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Quantifying the Effect of Component Inertial Properties on System Level Dynamics

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ABSTRACT

Structures are subject to many environments in the lifetime of an assembly, and mechanical environments such as vibration are particularly significant when considering structural integrity. In the early development cycle, mechanical environment test specifications are often derived from assemblies with simplified "mass mock" components. The assumptions for these simplified components generally mimic total mass and center of gravity, but do not always capture moments of inertia. Historically, environments for mass mock components are enveloped and used for future iterations of the true component's qualification. This work aims to understand and characterize differences in dynamic response due to changes in inertial properties of a component. The FEM of a test structure for this work includes a system level model with true components that will be compared to a FEM with mass mock components. Both versions of the structure will be evaluated based on dynamic response at the component and system levels. The validity and limitations of using mass mock components with approximate inertial properties for deriving environmental specifications will be explored.

Keywords: Inertia, mass mock, test specifications, boundary condition, component environments

INTRODUCTION

The purpose of this work strives to analytically observe key differences between the use of mass mock components and their true configuration. In this analytical study, mass mock components preserve both mass and center of gravity, while geometric features are simplified, affecting component volume and inertial properties. Center of gravity is maintained through strategic geometric simplification, while component mass is preserved through material density modification. Mass mocks are used to streamline preprocessing and computational time, but are also necessary in early phases of a design cycle, as they allow for flexibility in terms of future detail revisions. As a component develops over time, the primary features such as mass and center of gravity can be held constant while design iterations can improve a characteristic or functionality of a component. Generally, inertia in these mass mocks is not strictly scrutinized, thus understanding how this can impact structural properties and environmental specification development is a goal for this analysis. Modal data, environment responses and specifications derived for component level tests will be the primary sources of comparison. Component specifications are generally derived from field environment tests of a system level structure, where the full assembly can either include true or mock components for this test. Responses at components are then used to develop environmental specifications for the component. Although center of gravity and mass are maintained, inertial properties can affect these specifications.

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Understanding changes in inertial properties of isolated components is valuable, but this does not encompass the complexity of coupling dynamics within a system. To emulate a practical application, the moments of inertia of mass mock components will be studied as part of a larger assembly. Understanding this behavior is important because specifications for component level testing are derived from system level tests. Errors due to inaccurate mass mocks can propagate into component specification error. Because of this, the primary goal of this work is characterizing differences in dynamic response due to changes in inertial properties of components.

MODEL SETUP & DEVELOPMENT

A modular system model was created, allowing for ease of component interchanging, so various fidelities could be utilized. The assembly is a three-tiered plate structure with components attached to the second tier, allowing for non-trivial inputs and coupled dynamics. The full structure and components, modeled as aluminum, has seventeen flexible modes occurring between below 60 Hz. The base is used to excite the structure via a concentrated mass, connected rigidly to the bottom plate, as shown in Figure 1.

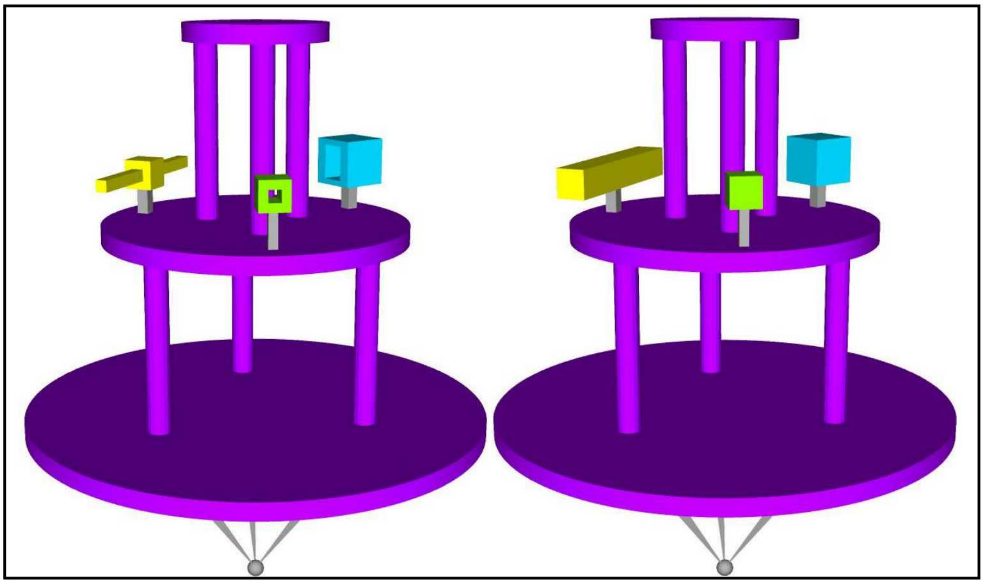

Figure 1: Assembly Level Configuration of Truth (left) and Mass Mock (right) Models

The columns that connect the circular plates are symmetric about the translational axes (X and Y) , as shown in Figure 2. Looking at the system from the axial axis, support columns and component connections are equally spaced.

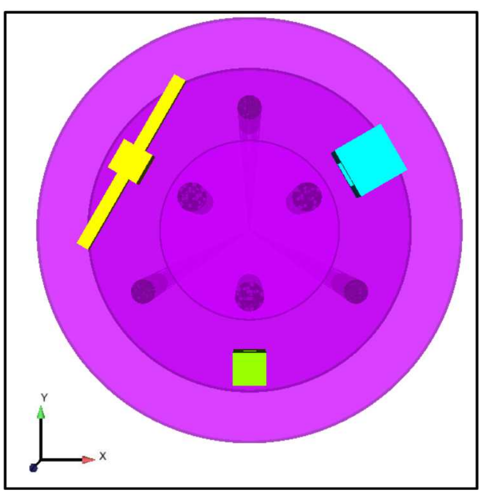

Figure 2: Assembly Top View

A variety of components were designed for being simplified on the system level structure. The mass mock components were designed to replace the truth components and match their center of gravity and mass. Three components were constructed, each with varying degrees of volume and inertia differences. The first two components, illustrated in Figures 3 and 4, are cube volumes with translational cuts of material removed from the 'truth' model and solid bodies for the mass mock. These components are identified as small and large box, respectively. Density values for mass mock components were adjusted, so the original mass was preserved.

