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Experimental Substructuring of the Dynamic Substructures Round Robin Testbed

D. Roettgen[1], G. Lopp[1], A. Jaramillo[1], B. Moldenhauer[2]
[1] Sandia National Laboratories*
[2] University of Wisconsin-Madison

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1 Abstract

Experimental-analytical substructuring has been a popular field of research for several years and has seen many great advances for both Frequency Based Substructuring (FBS) and Component Mode Synthesis (CMS) techniques. To examine these technical advances, a new benchmark structure has been designed through the SEM Dynamic Substructuring technical division to act as a benchmark study for anyone researching in the field. This work contains the first attempts at experimental dynamic substructuring using the new SEM testbed. Complete dynamic substructuring predictions will be presented along with an assessment of variability and nonlinear response in the test best assembly. Systems will be available to check out through the authors beginning in December of 2021 and this paper intends to initiate in full the round robin challenge.

2. Benchmark Structure

Tremendous progress has been made with research surrounding experimental-analytical substructuring when the SEM community previously rallied around a common test bed. In 2011, the experimental substructures focus group selected a testbed structure, the Ampair 600 Wind Turbine. The origin of this test bed is discussed in detail in [1]. Many researchers have studied this benchmark structure, see [2, 3, 4, 5, 6, 7, 8, 9]. During these studies several new methods and technologies were developed, but the Ampair 600 Wind Turbine turned out to be quite a challenging structure due to the complexity of joints and the nature of utilizing a structure not designed within the community. Despite these challenges the community made great strides in the field of dynamic substructuring.

At IMAC XXXVI the focus group on Dynamic Substructuring officially transitioned into a Technical Division of SEM titled Dynamic Substructures. During this inaugural meeting, the Technical Division discussed the creation of a new benchmark structure to kick-off a new era of research in experimental analytical substructuring. It was determined that a new benchmark structure would be an appropriate test of the current capabilities of the Dynamic Substructures Technical Division and would foster future collaboration. A group of researchers collaborated to generate the design of a new round-robin test vessel for dynamic substructuring. After a few design iterations the four-unit frame (shown in Figure 1) was selected in an airplane like configuration (shown in Figure 2).

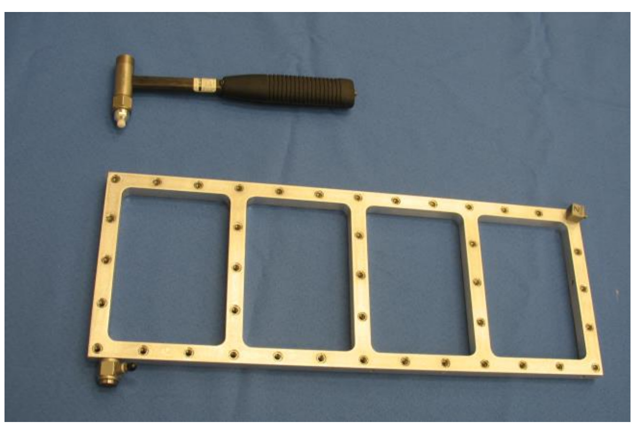

Figure 1. Four Unit Frame

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This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

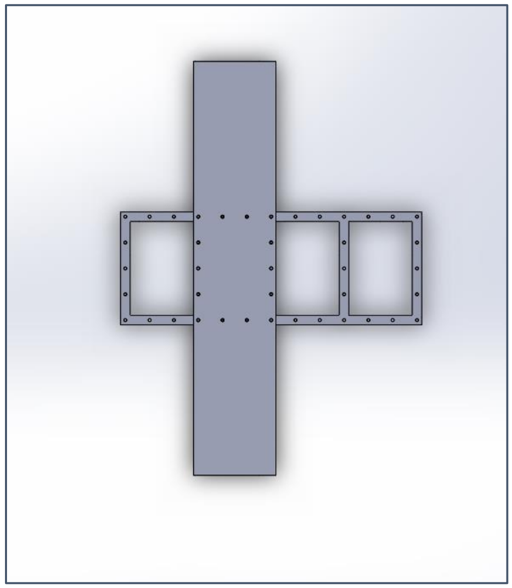

Figure 2. Airplane Configuration

Since finalizing the design 8 frames and 8 sets of wings (for each thickness) have been manufactured. Measurements, modes, weights, and detailed assembly instructions from these frames will be available on the Dynamic Substructuring wiki. To ensure that this structure is suitable for dynamic substructuring the team at Sandia National labs has completed an experimental substructuring prediction with the hardware.

