SPACE LAUNCH SYSTEM

Feasibility Study of SDAS Instrumentation's Ability to Identify Mobile Launcher (ML)/Crawler-Transporter (CT) Modes during Rollout Operations

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Purpose and Agenda

Objective:

- Present an analytical approach utilized to gain better understanding of test parameters that could help or hinder target mode extraction prior to performing the actual test.

Analysis Specific Goals:

- Determine the target modes
- Decide if layout of accelerometers (i.e. position and orientation) is sufficient to identify the target modes.
- Apply Generic Rollout Forcing Functions (GRFF's)[1] and vary parameters.

Content:

1. Hardware Configuration
2. Analytical Approach
3. Target Modes
4. Instrumentation Pretest Review (Position and Orientation)
5. Data Quality Checks
6. Parameter Sensitivity Results
7. Summary

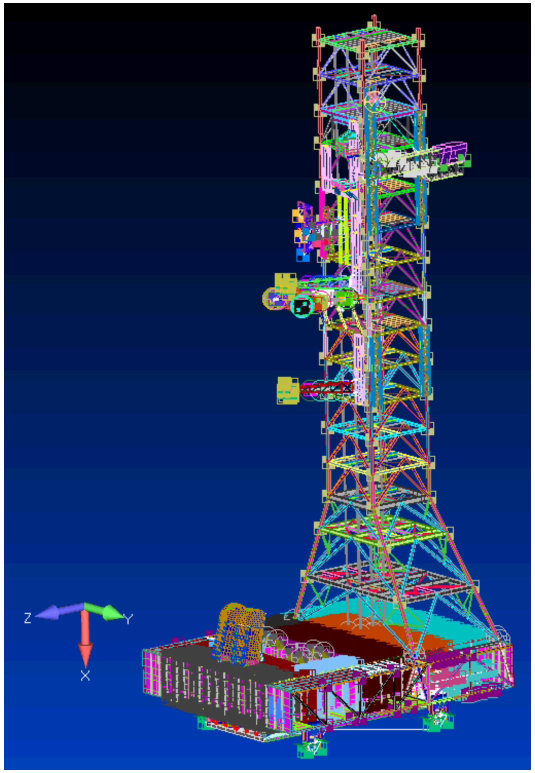
Assumptions and Clarifications:

- FEM is not test correlated and the forcing functions are not confirmed.
- This analysis is simulating an Experimental Modal Analysis (EMA) Multi-Input Multi-Output (MIMO) modal extraction approach. Another valid approach would be Operational Modal Analysis (OMA).

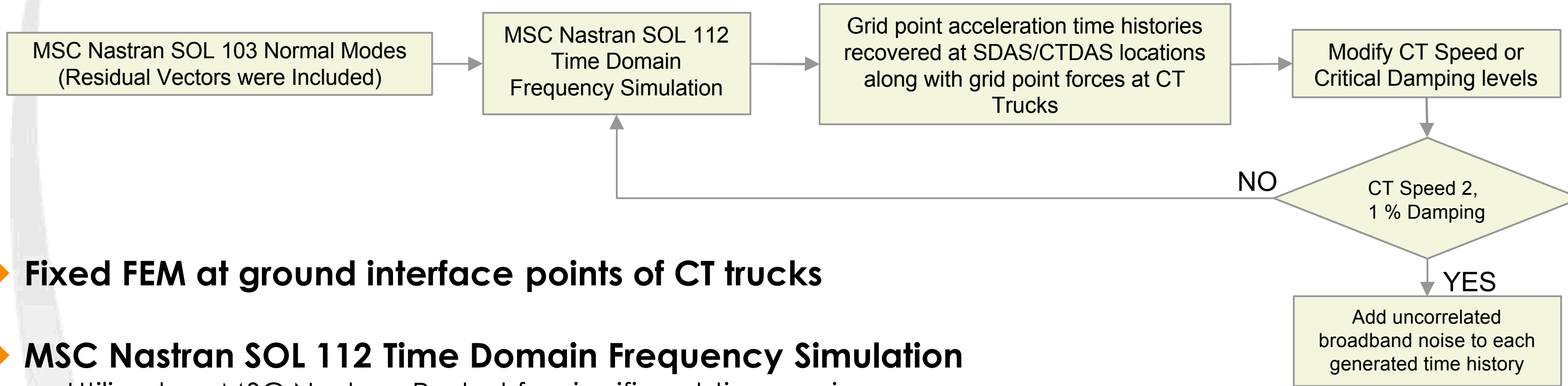
[1] "Development of Generic Crawler/Transporter Rollout Forcing Functions for Coupled System Dynamics Analysis," ESD 20038, July 31, 2018.