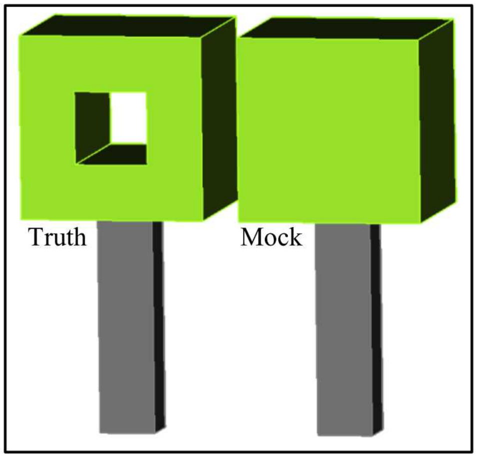

Figure 3: Small Box Component

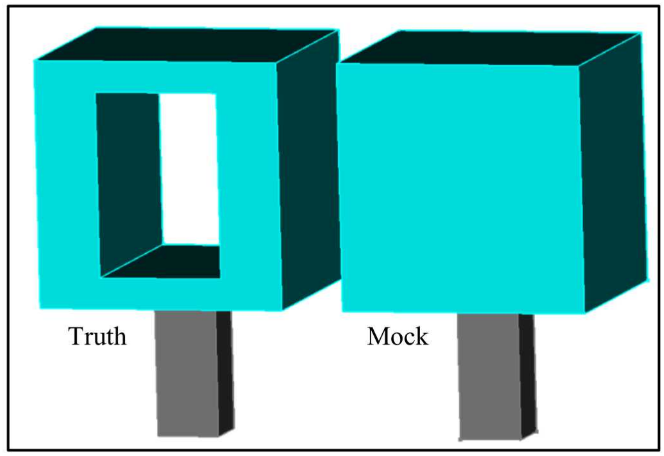

Figure 4: Large Box Component

The third 'beam' component, shown in Figure 5, features a small cube with symmetrical cantilevers suspended from each end. The mass mock block adds significantly more material than the first two components, but still maintains overall mass and center of gravity.

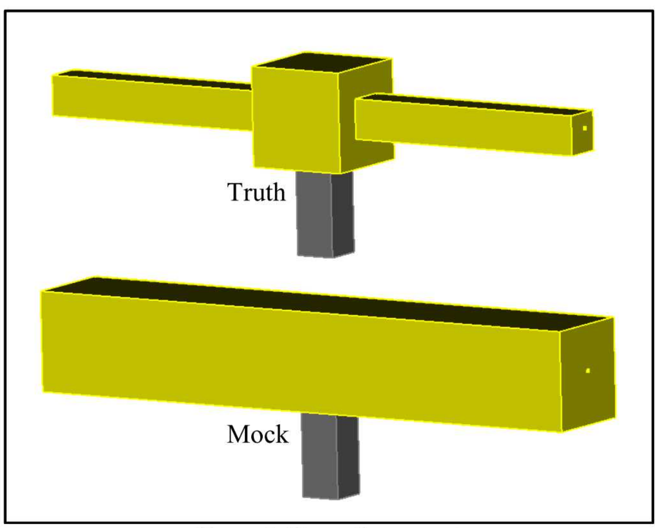

Figure 5: Beam Component

The mass, inertia and volume properties for each component are summarized in Table 1. It is evident that the small box has a slight shift in moment of inertia values, while the beam component changes drastically. Mass values are constant between the two iterations of the model and volume inherently changes when each of the components are updated. The table also gives a normalized difference between properties of the mock and truth components with percent difference values. The grey beams are used to connect components to the circular plate assembly, and are not included in Table 1's values, but are held constant between model iterations.

Table 1: Mass and Inertia Properties of the Truth and Mass Mock Components

Component	I_x $(kg * mm^2)$		I_y $(kg * mm^2)$		I_z $(kg * mm^2)$		Mass (g)		Volume (cm^3)	
	Truth	**Mock**	**Truth**	**Mock**	**Truth**	**Mock**	**Truth**	**Mock**	**Truth**	**Mock**
Small Box	**0.125**	**0.115**	**0.134**	**0.115**	**0.125**	**0.115**	*4.43*	*4.43*	1.64	1.95
(Percent Difference)	**-8.0%**		**-14.2%**		**-8.0%**		*0%*		18.9%	
Large Box	**1.17**	**0.9**	**1.07**	**0.9**	**1.1**	**0.9**	*13.5*	*13.5*	5.0	8.0
(Percent Difference)	**-23.1%**		**-15.9%**		**-18.2%**		*0%*		60.0%	
Beam	**1.92**	**3.49**	**0.74**	**1.33**	**2.51**	**4.57**	*9.49*	*9.49*	3.52	11.70
(Percent Difference)	**81.8%**		**79.7%**		**82.1%**		*0%*		232.4%	
Assembly	**4888**	**4889**	**4907**	**4907**	**4000**	**4002**	*1085*	*1085*	401.7	413.2
(Percent Difference)	**0.03%**		**0.01%**		**0.05%**		*0%*		2.86%	

MODAL RESULTS

Post processing of the eigen solutions of both the mass mock and truth assemblies were calculated. A Modal Assurance Criteria (MAC) comparison was performed between the two sets of mode shapes, which utilized a sampling of structure and component nodes with consistent locations between model iterations. The plot includes both the modal correlation by color, scaled with a minimum of 0.4 for clarity, as well as the percent difference in frequency of highly correlated modes. Additionally, modal frequencies for the respective system are found along the axes.

