the structural dynamic properties of the system predicted via the finite element model. Specifically, instrumentation design sought to adequately characterize mode shapes of interest using a discrete set of accelerometer measurements/degrees of freedom within some instrumentation budget. In this work, 30 modes (up to 1 kHz) were to be characterized by an instrumentation budget of 32 channels. Therefore, 32 accelerometer degrees of freedom were down-selected from a candidate set shown in Figure 5. The candidate locations were carefully chosen to not interfere with payload section hardware and assembly procedures. Overall, 150 candidate locations were considered with 3 translational degrees of freedom per location for a total of 450 candidate degrees of freedom. For simplicity, local accelerometer axes were aligned with the model cartesian coordinate system. The instrumentation set is down-selected using the effective independence method documented in Reference 7. After an initial down-select, the instrumentation set was augmented with four additional gages to add redundancy and robustness to gage loss. A total of 36 accelerometer degrees of freedom were used in the final instrumentation set. This process is illustrated in Figure 6.

Three additional gages were added as validation gages. These gages would provide flight data to compare the expansion method to but would not be used in the expansion process. The down-selected instrumentation set and validation gages are shown in Figure 7.

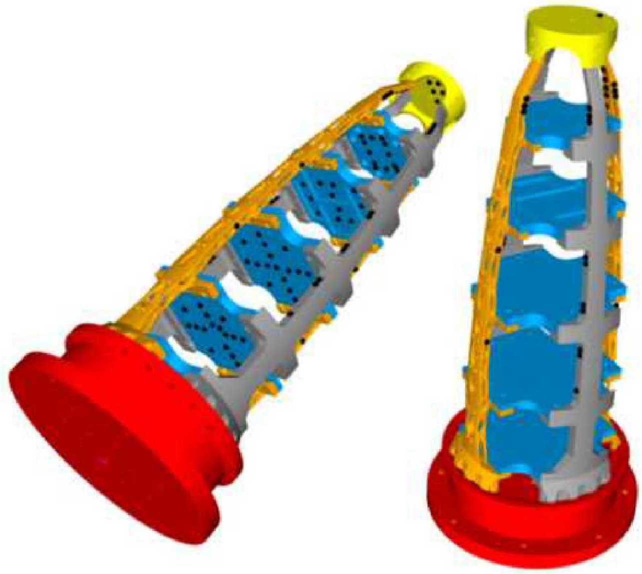


Figure 5 – Candidate accelerometer locations

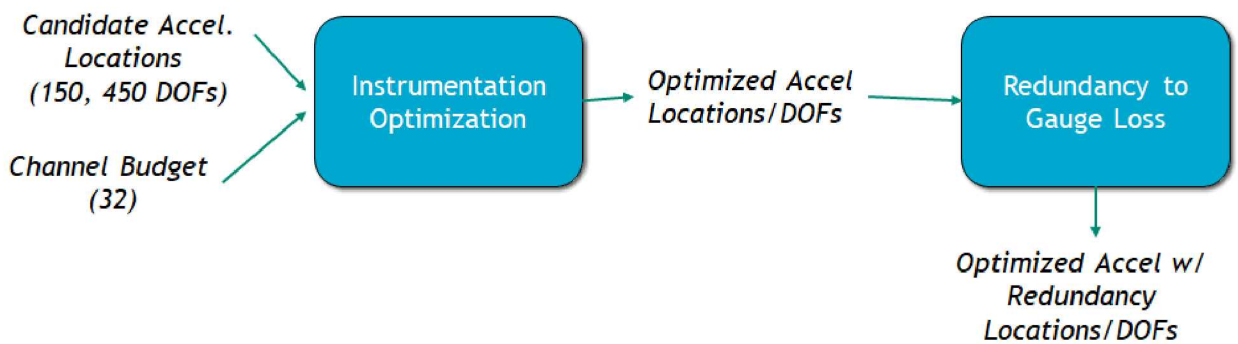


Figure 6 – Flow chart for instrumentation design process

FLIGHT EXPERIMENT AND RESULTS

After instrumentation design, some ground validation of the expansion process was performed using multi-shaker/Impedance Matched Multi-Axis Testing (IMMAT) [8]. This validation exercised excited the structure with vibration loads characteristic of the expected flight environment and allowed the expansion process to be tested on the ground. This will not be discussed in detail for brevity, but ground validation exercises were encouraging, and the experiment was deemed ready for flight testing.