ML/CT FEM Configuration

- **The Space Launch System (SLS) and its Mobile Launcher (ML) will be transported to the launch pad via the Crawler-Transporter (CT) system**
- **Critical to understand the dynamics of the ML/CT under realistic loading conditions**
  - Rollout loads impart structural loads on the launch vehicle that present a concern with respect to fatigue.
- **Desire to collect accelerometer data during rollout of ML/CT <u>without</u> SLS to assist engineers with FEM correlation using the realistic forces caused by CT truck excitation**



Analytical Approach – Nastran Steps (1 of 2)

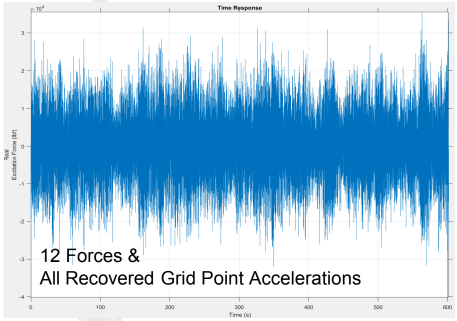


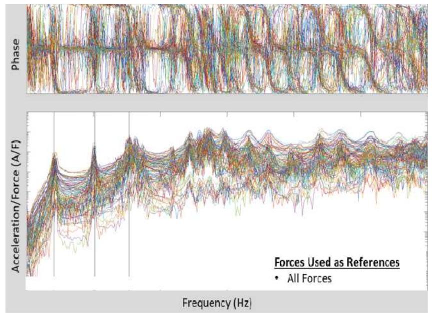
- **Fixed FEM at ground interface points of CT trucks**
- **MSC Nastran SOL 112 Time Domain Frequency Simulation**
  - Utilized an MSC Nastran Restart for significant time savings
- **Simulation Output = Time domain accelerations and forces**
  - Output format was a punch file due to ability to easily import into IMAT.
- **12 Generic Rollout Forcing Functions (GRFF's)**
  - 3 different orthogonal translational forces for each truck
  - Speed Dependent
- **Five Different CT Speed Settings**
- **Damping values (1%, 3%, and 5%)**
- **Sensor broadband noise Levels (30 µgrms, 100 µgrms, and 200 µgrms)**

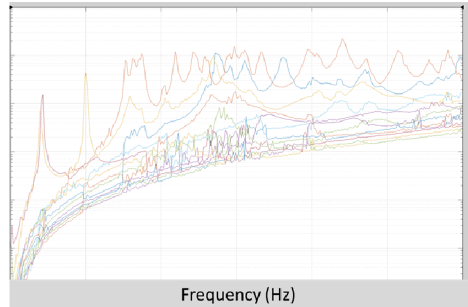
Parameter Variation Summary					
	CT Speed				
Damping	**1**	**2**	**3**	**4**	**5**
1%	X	X	X	X	X
3%	X	X	X	X	X
5%	X	X	X	X	X
	CT Speed				
Broadband Noise (1% Damping)	**1**	**2**	**3**	**4**	**5**
30 ugrms		X			
100 ugrms		X			
200 ugrms		X			

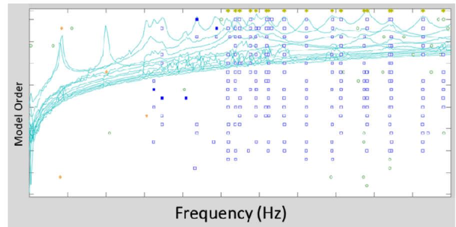
Analytical Approach – IMAT Steps (2 of 2)

Time Domain Generated Data (Nastran) → Frequency Domain Created → Complex Mode Indicator (IMAT) → Pole Selection (IMAT)









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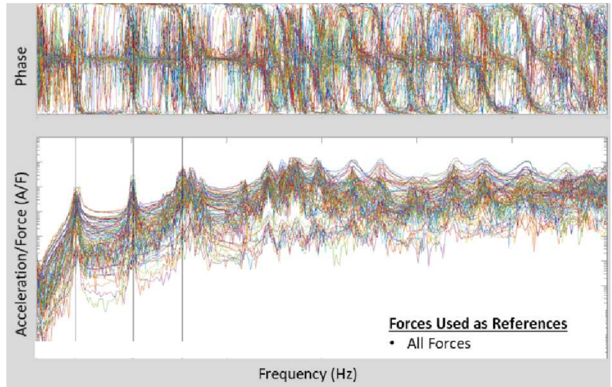