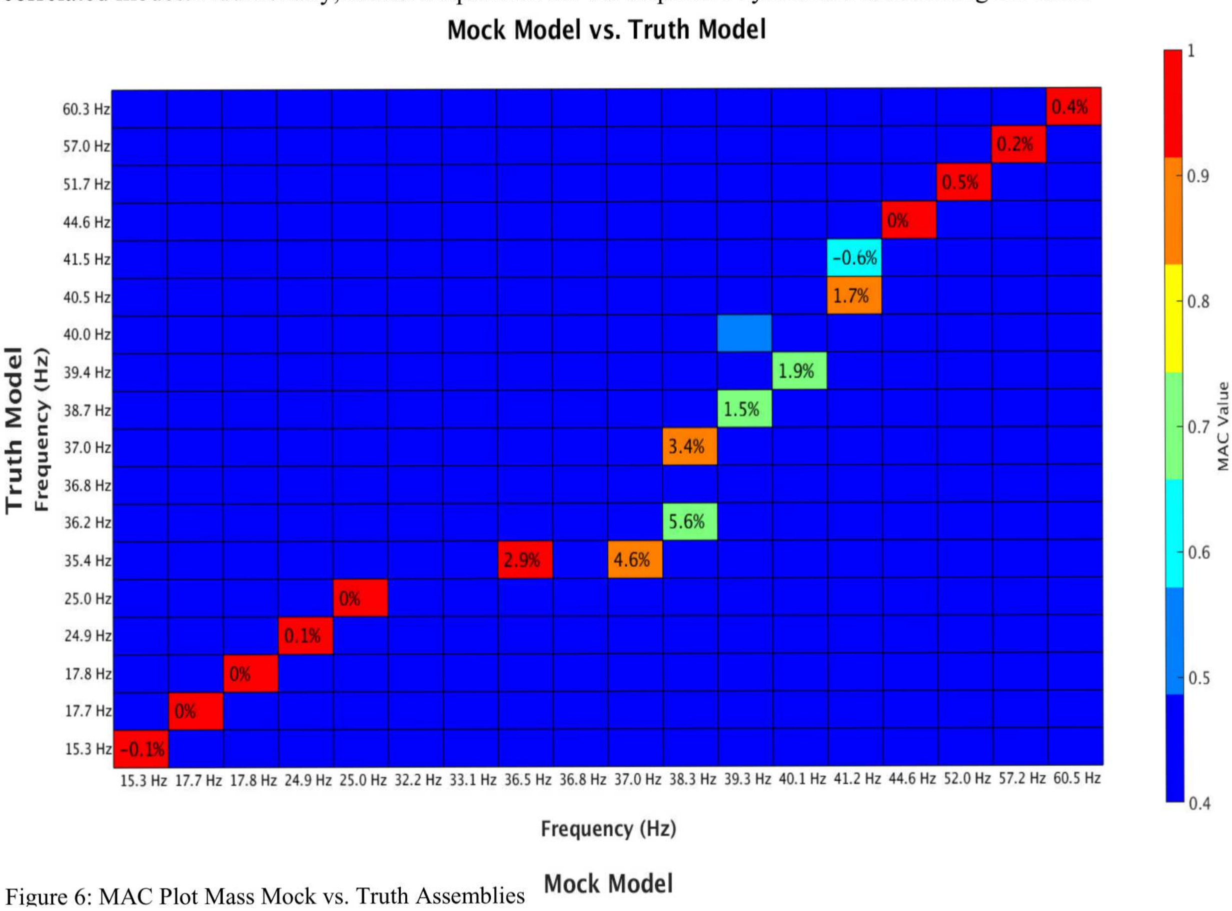

Figure 6: MAC Plot Mass Mock vs. Truth Assemblies

From Figure 6, modal correlation for the first five flexible modes, as well as the final four displayed in the MAC table, are predominantly dictated by system response and are not sensitive to component fidelity. The first two mock assembly modes that do not align well are primarily influenced by the motion of the beam component, illustrated in Figure 7.

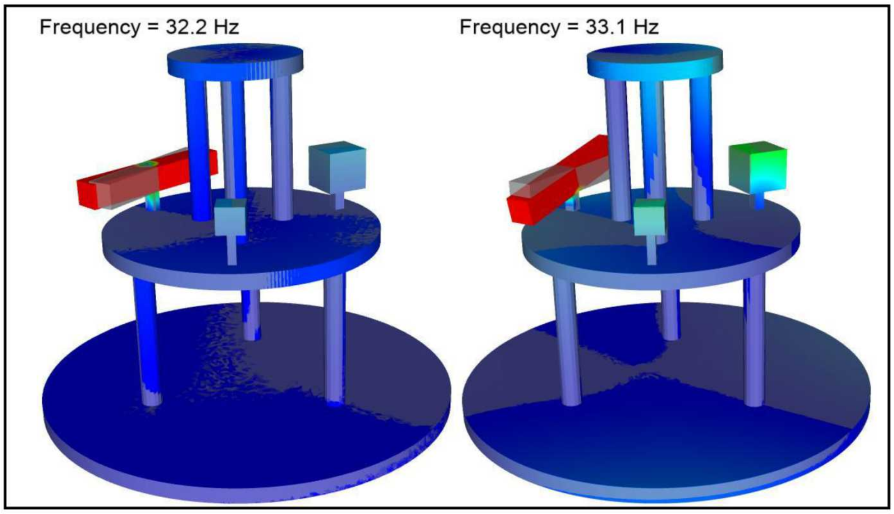

Figure 7: Mock Model Modes Without Correlation to Truth Model Modes

Differences start arising in modal comparison as dynamic coupling occurs in the structure and component behavior primarily drives mode shapes. Because the discrepancies in moments of inertia of the components and assembly, these differences emerge. Additionally, a large number of modes occur in a relatively small frequency range, such as the mode shapes in Figures 8 and 9, so linear combinations can account for other differences.

Figure 8: Assembly Flexible Modes – Truth

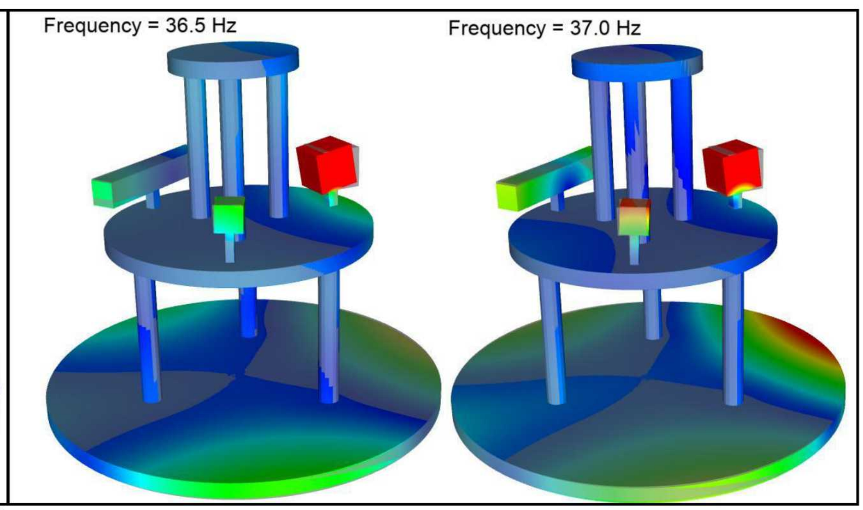

Figure 9: Assembly Flexible Modes – Mock

The modes in the central region of the MAC plot above are primarily driven by component behavior, and tend to be higher in frequency for the mock assembly. Taking a closer look at the mock mode occurring at 38.3 Hz and corresponding truth mode at 37.0 Hz, this can be rationalized with the equation 1, where ω is modal frequency, K is stiffness and m is mass. This behavior for this mode is driven by the small and large box components, whose moments of inertia are reduced in each direction for the mock model. Because inertia is a mass property and it is decreased, the resulting frequencies are expected to higher for the mock model.