Figure 8 shows the launch of the sounding rocket flight experiment with a depiction of the payload section within the launch vehicle. The flight was successfully completed, and accelerometer data was collected. Signal processing of the data was performed to ensure consistency and quality of the data to be used in the expansion process.

Figure 9 shows the accelerometer data collected at a validation "truth" gage and expanded flight data at this location. Overall, very good agreement is observed across the various flight events such as launch, stage separation, stage ignition, and aerodynamic loading. Figures 9 and 10 also show "zoomed-in" predictions for early and middle flight segments respectively. Remarkable agreement is observed during these flight segments, throughout other flight segments, and other validation gage locations. Although slight differences are observed, such a prediction would be extremely valuable in developing environmental specifications at un-instrumented locations.

Finally, the expansion process can be extended beyond specific discrete points at which environments are desired. The process can be applied to every DOF in the finite element model to visualize detailed displacement, velocity, and acceleration contours. Furthermore, strain and stress mode-shapes can be employed in the method to predict full-field stress and strain from limited flight measurements. An example of the expansion process applied to full-field strain contours is shown in Figure 11.

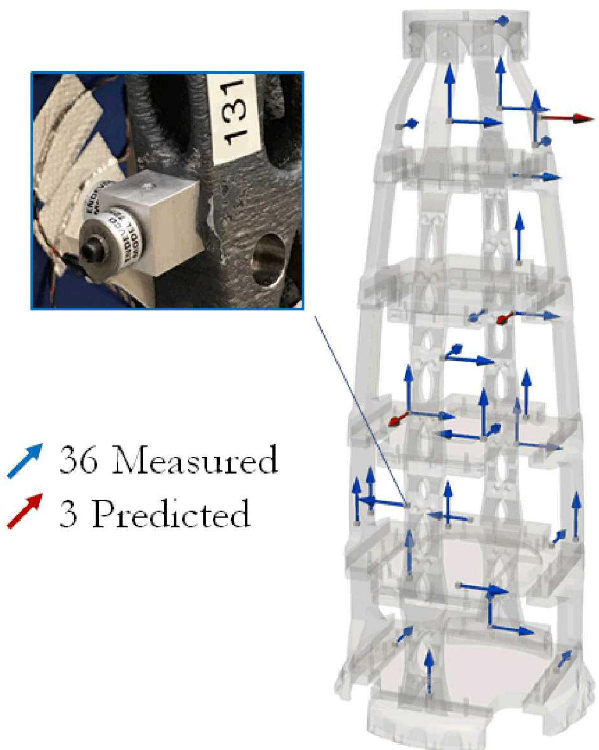


Figure 7 – Down-selected accelerometer degrees of freedom and validation(predicted) degrees of freedom