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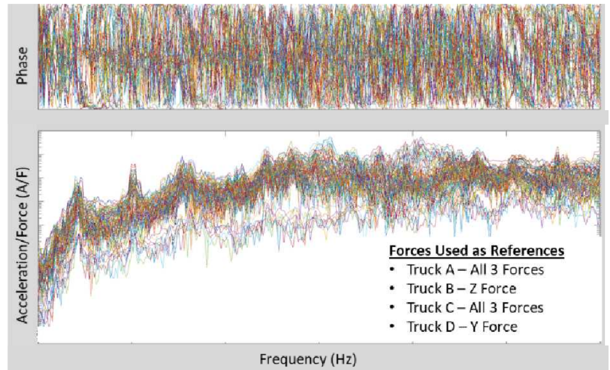


- **ATA Engineering's Interface between MATLAB, Analysis, and Test (IMAT) Signal Processing Toolbox utilized for FRFs**
  - Trade studies of using varying amounts of the 12 forces were completed, but using all 12 gave best results. (Figure A vs B)
- **IMAT's AFPOLY toolbox was used to generate complex mode indicator functions and modal parameters were extracted.**
- **In an effort to be as close to a real test environment as possible, poles were <u>NOT</u> manually selected**
  - Exception: First three modes
  - Observation: Too conservative

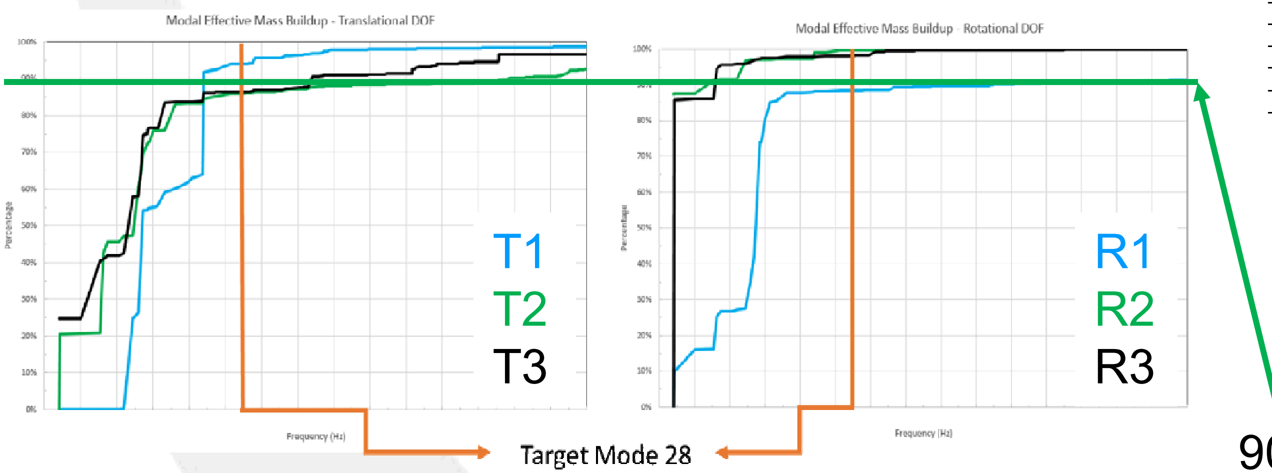
Target Mode Identification

- **Normal modes computed using McNeil Schwindler (MSC) Nastran**
- **~400 Modes exist in double the frequency range of interest.**
  - Only had to run once due to utilization of restart
- **Goal: 90% Modal Effective Mass Factions (MEFF)**
- **28 Target Modes**
  - Not all these had high effective mass