$$\omega = \sqrt{\frac{K}{m}} \qquad (1)$$

Overall, modal correlation is strong in the low and high ends of the frequency range reported in Figure 6. These modes are primarily driven by the assembly's motion, which have little to no contribution from the components. Mid-ranged frequency modes are dictated by component behavior, thus the change in inertia between mock and truth models explains differences shown in Figure 6. These differences could be minimized by developing mass mocks that more accurately match the inertia properties of the truth components along with the mass and center of gravity properties.

FREQUENCY RESPONSE FUNCTION & COMPONENT TEST RESULTS

Using a modal based frequency response function (FRF) solution in Sierra Structural Dynamics (Sierra SD) [1], both the mass mock and true component systems were driven with a six degree of freedom base input, to derive the field environment for each of the components. This input force consisted of 10 N in each translational direction and 1 N-m for each rotational direction in the 1 to 60 Hz frequency regime. The scaling of these loads was chosen to achieve similar response magnitude in the assembly, when isolated. Responses from this excitation, found at the base of each mass mock component were then used as an input into a component-level test, which is shown in Figure 10. Both levels of component fidelity in the system level test were used to derive input specifications for component level tests on the true geometry.

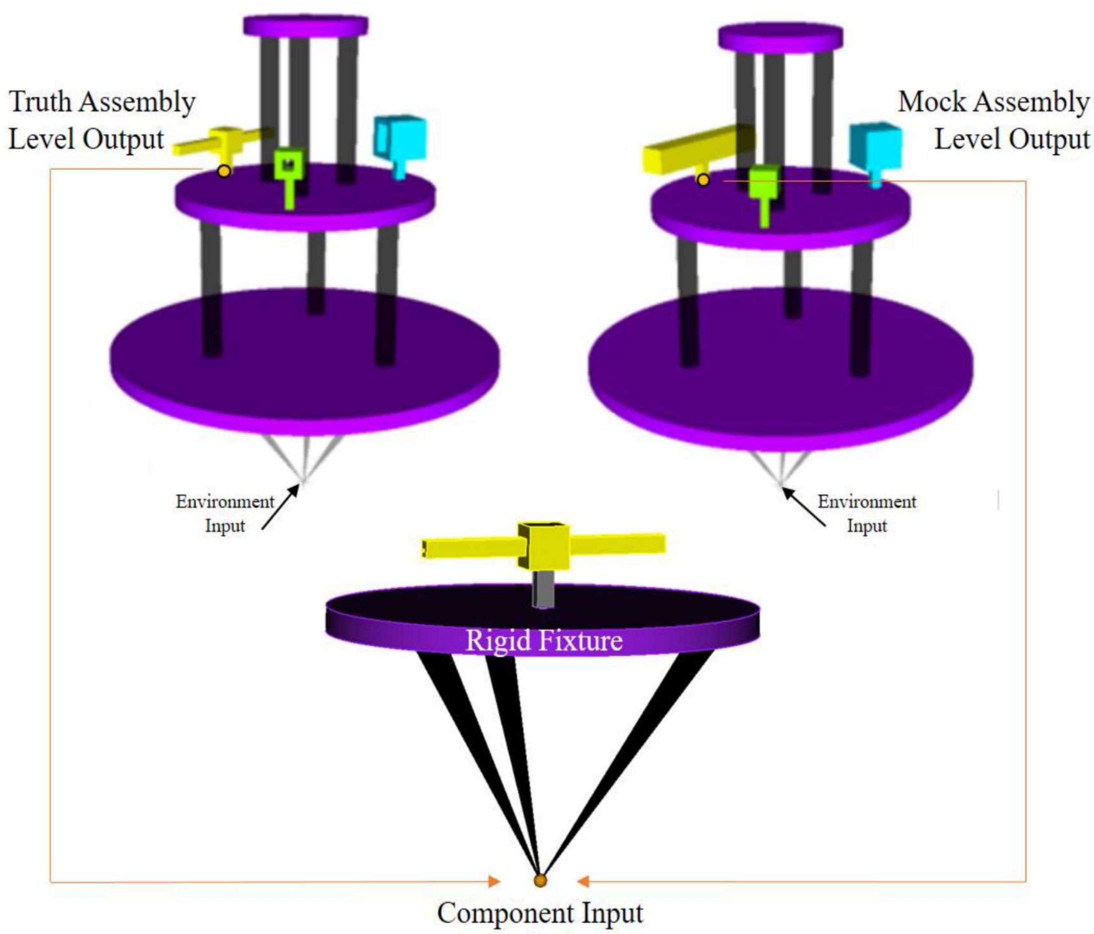

Figure 10: Component Level Test Inputs

A sample of data was taken from the system and component level tests, as shown in Figure 11 to evaluate differences in plate and component responses. These nodal locations were consistent between both the mock and truth models, even with the differences in component geometry. Variations in response caused by inertial differences are summarized below.

