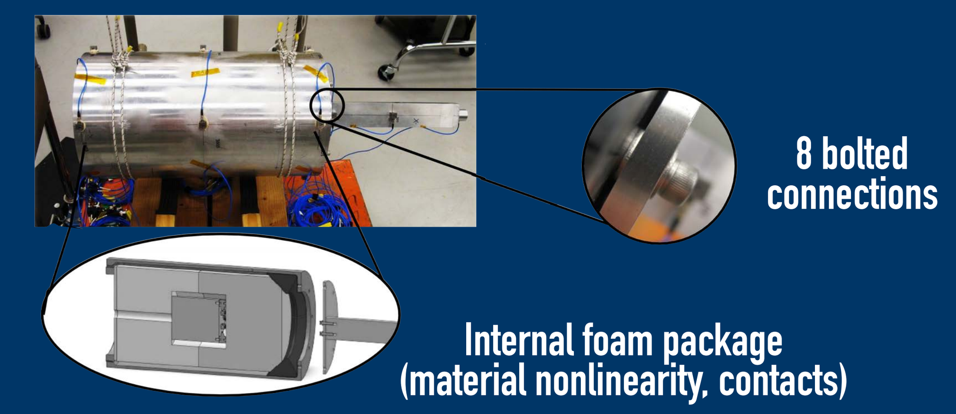
Reduced Order Modeling Techniques in Experimental Dynamic Substructuring



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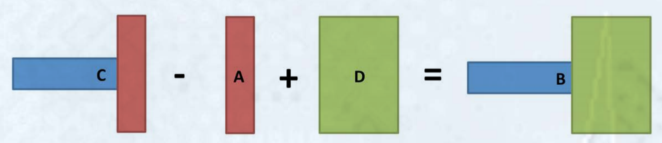
Objective

- *Compare different experimental substructuring techniques using two different systems*
- *Discover the best practices for experimental-numerical substructuring*

Substructuring Theory

- *Component Mode Synthesis (CMS) is used to combine two substructures to predict the dynamic response of the assembly*
- *This is useful when testing a full assembly is impractical or trying to analyze the effects of changing out different sub-assemblies*
- *These predictions can be very sensitive to interface errors where two substructures are joined*
- *In order to exercise the joints as seen in the assembly the experiment can be connected to known fixture or transmission simulator (TS)*
- *The Craig-Mayes method uses the transmission simulator theory to create an experimental Craig-Bampton like form of the experimental results*



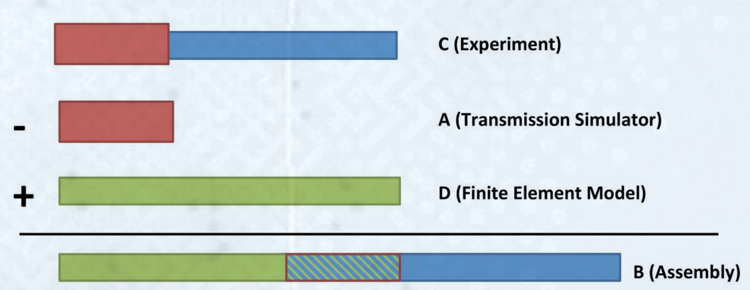
C - A + D = B

- In the transmission simulator method a known transmission simulator (A) is subtracted from the experimental subsystem (C)
- Next a new subsystem (D) is added to the result creating the target assembly (B)

$$\begin{bmatrix} I_C & 0 & 0 \\ 0 & I_D & 0 \\ 0 & 0 & -I_A \end{bmatrix} \begin{Bmatrix} \ddot{q}_C \\ \ddot{q}_D \\ \ddot{q}_A \end{Bmatrix} + \begin{bmatrix} 2\zeta_C\omega_C & 0 & 0 \\ 0 & 2\zeta_D\omega_D & 0 \\ 0 & 0 & -2\zeta_A\omega_A \end{bmatrix} \begin{Bmatrix} \dot{q}_C \\ \dot{q}_D \\ \dot{q}_A \end{Bmatrix} + \begin{bmatrix} \omega_C^2 & 0 & 0 \\ 0 & \omega_D^2 & 0 \\ 0 & 0 & -\omega_A^2 \end{bmatrix} \begin{Bmatrix} q_C \\ q_D \\ q_A \end{Bmatrix} = \begin{Bmatrix} \phi_C^T F_C \\ \phi_D^T F_D \\ \phi_A^T F_A \end{Bmatrix}$$

