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Using Component Based TPA to Translate Vibration Environments Between Versions of the Round Robin Structure with FRFs Derived from Analytical Models

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ABSTRACT
This paper will show the results of a study where component-based transfer path analysis was used to translate vibration environments between versions of the round robin structure. This was done to evaluate a hybrid approach where the responses were measured experimentally, but the frequency response functions were derived analytically. This work will describe the test set-up, force estimation process, response prediction (on the new system), and show comparisons between the predicted and measured responses. Observations will also be made on the applicability of this hybrid approach in more complex systems.

Keywords: transfer path analysis, round robin structure, vibration environments

INTRODUCTION AND MOTIVATION

Component-based transfer path analysis (TPA) shows significant promise for generating virtual field data to develop multi-axis vibration test specifications [1]. This is because the estimated forces are a property of the source system and can be applied to any version of the coupled source-receiver system, assuming the source system (loads and structural dynamics) remains the same. The reader is referred to [2] for a complete derivation of the method.

In this case, inverse force estimation from Equation 1 was used, based on the equation of motion in Equation 2. where $[F(\omega)]$ is the cross power spectral density (CPSD) matrix of the forces, $[X(\omega)]$ is the CPSD matrix of the system responses, and $[H(\omega)]$ is the frequency response function (FRF) matrix of the coupled source-receiver system. Note that the "+" indicates a pseudo inverse and the "*" indicates a conjugate transpose.

$$[F(\omega)] = [H(\omega)]^{+}[X(\omega)][H(\omega)]^{+*} \tag{1}$$

$$[X(\omega)] = [H(\omega)][F(\omega)][H(\omega)]^{*} \tag{2}$$

The sketch in Figure 1 shows a picture of a source-path-receiver system that is described in the above equations. In this case, the responses on the payload are the receivers ($X(\omega)$), the forces acting on the payload are the sources ($F(\omega)$), and the frequency response functions (FRFs) between the forces and responses are the paths ($H(\omega)$). Virtual field data can be generated for a new payload assuming the following: the new payload is coupled to the same propulsion system as the original payload, the FRFs are gathered from the coupled source-receiver system, and field data exists from an original version of the system to perform the inverse force estimation. The process for generating virtual field data is as follows:

1. Collect field data and FRFs on an original version of the system

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2. Estimate the forces on the source (propulsion) system via FRF matrix inversion
3. Collect FRFs on a new version of the system, where only the payload is changed (this is a requirement for component-based TPA)
4. Propagate the forces through the new system FRFs to generate the virtual field data on the new receiver (payload)

This process obviously requires accurate FRFs, as any errors in those will propagate into the force and response estimates. The FRFs are typically acquired via a test on the exact device under test (DUT) to reduce these types of errors. However, it can be difficult or impossible to collect this data when the DUT is unavailable (e.g., when using legacy data) or when it is extremely valuable, limiting test access (which is common in the aerospace community). As such, it would be beneficial if a finite element (FE) model could be used to derive the FRFs.