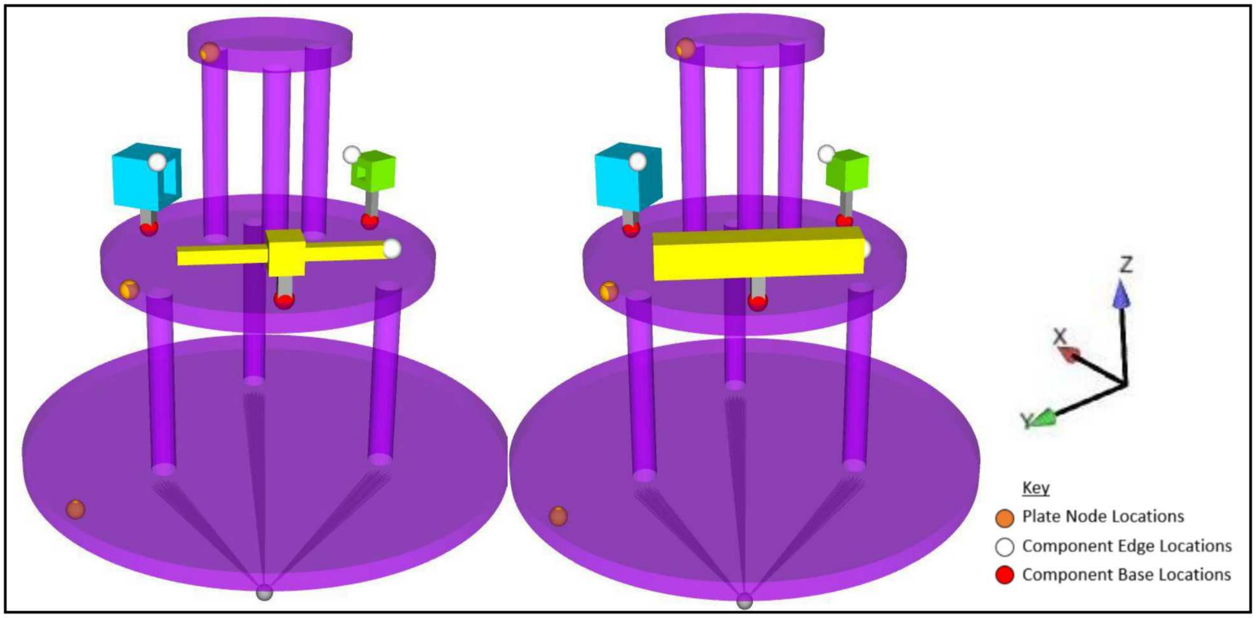

Figure 11: Response Node Locations

PLATES- Assembly Level Responses

With the multi-axis input applied to the concentrated masses of the truth and mock systems, plate responses in the axial direction experience a small propagation of error when comparing the responses of the same points on the truth and mock models. The bottom plate had little variation between the mass mock and truth models, because the components weren't affecting the modes in which this plate was participating. Figure 12 illustrates the similarity in translational response of the bottom plate, as they are nearly visually identical. The translational directions, X and Y, revealed fewer differences and were not reported for this reason.

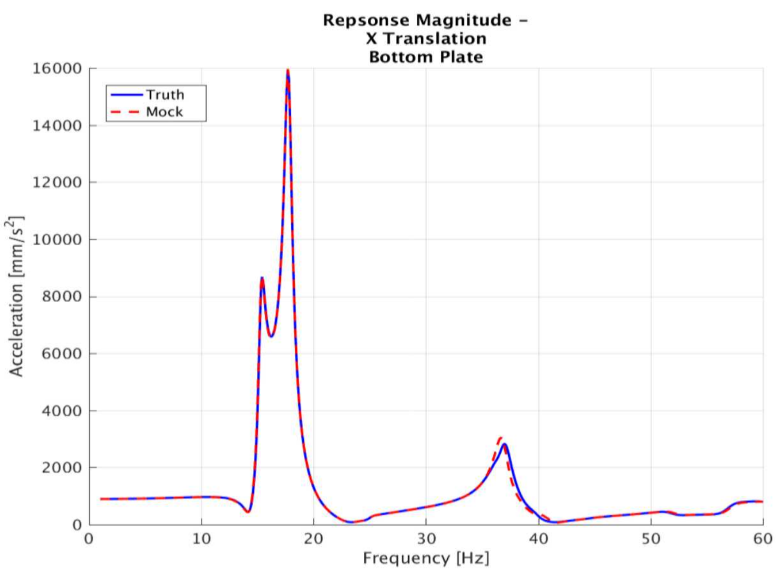

Figure 12: Bottom Plate X Translation Response

The middle and top plates revealed differences in translational response with the multi-axis input. Both plates follow a general response trend except around 40 Hz, where the driving modes of the system are largely influenced by component behavior. Figure 13 and 14 show the response FRF for both the middle and top plates, as well as the driving modes in the frequency range of discrepancy.