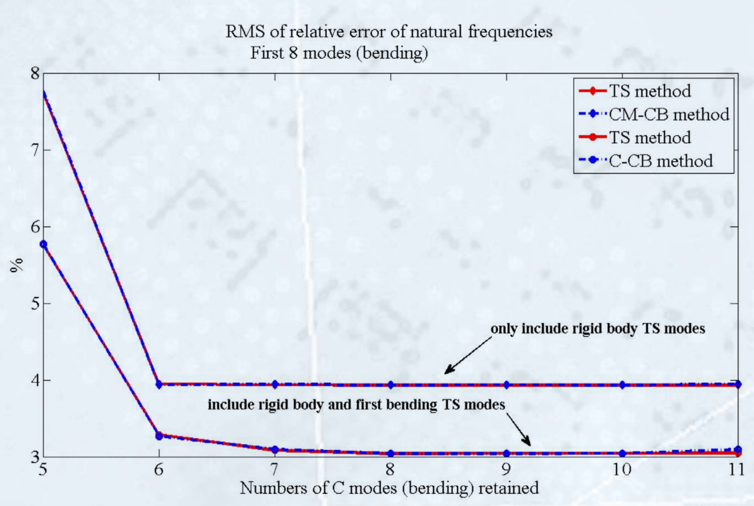
$$\begin{bmatrix} \phi_A^+ & 0 \\ 0 & \phi_A^+ \end{bmatrix} \begin{bmatrix} \phi_C & 0 & -\phi_A \\ 0 & \phi_D & -\phi_A \end{bmatrix} \begin{Bmatrix} q_C \\ q_D \\ q_A \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix}$$

Beam Example



Substructuring B=D+C–A by

- *Craig-Mayes model of C–A attached to Craig-Bampton model of D (CM-CB) and traditional transmission simulator (TS)*
- *2 degrees of freedom used at 3 node locations as connection*

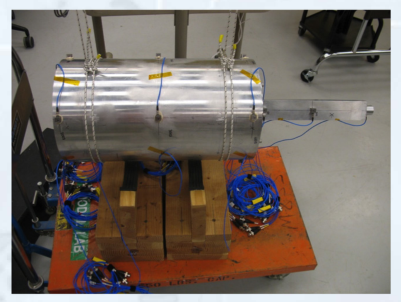


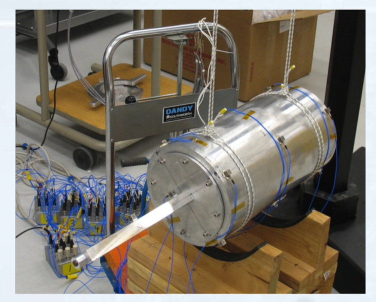
Convergence Test

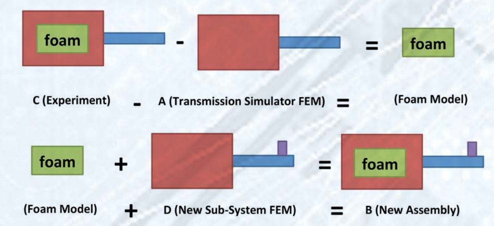
- *In this simulation, the TS and CM-CB method show similar convergence rates given the same TS and experimental modes*
- *The convergence improves when TS modes estimate the connection points motion more accurately*
- *After including sufficient (e.g., >6) experimental modes convergence rates show no significant improvement*
- *Further improvement is observed when the first bending mode of TS is included*

Experimental System

- *Experimental system consists of the can-plate-beam system packed with foam and some internal instrumentation pieces*
- *Testing complete with low-level excitations to avoid non-linearities in the system*
- *14 Elastic modes extracted from experimental data*