3. Example

The goal of this substructuring exercise was to ensure that substructuring of the new round robin structure was possible before sending out the set of units to interested researchers. Multiple substructuring configurations have been tested and one is shown here for brevity. The intent of this exercise is to connect an experimental model of the thin wing to an experimental model of the frame. The hardware used included frame SN001, thin wing SN WING006A, and a plate acting as a transmission simulator. This hardware was assembled using four steel fasteners, one at each corner, with washers between the subcomponents. Experiments were performed on substructures 1, 2, and 3 shown in Figure 3 using a laser doppler vibrometer.

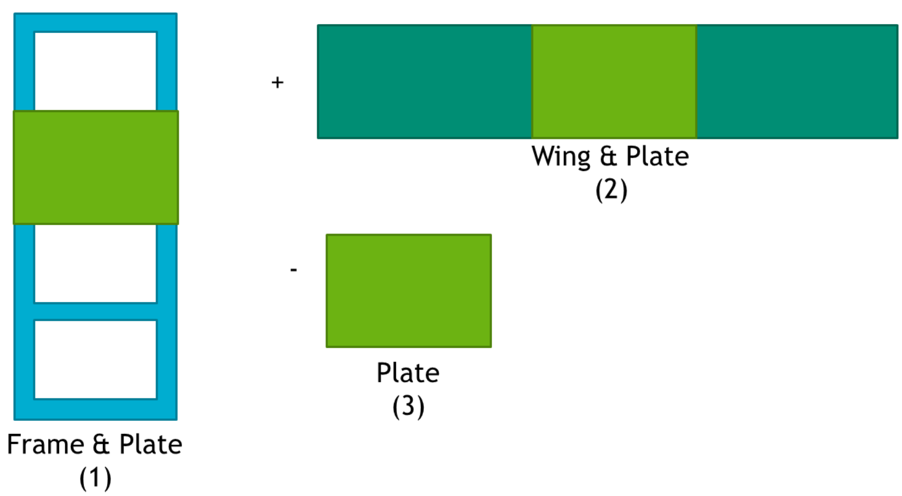

Figure 3. Substructure Configurations

Transmission simulator theory [10] was used where a fixture plate is attached near the connecting hardware. Note, a transmission simulator was attached to both the frame and wing in this example, but only one fixture plate was removed – thus the truth comparison also includes one fixture plate. A summary of the substructuring technique is repeated here for reference. First, measurements were taken on all three systems and a set of uncoupled block-diagonal equations of motions was written using the measured modal parameters.

$$\begin{bmatrix} I_1 & 0 & 0 \\ 0 & I_2 & 0 \\ 0 & 0 & -I_3 \end{bmatrix} \begin{Bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3 \end{Bmatrix} + \begin{bmatrix} \left[\ddots \omega_1^2 \ddots \right] & 0 & 0 \\ 0 & \left[\ddots \omega_2^2 \ddots \right] & 0 \\ 0 & 0 & -\left[\ddots \omega_3^2 \ddots \right] \end{bmatrix} \begin{Bmatrix} q_1 \\ q_2 \\ q_3 \end{Bmatrix} = \begin{Bmatrix} \phi_1^T F_1 \\ \phi_2^T F_2 \\ \phi_3^T F_3 \end{Bmatrix} \quad (1)$$

A set of constraints is defined linking motion on the transmission simulator plate in all three structures.

$$\begin{bmatrix} \phi_3^+ & 0 \\ 0 & \phi_3^+ \end{bmatrix} \begin{bmatrix} \phi_1 & 0 & -\phi_3 \\ 0 & \phi_2 & -\phi_3 \end{bmatrix} \begin{Bmatrix} q_A \\ q_B \\ q_{TS} \end{Bmatrix} = \tilde{B} \begin{Bmatrix} q_1 \\ q_2 \\ q_3 \end{Bmatrix} = 0 \quad (2)$$