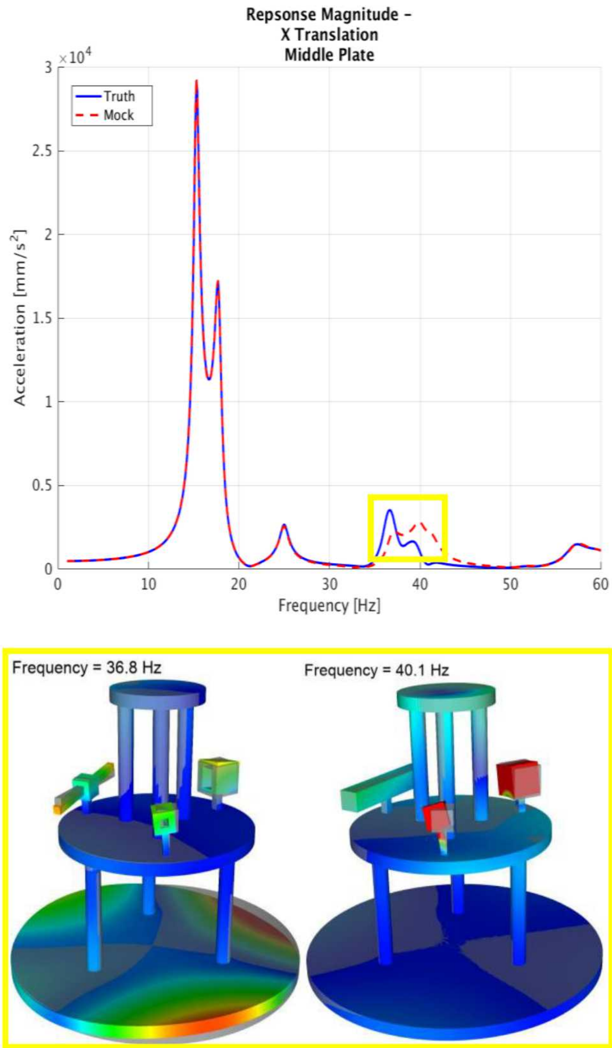

Figure 13: Middle Plate X Translation Response

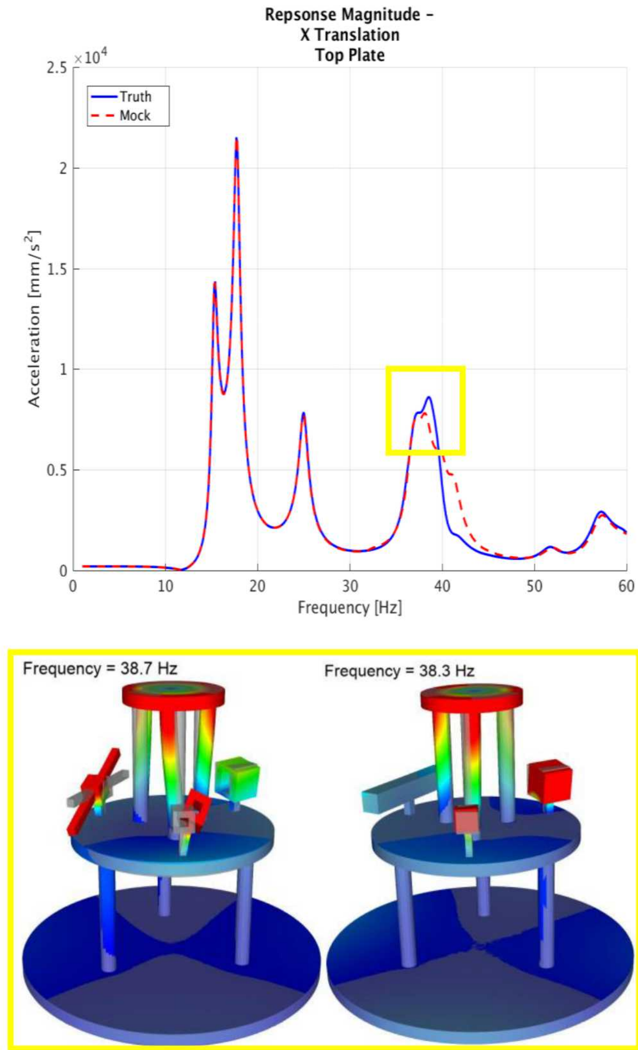

Figure 14: Top Plate X Translation Response

Responses observed in the Y translational direction shared similar differences between the truth and mock configurations as displayed above for X translation. Axial responses for each plate did not reveal significant differences in magnitude or frequency. There is slight variation, but overall the responses of in the plates of the system are not significantly affected by component fidelity.

SMALL BOX COMPONENT – Assembly and Component Level Responses

Although the differences both in volume and inertia are small between the true and mass mock small box components, there is a slight variation in response for each direction, based on if the mock or true geometry was utilized in the system level assembly. The axial response at the base of the small box component, responses appear to be visually identical, until about 37 Hz where a small amount of variation arises, shown in Figure 15.

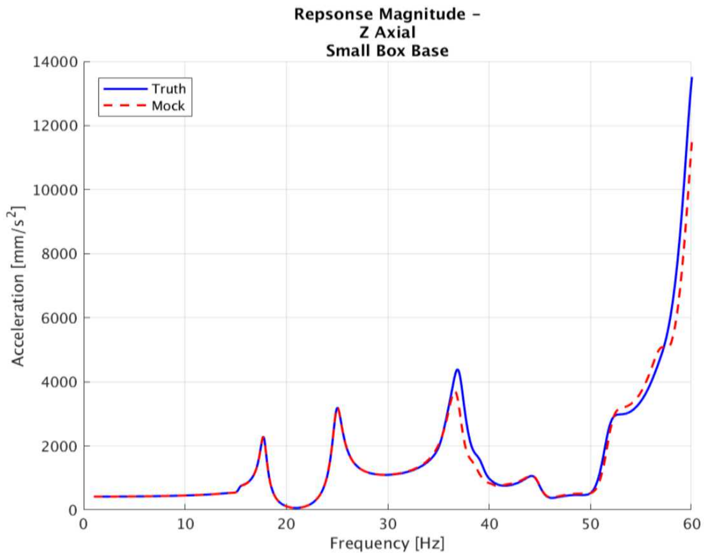

Figure 15: System Level Axial Response - Small Box

Using the response output from the base of both the true and mock small box component configurations, shown in Figure 15, the specification for the component level test was derived and tested on the truth component. Component test responses are depicted in lighter colors, as seen in Figure 16. There is a slight shift in frequency content as well as response magnitude, even though the inputs only have slight variation. When RMS Von Mises stress was evaluated over the domain, the resulting stress fields on the component are characteristically similar, with roughly a 9% difference in maximum value. RMS stress values were reported in pascals, illustrated in Figure 17. With the amount of conservativism that is generally introduced into environmental specification development for a component, this difference is minimal.