Order	T1	T2	T3	R1	R2	R3
1	0.0%	0.0%	24.6%	0.0%	87.4%	0.0%
2	0.0%	20.5%	0.0%	9.8%	0.0%	85.8%
3	0.0%	0.1%	0.0%	6.2%	0.0%	0.2%
4	0.0%	0.3%	15.9%	0.1%	3.8%	0.1%
5	0.1%	21.6%	0.4%	9.1%	0.1%	8.4%
6	0.0%	3.1%	0.9%	1.5%	0.2%	1.0%
7	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%
8	0.1%	1.6%	0.5%	0.4%	0.1%	0.3%
9	24.5%	0.2%	15.4%	0.3%	5.0%	0.0%
10	1.5%	13.0%	0.3%	7.8%	0.3%	0.5%
11	19.5%	5.1%	9.2%	6.8%	0.0%	0.5%
12	8.5%	4.0%	7.3%	6.6%	0.0%	0.2%
13	0.0%	2.7%	0.3%	22.9%	0.0%	0.3%
14	0.4%	0.2%	1.2%	2.3%	0.0%	0.0%
15	0.2%	0.4%	0.4%	0.1%	0.1%	0.0%
16	0.1%	3.0%	0.0%	6.7%	0.0%	0.1%
17	0.2%	0.0%	0.1%	2.4%	0.0%	0.0%
18	0.6%	0.0%	0.0%	2.0%	0.0%	0.0%
19	3.3%	0.1%	6.9%	0.4%	0.0%	0.0%
20	1.2%	7.2%	0.1%	2.2%	0.0%	0.4%
21	1.4%	0.0%	0.1%	0.0%	0.0%	0.0%
22	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%
23	1.0%	0.0%	0.2%	0.3%	0.1%	0.0%
24	27.9%	1.3%	2.2%	0.1%	1.6%	0.0%
25	0.6%	0.6%	0.0%	0.0%	0.0%	0.2%
26	0.0%	0.0%	0.2%	0.0%	0.1%	0.0%
27	1.7%	0.8%	0.0%	0.2%	0.6%	0.0%
28	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total Mass Percentage	94.1%	86.0%	86.4%	88.4%	99.7%	98.1%

>5% MEFF

1%<X<5% MEFF



Instrumentation Pretest Review

- **Instrumentation is already installed on both the ML and CT to record data during rollout**
  - Sensor Data Acquisition System (SDAS) and CT Data Acquisition System (CTDAS)
- **Test Analysis Model (TAM) modes are computed from the analytical FEM having undergone a Guyan (i.e. static) reduction.**
- **The cross-orthogonality between the (TAM) modes and the FEM modes was used to evaluate the ability of the instrumentation to identify a set of target modes.**
- **Past experience has shown that the frequency comparison is usually the most important indicator.**
  - Mode pairs on larger test articles are often harder to differentiate.
  - Probably good enough to identify target modes up to Mode 23.

FEM/TAM Cross Orthogonality Table

FEM Shapes

TAM Shapes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	% Frequency Difference
1	-1.00																									-0.12			0.15
2		1.00																							0.15				0.19
3			1.00																										0.75
4				1.00																						0.10			1.22
5					-1.00																								1.40
6						1.00																							1.12
7							-0.97	0.30																					3.53
8							0.23	0.95																					4.28
9									0.99		0.12																		2.62
10										0.99																			2.42
11											0.94	-0.32				0.13													2.65
12											-0.30	-0.91	-0.14	0.20															2.39
13													-0.74	-0.67															0.46
14												0.21	-0.65	0.71															0.58
15															1.00														4.07
16																0.95	-0.22	0.19											2.28
17																-0.23	-0.93	0.27											1.76
18																	-0.28	-0.94											2.97
19																			1.00										3.22
20																				1.00									4.44
21																					1.00								1.69
22																						1.00							3.47
23																							-0.37	0.93			-0.15		6.20
24																							0.92	0.35					2.93
25																									-0.39	-0.89			10.08
26																									0.89	-0.38	0.12		9.11
27																											0.96	-0.11	11.08
28																												0.98	11.95

Guidelines

- Diagonal > 0.9
- Off-Diagonal < 0.1
- Frequency Difference < 5%

Data Quality Checks – Summary (1 of 5)

- **Several different data quality checks were made along the analytical process to ensure nothing was missed or incorrectly set.**

1. Check the EMA MIMO analytical approach using perfect broadband white noise signals to verify all the target modes can be extracted