Figure 8 – Sounding rocket launch with depiction of payload section

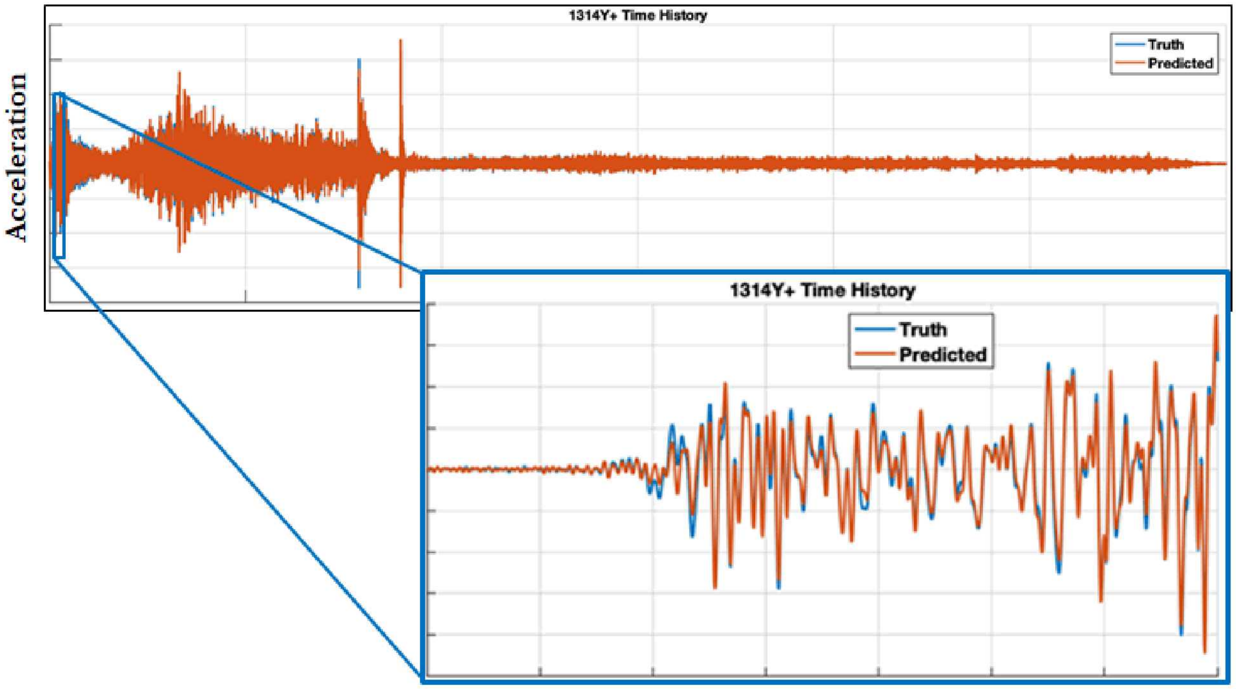


Figure 9 – Acceleration trace of predicted and “truth” data for a validation gage for early flight segment