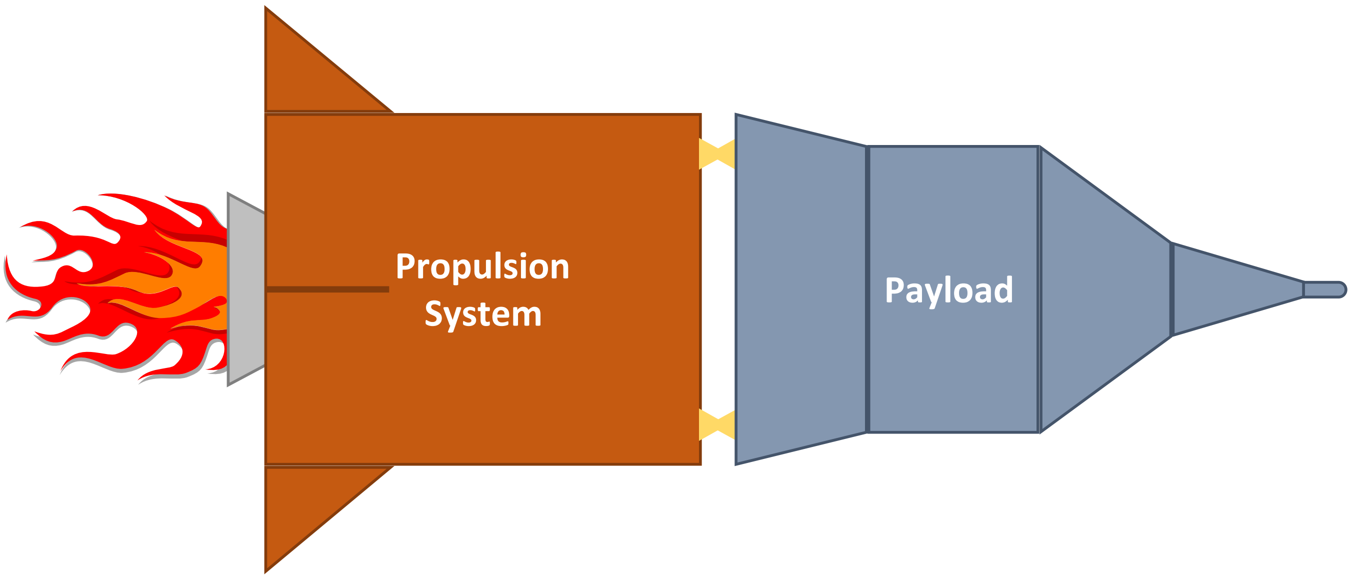

Figure 1: Sketch of a system showing clear delineations between the source and receiver

The use of an FE model introduces additional uncertainties into the TPA process, given the modeling errors (and resulting errors in the FRFs). This work is a first attempt to gain an understanding of how the modeling errors will propagate into force and response estimates. It will exercise the full "hybrid TPA" process, where the response data is gathered experimentally and the FRFs are derived from an FE model. This will be done for two versions of the round robin system [3, 4], where the forces are estimated on an "original" version of the system and then applied to a "new" version of the system to "translate" the vibration environment between the systems. The goal of this work is to determine the most significant sources of error in the hybrid TPA process to guide future research efforts. It should be noted this work may not result in accurate estimates of the new system response (since the goal is to find the sources of error, *not* to fix the sources of error).

Note that this paper is only presenting the initial findings from this study. Further work is underway and will be presented at the conference.

DESCRIPTION OF THE SYSTEM UNDER STUDY

This work is being performed on the round robin system of the Society for Experimental Mechanics (SEM) Dynamic Substructures Technical Division. This system is shown in Figure 2 and is the aluminum copy of the system with the thick (0.25") and thin (0.125") straight wings. This figure also shows the attachment points that are being used. The FE model makes these connections using JOINGT2G elements, which are a native element in the Sandia in-house FE analysis software, Sierra/SD (they are analogous to Nastran CBUSH elements). See [5] for a more complete description of the model. However, some of these parameters may change in a FE model updating process. Also note that the "single point attachments" are being made in the physical version of the system by putting washers between the wing and frame at the bolt locations.