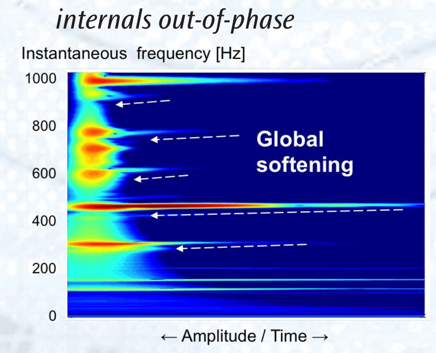




Nonlinearity Characterization

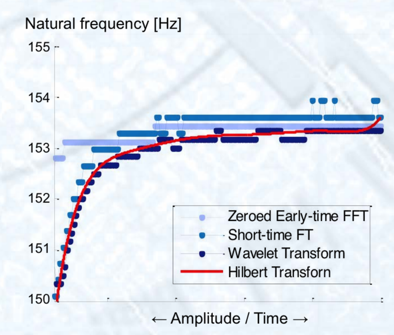
DETECTION - Wavelet Transform
Most nonlinear modes (exercising the joints)

- *Mode 1: First bending mode of the beam in the horizontal plane*
- *Mode 2: First bending mode of the beam in the vertical plane*
- *Mode 6: Axial mode, beam and internals out-of-phase*

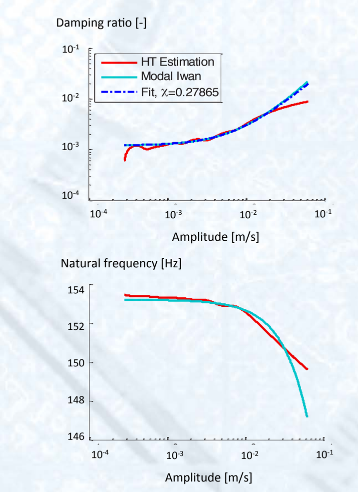


CHARACTERIZATION & QUANTIFICATION
Amplitude ↗ ⇒ Natural frequency ↘
Amplitude ↗ ⇒ Damping ratio ↗
Natural frequency variations

- *Mode 1: - 4%*
- *Mode 2: - 3%*
- *Mode 6: - 2.5%*

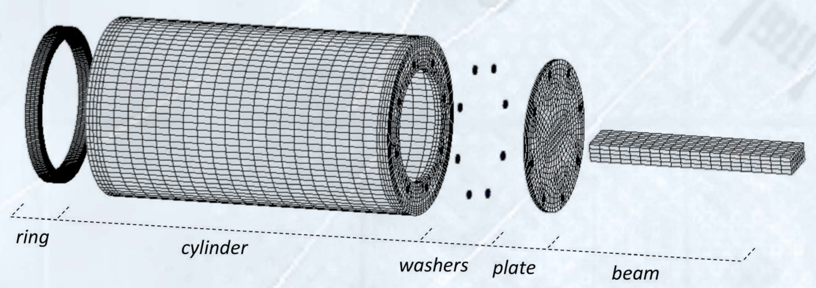


PARAMETER ESTIMATION
Fitting a modal Iwan model on damping and natural frequency vs. amplitude curves using Hilbert transform



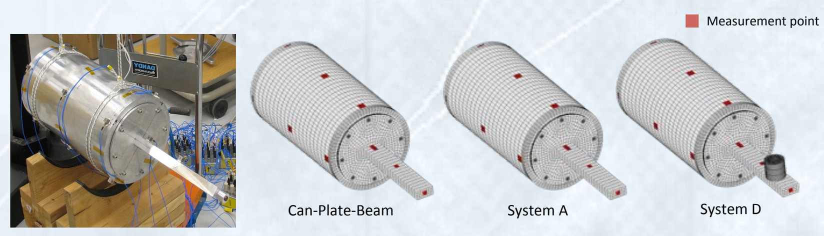
Finite Element Model

- *Transmission components and properties*



Components	Element type	Material
Beam, plate, cylinder, ring	Higher order 3-D 20 node solid	6061-T6 Aluminum
Washer	Higher order 3-D 20 node solid	Steel