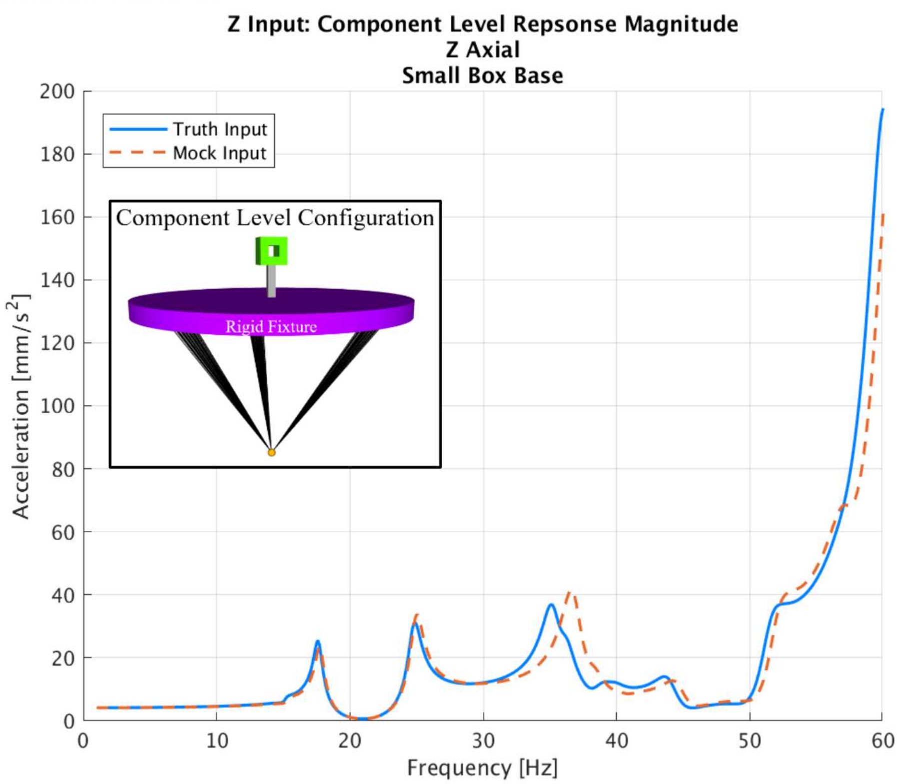

Figure 16: Component Level Axial Response- Small Box

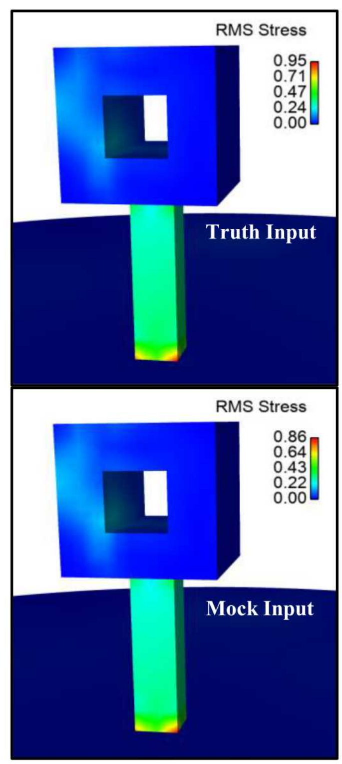

Figure 17: Component Level RMS Stress- Small Box

BEAM COMPONENT- Assembly and Component Level Responses

Assembly level responses observed at the base of the beam component are did not have large differences, as shown in Figure 18. In terms of the system, there were no changes to the structure and component support, so it’s reasonable that the responses in this part of the model are similar. Observing responses from one of the beam edges revealed significant variation, illustrated in Figure 19. This node on the edge of the beam component, Figure 19, captured the propagation of response error in utilizing mass mocks. Peak differences were apparent in the edge node’s FRF below and were further supported by modal and inertial differences of this component in particular.

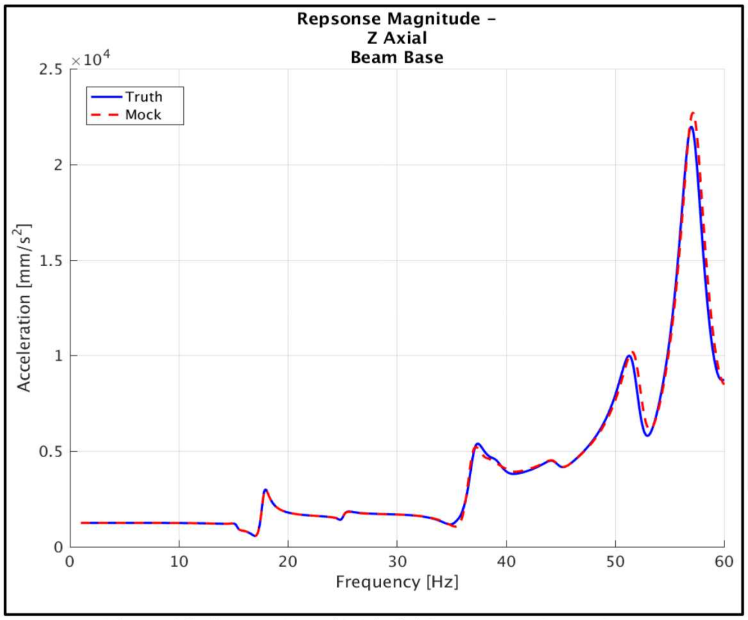

Figure 18: System Level Z Axial Response - Beam Base

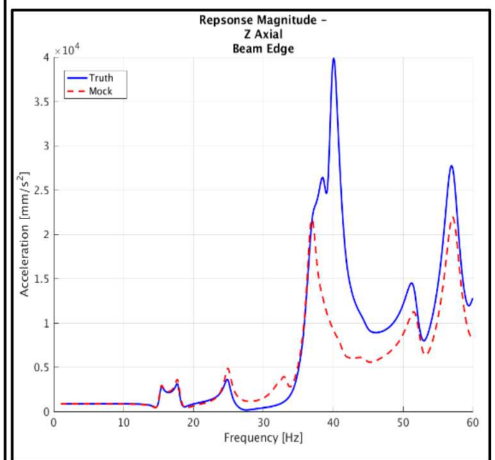

Figure 19: System Level Z Axial Response - Beam Edge

Similar to the workflow of the small box component, beam base responses were then used as component level inputs, where only the high-fidelity model was utilized. There were similar beam base responses observed at the system level structure, Figure 18, but the component level responses to these inputs experienced some discrepancy, as depicted in Figure 20.