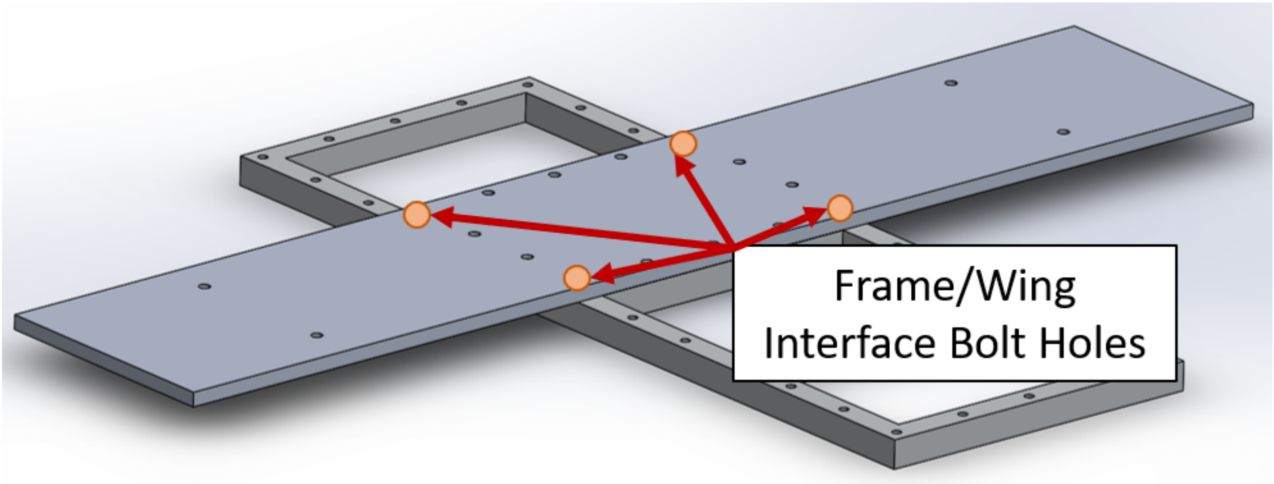

Figure 2: Computer aided design model of the round robin system

DESCRIPTION OF THE PERFORMED EXPERIMENTS

A variety of tests were performed on both (thick and thin wing) versions of the system. These tests included a "field test" where the systems were excited by electrodynamic shakers that were connected to the frame. Modal tests were also performed on the assembled systems and system components to enable model updating in case this was deemed to be necessary. Figure 3 shows an image of the field test and Figure 4 shows a picture of the modal test on the assembled system.

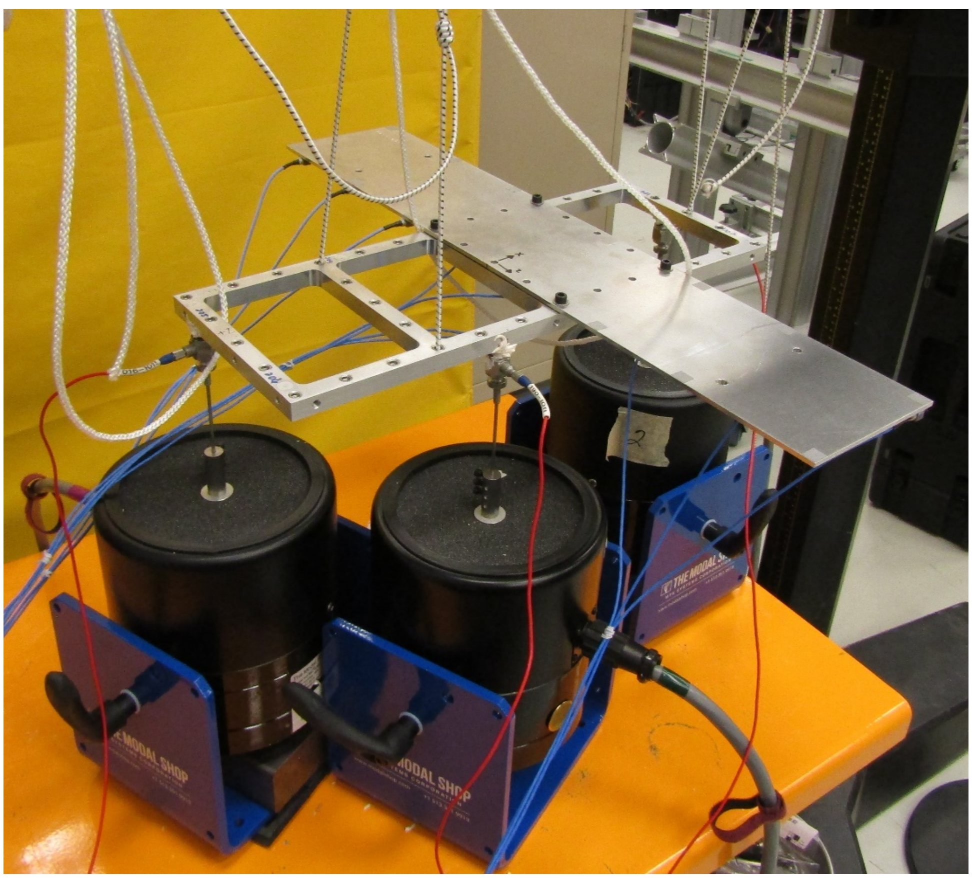

Figure 3: Set-up for the "field test"