A synthetization matrix L is found such that the constraints are non-arbitrary.

$$L = \text{null}(\tilde{B}) \quad (3)$$

This matrix is used to transform the original equations of motion into a coupled prediction.

$$L^T \begin{bmatrix} I_1 & 0 & 0 \\ 0 & I_2 & 0 \\ 0 & 0 & -I_3 \end{bmatrix} L \begin{Bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3 \end{Bmatrix} + L^T \begin{bmatrix} \left[\ddots \omega_1^2 \ddots \right] & 0 & 0 \\ 0 & \left[\ddots \omega_2^2 \ddots \right] & 0 \\ 0 & 0 & -\left[\ddots \omega_3^2 \ddots \right] \end{bmatrix} L \begin{Bmatrix} q_1 \\ q_2 \\ q_3 \end{Bmatrix} = L^T \begin{Bmatrix} \phi_1^T F_1 \\ \phi_2^T F_2 \\ \phi_3^T F_3 \end{Bmatrix} \quad (4)$$

Modes were retained to 1,000 Hz for the substructures 1 and 2, while only rigid modes were retained for substructure 3. Table 1 contains the blind-substructuring predictions and their accuracy compared to a truth test and Figure 4 shows a comparison from measured truth to predicted shapes through a MAC plot. Our quality metric was set such that frequency errors under 10% were considered quality while damping errors under 50% were considered quality. Most frequency errors were in the quality range with 2 modes outside in the first 700 Hz, the damping quality was slightly poorer as expected and may be corrected by fine-tuning subcomponent damping. Additional substructuring configurations and predictions were completed and will be presented as a part of the IMAC presentation.

Table 1. Substructuring Prediction Results

Elastic Mode Index	Truth		Prediction		Error	
	fn	zt	fn	zt	fn	zt
1	61.91	0.231%	55.76	0.033%	-9.93%	-85.83%
2	107.19	0.185%	96.16	0.123%	-10.29%	-33.70%
3	230.00	0.073%	225.92	0.069%	-1.77%	-5.42%
4	277.66	0.143%	272.85	0.045%	-1.73%	-68.61%
5	341.56	0.246%	330.92	0.104%	-3.12%	-57.59%
6	369.06	0.131%	352.90	0.072%	-4.38%	-45.50%
7	418.91	0.145%	396.28	0.067%	-5.40%	-53.61%
8	499.06	0.251%	598.74	0.100%	19.97%	-59.96%
9	656.09	0.103%	611.07	0.116%	-6.86%	12.57%
10	696.41	0.095%	688.10	0.164%	-1.19%	72.45%
11	798.75	0.029%	726.60	0.093%	-9.03%	215.58%
12	807.50	0.084%	733.88	0.069%	-9.12%	-17.92%
13	857.19	0.197%	784.65	0.119%	-8.46%	-39.35%
14	976.25	0.182%	784.65	0.119%	-19.63%	-34.25%