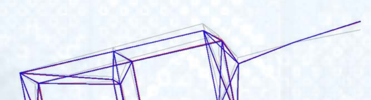
- *System frequencies*

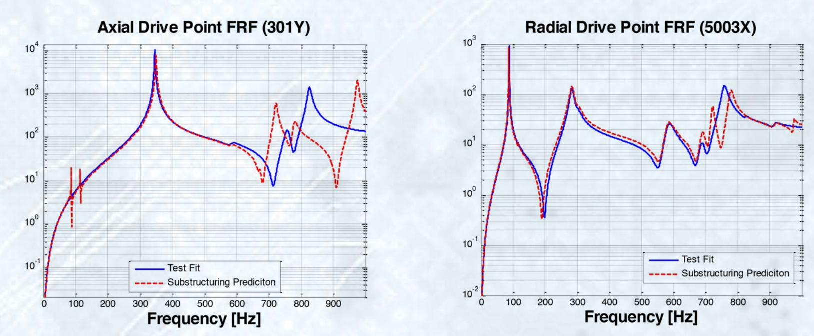


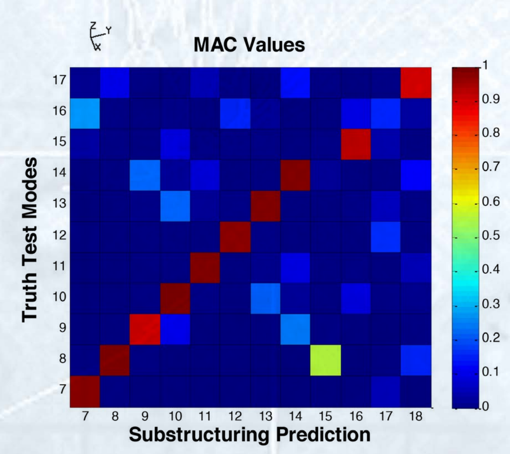
Experiment [Hz]	Can-Plate-Beam Only		System A Can-Plate-Beam with Ring		System D Validation Structure
	[Hz]	% Difference	[Hz]	% Change	
134.2	136.8	1.90	137.2	2.23	101.9
171.2	175.8	2.60	177.5	3.68	133.9
430.0	422.8	1.70	848.5	97.32	848.5
511.2	525.9	2.80	540.8	5.78	407.6
975.7	960.6	1.50	993.8	1.85	993.8
1027	1025	0.19	1026	0.019	861.5
1312	1312	0.00	1549	18.04	1548.7
1528	1535	0.45	1598.5	4.62	1598.6
1637	1610	1.68	1598.2	2.37	1707.8
1801	1835.15	1.86	1834.2	1.85	1924.6
1833	1835.35	0.12	1835.3	0.13	2108.5

Substructuring Predictions

- *Transmission Simulator approach completed using 13 modes from the transmission simulator (A) and 17 modes of the new subsystem (D)*
- *Modes of system A kept up to 989 Hz*
- *Modes of system D kept up to 1495 Hz*







Mode #	f_{test} [Hz]	$f_{prediction}$ [Hz]	f_n Error [%]	ζ_{test}	$\zeta_{prediction}$	ζ Error [%]	MAC
7	88.33	87.09	-1.41%	0.00196	0.00214	8.83%	.9798
8	115.80	115.13	-0.58%	0.00163	0.00207	26.75%	.9925
9	275.97	276.21	0.09%	0.02468	0.02465	-0.14%	.9116
10	283.32	283.45	0.05%	0.02151	0.02166	0.72%	.9957
11	301.40	301.76	0.12%	0.02327	0.02290	-1.60%	.9869
12	346.25	349.95	1.07%	0.00291	0.00358	23.33%	.9683
13	584.71	583.33	-0.24%	0.02119	0.02138	0.92%	.9963
14	635.16	634.96	-0.03%	0.02037	0.01897	-6.85%	.9955
-	NA	671.02	NA	NA	0.00505	NA	NA
15	688.92	690.42	0.22%	0.01515	0.01367	-9.73%	.9372
-	NA	721.79	NA	NA	0.00579	NA	NA
16	758.36	NA	NA	0.01131	NA	NA	NA
17	769.71	771.16	0.19%	0.01191	0.01203	1.09%	.9121

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