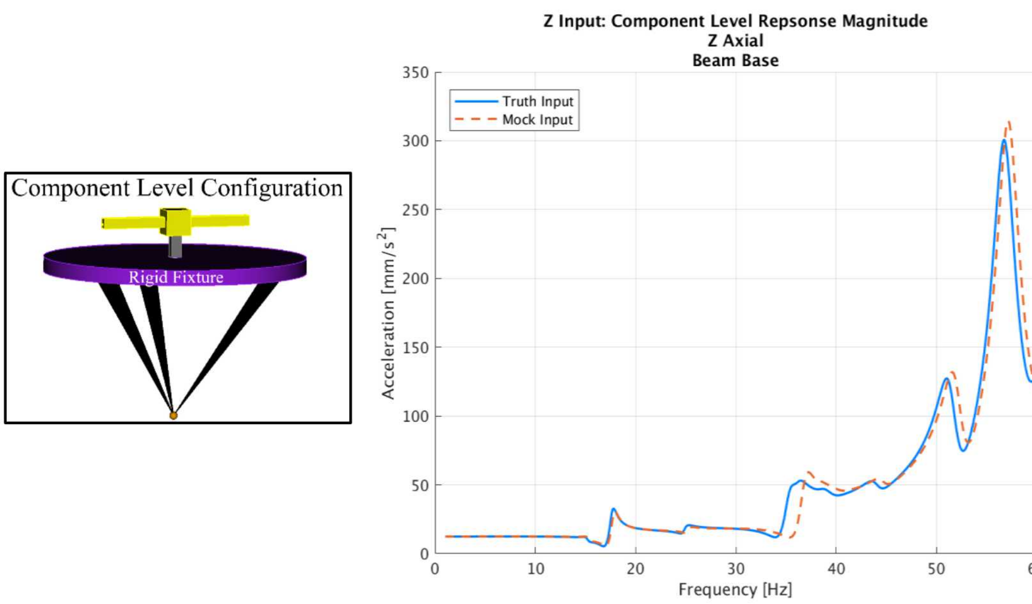

Figure 20: Component Level Z Axial Response - Beam Base

RMS stresses in the component level test revealed differences in maximum values. The overall stress field between the models has slight variation and the environment derived from the truth assembly resulted in stresses roughly 5.4% larger than that of the mass mock derived environment. Figure 21 depicts differences in RMS stress between the two inputs and the resulting intensity of stress experienced. This difference in Von Mises RMS stress is relatively small and would likely be accounted for through conservativeness commonly built into testing, but it's important to note that portions of the stress field are not fully captured with the mock input. This is seen near the beam edges as well as the component's center block.

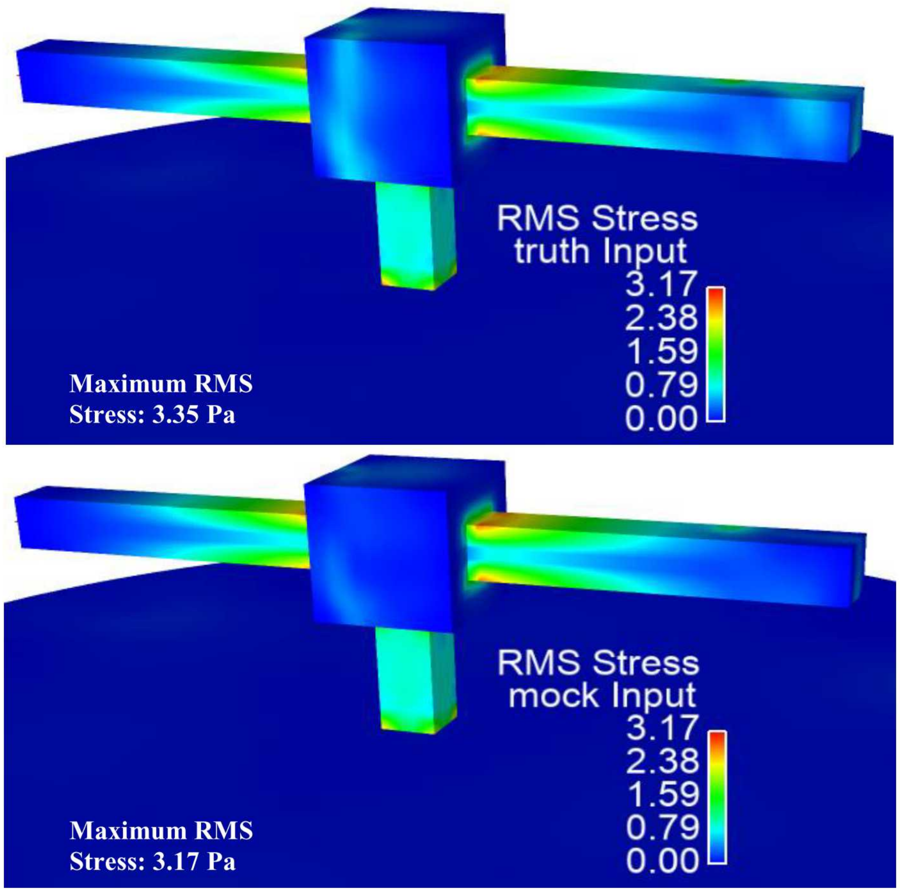

Figure 21: Component Level Beam RMS Stress

For this specific model configuration, it appears that inertia discrepancies less than about 25% assumed a reasonable amount of error in stress and dynamic response, while more significant differences were observed for inertia discrepancies greater than this. Overall model inertia played a key role in resulting component behavior as well. Axial inertia for the assembly was altered the most, 0.05%, and the resulting error in stresses with axial inputs is larger for each respective component compared to both translational directions. This suggests the importance of component inertias on assembly dynamics.

CONCLUSION

Mass mock components are useful in streamlining computational simulations and are necessary for environment testing during a component's development, but while mass and center of gravity are generally preserved, inertial properties are often not held constant. As seen in this analysis, component inertias can have relatively small but important effects on system level dynamics and consequent component environment specifications. In normalizing the differences in inertia and RMS stress values, this analysis revealed a general trend of increasing error reported in component level RMS stresses, as the percent difference of a component's inertia increased. It should be emphasized that this trend is specific to the model used in this analysis and future work would be necessary before definitively correlating these properties. These normalized inertia differences, found in Table 1, and RMS stress errors were not directly proportional, but the general trend for the model utilized in this work suggests the importance of preserving inertial integrity of mass mock components, particularly for deriving component specifications. Further analysis of studying inertial effects in other model configurations would be needed before conclusively characterizing this behavior, however the presence of these issues demonstrated in a simple model highlights potential problems of inertial approximation.

Although this case study did not reveal significantly large differences in response and RMS stress between mock and truth models, it's important to note that component modes were not excited to high levels. From the modal results and assembly level output FRF's, Figure 12-15 and Figure 18, it's apparent that component modes were not the primary source of motion in the frequency range of interest. Evaluating component inertial approximation in a case study that experiences large response magnitudes in component driven modes would likely result in larger discrepancies in dynamic response and RMS stresses.

Future work should continue to develop the understanding of inertial effects on component response and stresses in a more general sense. This work should aim to better define the relationship between response and inertial properties, possibly through exploring frequency response assurance criterion (FRAC) [2] methods. Additionally, designing a model with inertial variation and better modal correlation would isolate key drivers of output differences.

All in all, understanding the effect of inertial approximation on environmental specification development is important and this study can serve as general guideline for the impact of inertial approximations and discrepancies on component responses and the resulting specifications.

REFERENCES

[1] Sierra Structural Dynamics Development Team. Sierra Structural Dynamics - User's Notes. Technical Report SAND2017-3553, Sandia National Laboratories, April 2017.

[2] Marinone, Timothy. Comparison of FRF Correlation Techniques. Technical Report SAND2014-18820C, Sandia National Laboratories & ATA Engineering Inc., 2014.