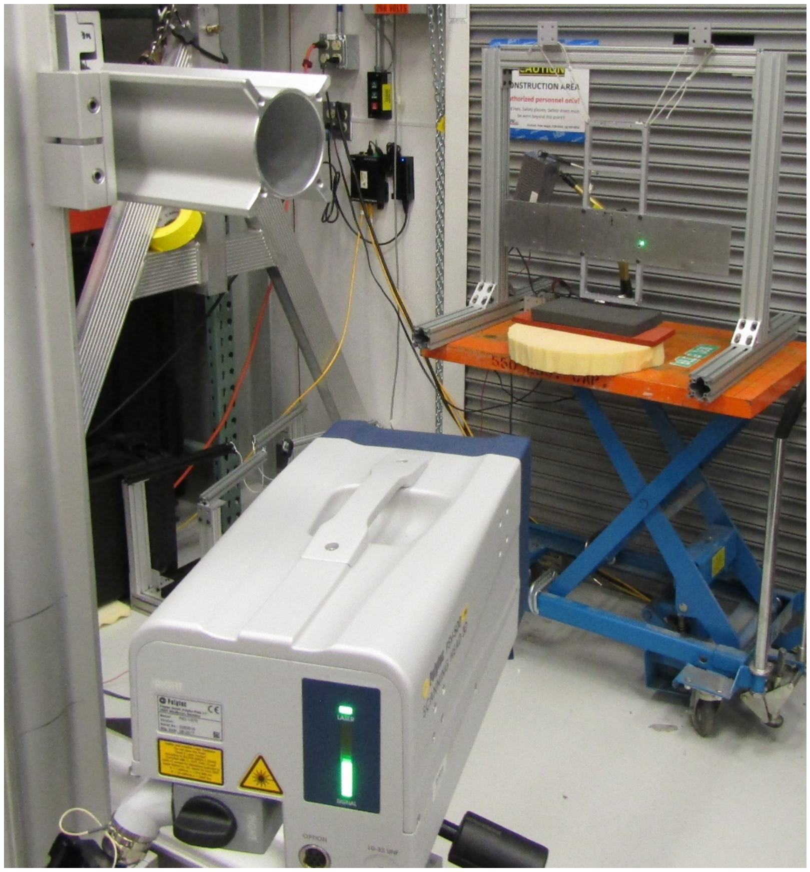

Figure 4: Set-up for the modal test

The field test was performed by playing controlled forces into the system at three locations using electrodynamic shakers and the Rattlesnake vibration controller [6]. Note that these forces were initially generated on the original (thick wing) system by playing flat voltages through each of the shakers (i.e., the measured force CPSDs from the first test became the control specification for the following tests). The responses were measured at ten locations with triaxial accelerometers, as shown in Figure 5 on a stick model of the system.

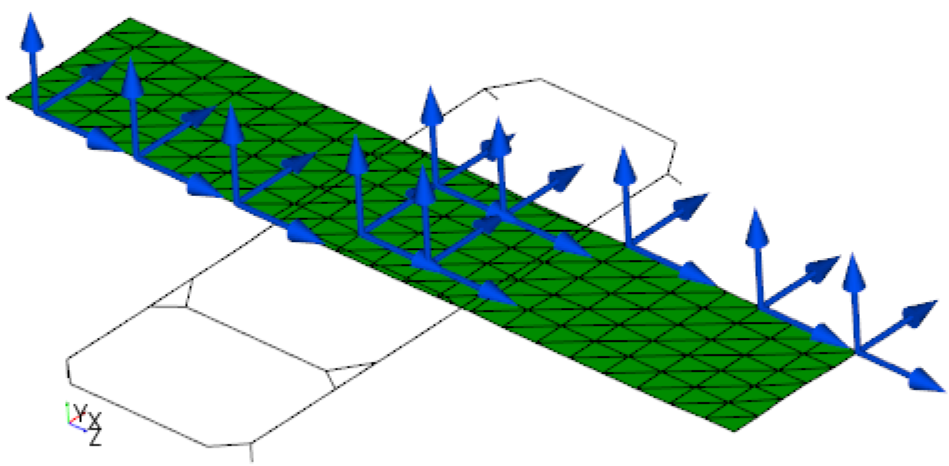

Figure 5: Field data response measurement locations on stick model of the round robin system

These measurement locations were chosen subjectively, based on experience and some numerical studies into the accuracy of component-based TPA. Additionally, the test was intentionally limited to 30 response degrees of freedom (DOFs) to replicate what is typically seen in flight testing, where the minimum number of transducers are used. Lastly, Figures 6-8 show the force auto-power spectral densities (APSDs) that were applied to both versions of the system, indicating the similarity of the source environments for each system.