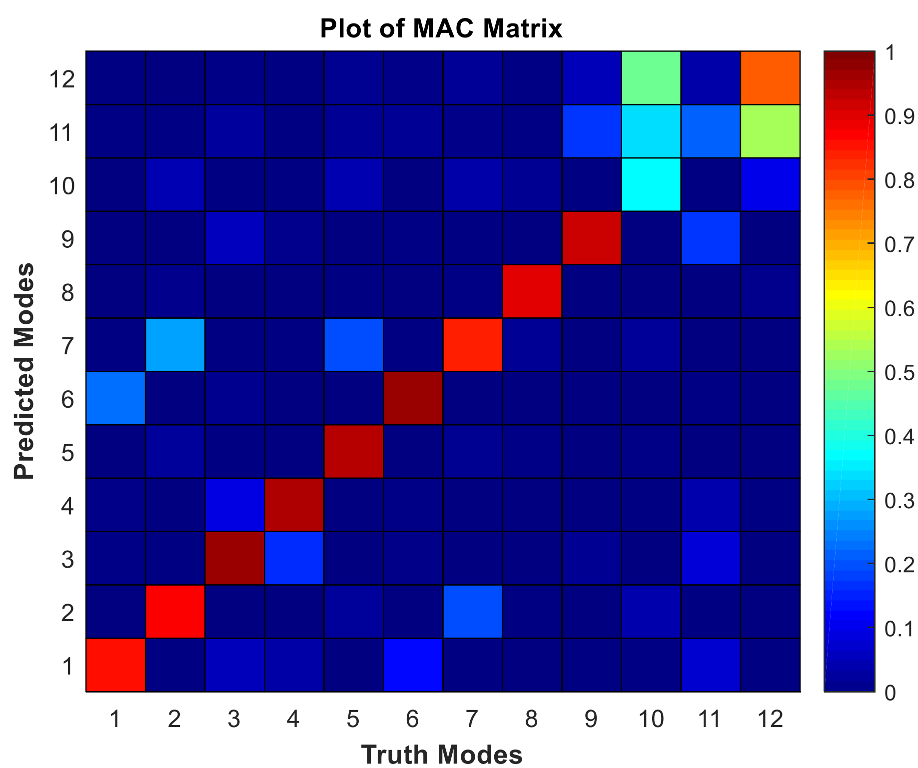

Figure 4. MAC of Prediction Results and Truth Results

4. Kick-Off

The Dynamic Substructures technical division round robin is now ready to begin. Please contact Dan Roettgen at drroett@sandia.gov to sign up. For detailed instructions on the challenges please visit the dynamic substructures wiki during and after IMAC XL. The results presented in this work and presentation capture a small fraction of the research that will be completed using this new benchmark structure. We look forward to participation and collaborations among research groups for years to come.

References

[1] R. L. Mayes, "An Introduction to the SEM Substructures Focus Group Test Bed – The Ampair 600 Wind Turbine," in *Topics in Experimental Dynamics Substructuring & Wind Turbine Dynamics*, Jacksonville, FL, 2012.

[2] D. P. Rohe and R. L. Mayes, "Coupling of a bladed hub to the tower of the ampair 600 wind turbine using the transmission simulator method," in *Topics in Experimental Dynamics Substructuring, Vol. 2*, Orlando, FL, 2014.

[3] D. R. Roettgen and R. L. Mayes, "Ampair 600 Wind Turbine 3-Bladed Assembly Substructuring using the Transmission Simulator Method," in *Proceedings from the XXXIII IMAC Conference*, Orlando, FL, 2015.

[4] S. Rahimi, D. deKlerk and D. J. Rixen, "The Ampair 600 Wind Turbine Benchmark: Results From the Frequency Based Substructuring Applied to the Rotor Assembly.," in *Proceedings of the 31st International Modal Analysis Conference*, Orlando, FL, 2013.

[5] J. Brunetti, A. Culla, W. D'Ambrogio and A. Fregolent, "Experimental Dynamic Substructuring of the Ampair Wind Turbine Test Bed," in *Proceedings of the International Modal Analysis Conference*, Orlando, FL, 2014.

[6] M. S. Allen, H. M. Gindlin and R. L. Mayes, "Experimental modal substructuring to estimate fixed-base modes from a test on a flexible fixture," *Journal of Sound and Vibration,* vol. 330, no. 18-19, pp. 4413-4428, 2011.

[7] J. Harvie and P. Avitable., "Comparison of Some Wind Turbine Blade Tests in Various Configurations," in *Proceedings from the 30th International Modal Analysis Conference*, Orlando, FL, 2012.

[8] J. Gross, B. Seeger, S. Peter and P. Reuss, "Applying the Transmission Simulator Techniques to the Ampair 600 Wind Turbine Testbed," in *Dynamics of Coupled Structures, Volume 4: Proceedings of the 34th IMAC*, Orlando, FL, 2016.

[9] M. Cwenarkiewicz and T. Johansson, "Experimental Dynamic Substructirng of an Ampair 600 Wind Turbine Hub together with Two Blades," Linnaeus University Thesis Under Advisor: Andreas Linderholt, 2016.

[10] M. Allen, R. Mayes and E. Bergman, "Experimentsal modal substructuring to couple and uncouple substructures with flexible fixtures and multi-point connections," *Journal of Sound and Vibration,* vol. 329, pp. 4891-4906, 2010.