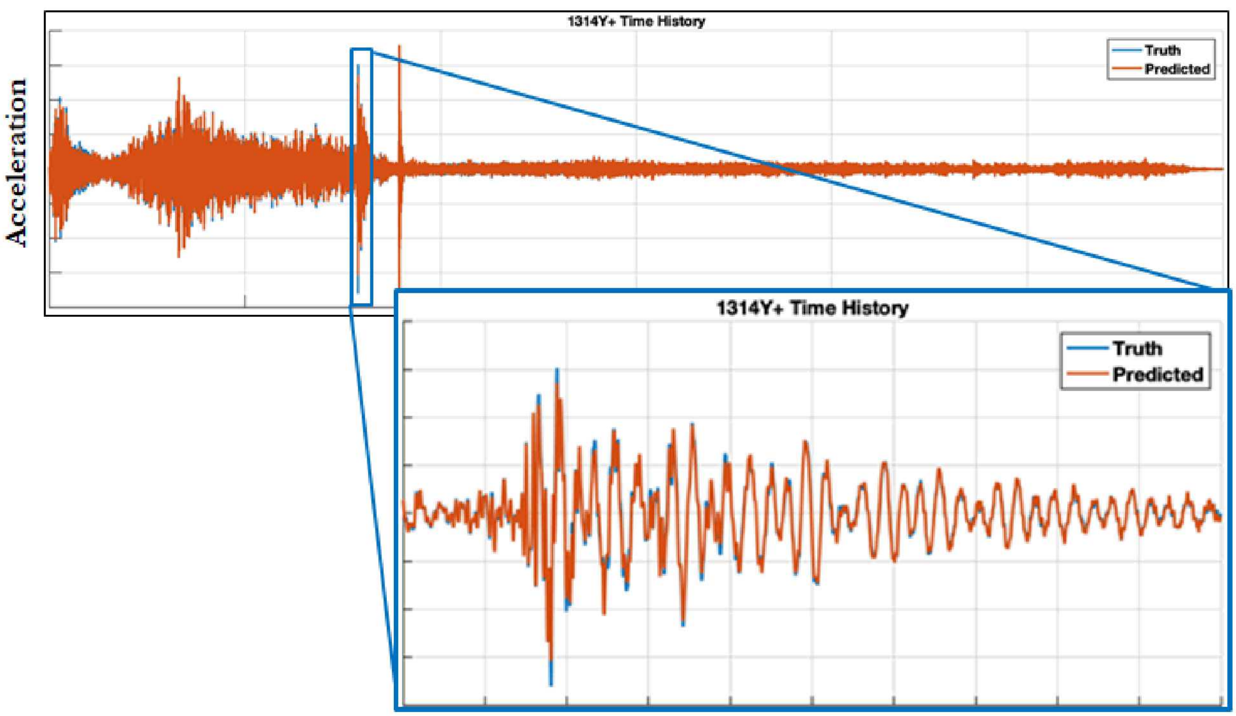
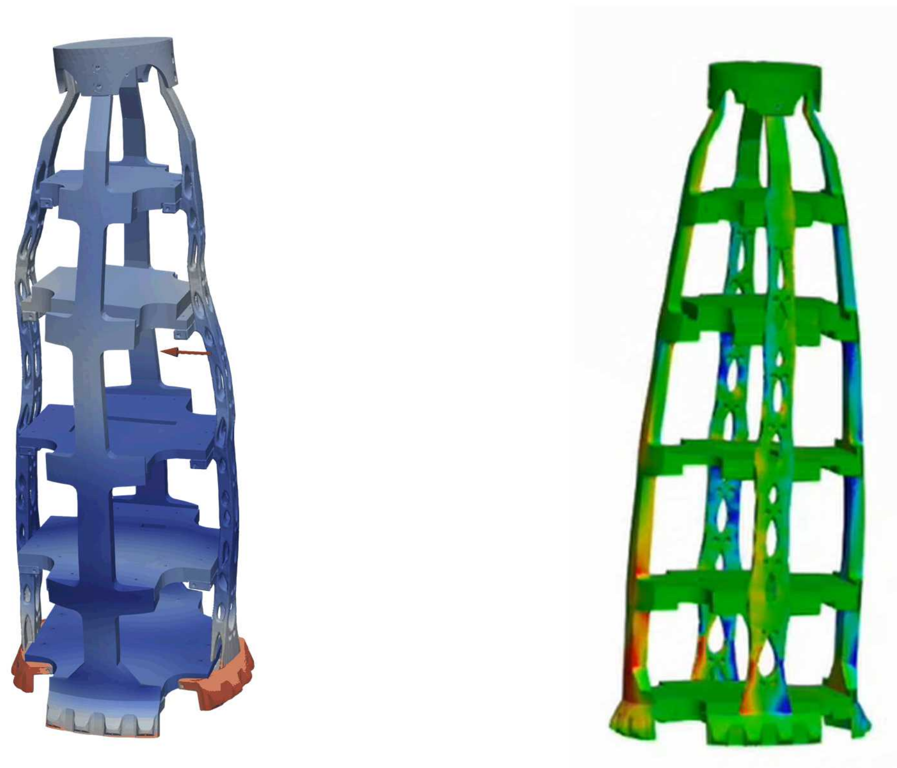


Figure 10 – Acceleration trace of predicted and “truth” data for a validation gage for middle flight segment



a) Expanded displacement contours b) Expanded strain contours

Figure 11 – Expansion of flight environments to predict full-field displacement and strain contours

CONCLUSIONS

This work has demonstrated a hybrid experimental-analytical modal extraction and expansion method to supplement flight test data. The expansion process relies heavily on structural dynamic mode shapes at discrete locations, requiring a high-quality instrumentation set to characterize modal response of a system under arbitrary shock and vibration environments. This work described the use of a structural dynamics finite element model for test hardware design, instrumentation, and model expansion.

Validation against truth responses showed very good agreement when the expansion process is used to predict responses at un-instrumented locations. Furthermore, full-field expansion has the potential to provide valuable insight on system performance and greatly enhance our understanding of flight environments. Future work will consider tighter integration of uncertainty quantification in this process and consider approaches to reduce the required instrumentation for expansion methods.

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