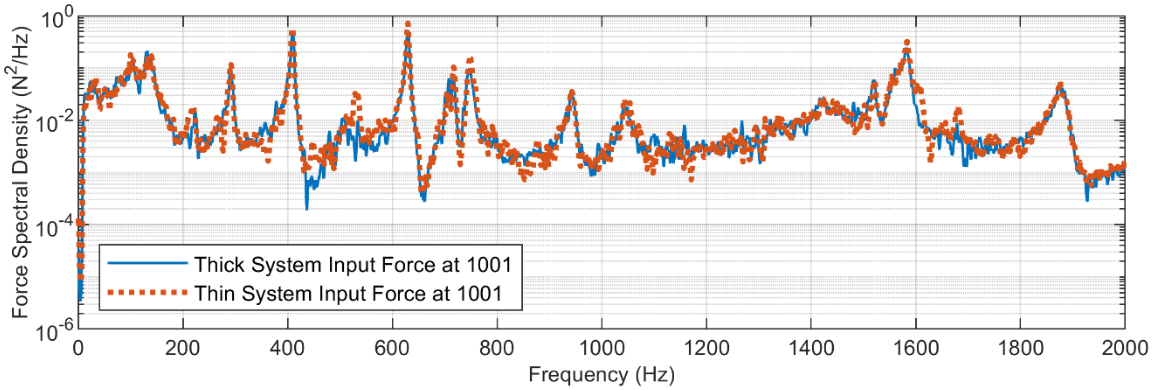

Figure 6: Comparison of the input forces for both versions of the system at point 1001 (aft)

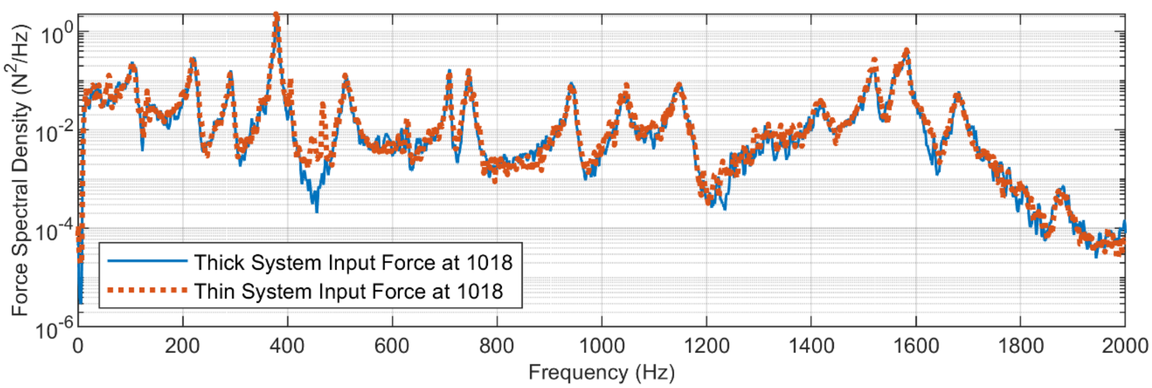

Figure 7: Comparison of the input forces for both versions of the system at point 1018 (forward)

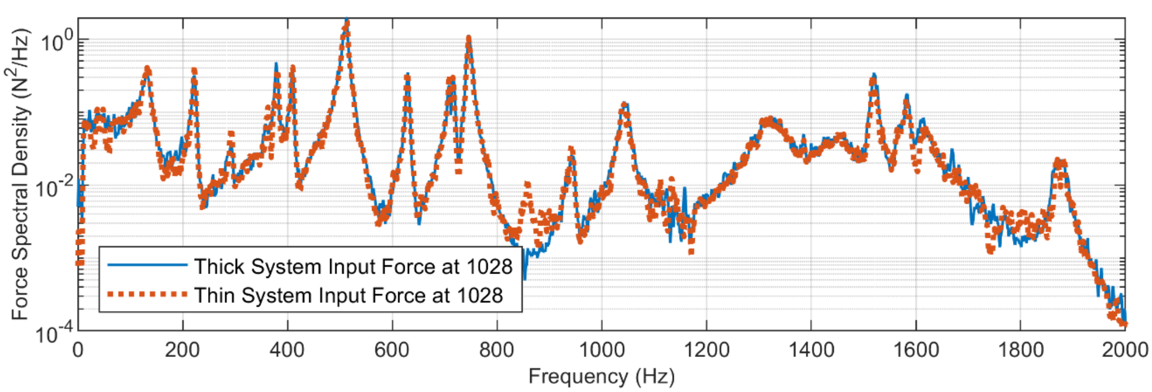

Figure 8: Comparison of the input forces for both versions of the system at point 1028 (right side)

The modal test was performed using a scanning laser doppler vibrometer (SLDV) and an automatic impact hammer, which excited the system at multiple locations and directions. The (triaxial) response measurement locations matched a reduced set of nodes from the FE model. There were 164 response nodes for the assembled system tests, 138 response nodes for the wing tests, and 42 response nodes for the frame test. It should be noted that the modal tests were performed with the accelerometers removed from the wings but with the load cells left on. This change could be significant, since removing the accelerometers is expected to influence the system damping (due to the influence of the cables).

INITIAL TPA EFFORTS AND RESULTS

The initial efforts attempted to estimate the interface forces on the thick wing system and then apply them to the thin wing system to predict its response. This procedure was done using non-calibrated models of the systems to generate the necessary FRFs. The damping ratios were determined from the field test and were set to 0.266% for all the thick wing system modes and 0.417% for all the thin wing system modes. The forces were estimated at the frame side (JOINT2G) interface node between the frame and wing in the vertical direction (perpendicular to wing) only.

A first attempt used 3DOF (X, Y, Z) forces at each interface, but this clearly resulted in an overfit solution like the one that was seen in [5]. The reasons for this overfit solution are unclear, but it is likely related to the small number of true sources acting on the system limiting the possible number equivalent sources (that are estimated in the inversion process). However, numerical studies have shown that there isn't a 1:1 relationship between the number of true sources and possible equivalent sources, making it difficult to choose appropriate FRF reference DOFs. Improved regression methods, such as Bayesian inference [7, 8], could reduce the possibility of an overfit solution while still including 3DOF forces in the estimate and this is a topic of current study.

The DOF averaged spectrum results for the initial work is shown in Figure 9 and Figure 10 for thick and thin wing systems, respectively. The dB error spectra for each response DOF (as well as the average dB error) on the thin wing is also shown Figure 11. As expected, there is a very good match between the measured and reconstructed responses on the thick wing system. This match may indicate that it is appropriate to only use the vertical forces at the interface, but further study would be needed to confirm this conclusion. Additionally, it is important to note that this check only provides a minor validation of the forces, as it is a check on the least square solution and *not* the accuracy of the forces.

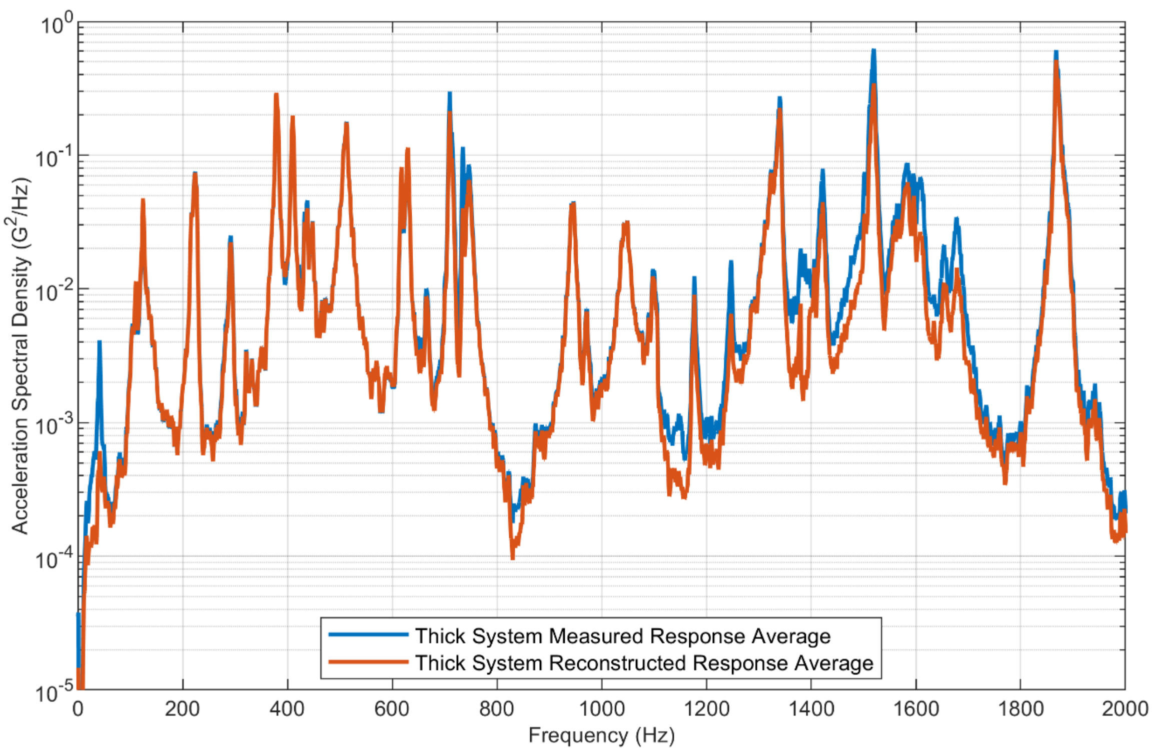

Figure 9: Comparison of the DOF averaged measured and reconstructed responses on the thick wing system

The thin wing estimated responses show a reasonable match to the measured data, especially below ~600 Hz. The estimated responses would provide useful "virtual field data" (over the whole frequency range) if measured data was not available, but there is obvious room for improvement. The reasons for the mismatch between the estimated and measured response is unknown. It is suspected that the errors are due to both model inaccuracies and poor conditioning/setup in the inverse solution. Work is currently underway to better understand the causes of these errors.

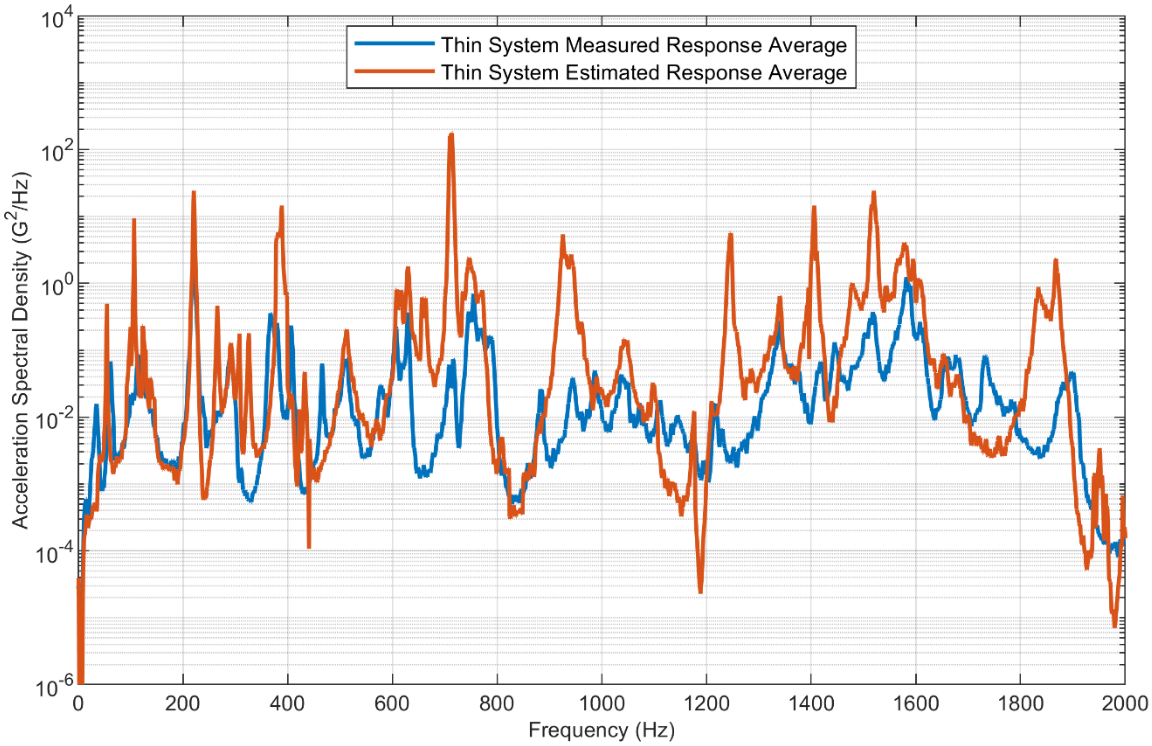

Figure 10: Comparison of the DOF averaged measured and estimated (from the thick wing interface forces) responses on the thin wing system

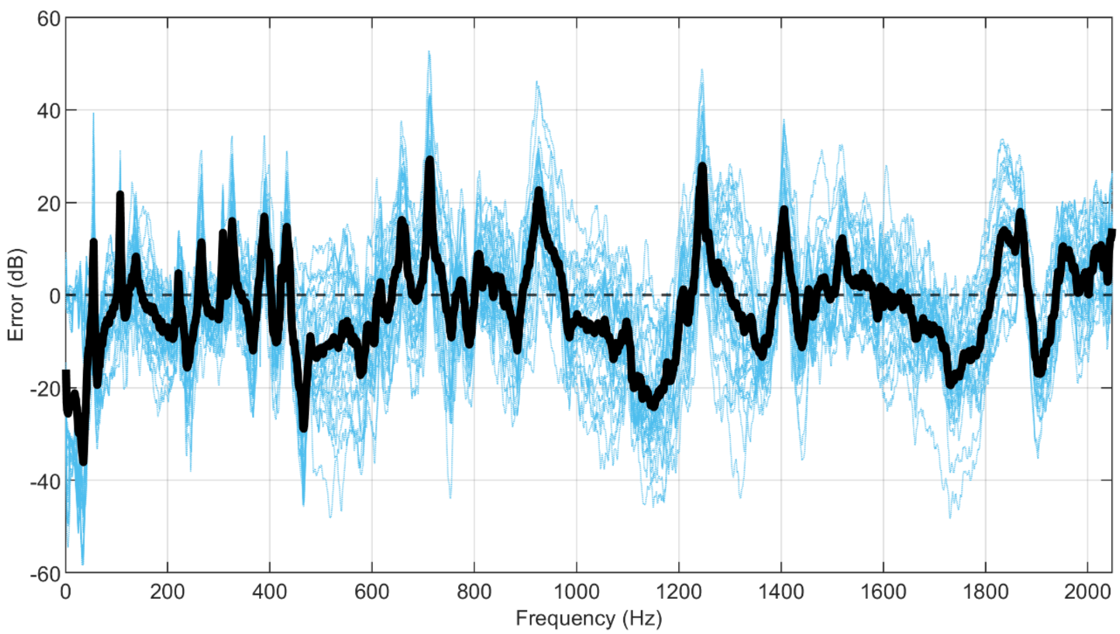

Figure 11: Per DOF dB spectrum error for the thin wing system. The dashed black line is the zero axis, the solid black curve is the mean dB error, and the blue curves are the dB error for each response DOF.

CONCLUSIONS

This paper showed the initial attempts at using component-based TPA to translate vibration environments between versions of the round robin structure. In this case, forces were estimated at the frame/wing interface on the thick wing system and then applied to the thin wing system to generate response estimates. The initial results showed reasonable comparisons to the measured data, but there is obvious room for improvement. Work is currently underway to better understand and mitigate the sources or error, with the goal to present updated results at the conference.

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