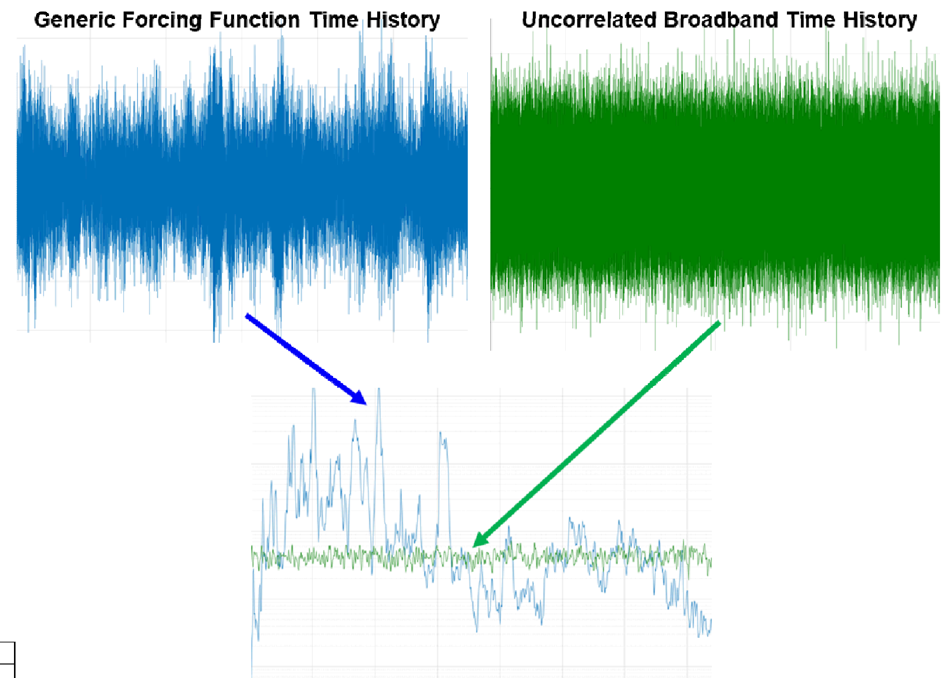
2. Correlation between the forcing functions checked to see if the EMA MIMO approach to processing the data is valid

3. Compare FRFs generated using MSC Nastran Solution 112 "Dynamic Time Domain Simulation" and FRFs generated from MSC NASTRAN Solution 111 "Dynamic Frequency Domain Simulation" to ensure they match

4. Verify that the data being generated by NASTRAN using the generated forcing functions passes standard data quality checks usually performed on test data

Data Quality Checks – Simple Input (2 of 5)

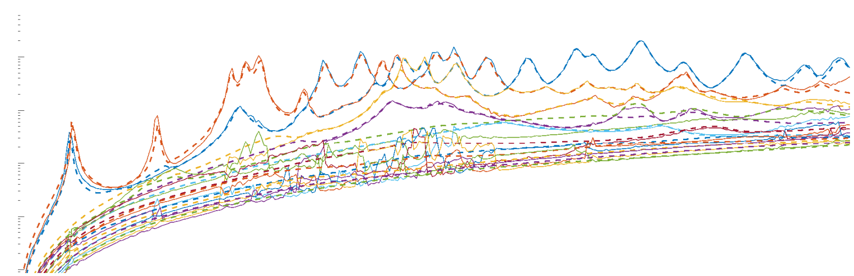
- Utilized Matlab to generate 12 uncorrelated broadband time force time histories
- Using the IMAT function "writefemap" to generate Nastran force function data tables
- Checked correlation between these uncorrelated forces
- Ran through analytical process and all target modes easily extracted



Auto-Spectrum Comparison

1.000	0.004	0.001	0.004	0.002	0.003	0.000	0.000	0.001	0.001	0.001	0.000
0.004	1.000	0.001	0.005	0.004	0.002	0.003	0.003	0.002	0.003	0.002	0.001
0.001	0.001	1.000	0.004	0.001	0.002	0.001	0.001	0.002	0.002	0.006	0.004
0.004	0.005	0.004	1.000	0.002	0.001	0.002	0.002	0.001	0.001	0.000	0.001
0.002	0.004	0.001	0.002	1.000	0.003	0.001	0.000	0.000	0.003	0.002	0.004
0.003	0.002	0.002	0.001	0.003	1.000	0.003	0.002	0.002	0.002	0.001	0.001
0.000	0.003	0.001	0.002	0.001	0.003	1.000	0.003	0.000	0.003	0.000	0.002
0.000	0.003	0.001	0.002	0.000	0.002	0.003	1.000	0.001	0.003	0.003	0.003
0.001	0.002	0.002	0.001	0.000	0.002	0.000	0.001	1.000	0.001	0.001	0.002
0.001	0.003	0.002	0.001	0.003	0.002	0.003	0.003	0.001	1.000	0.000	0.002
0.001	0.002	0.006	0.000	0.002	0.001	0.000	0.003	0.001	0.000	1.000	0.004
0.000	0.001	0.004	0.001	0.004	0.001	0.002	0.003	0.002	0.002	0.004	1.000

Perfectly Uncorrelated Forces



CMIF Fit using Uncorrelated Forces

- **EMA requires that the forcing functions are uncorrelated to each other, which was already known not to be fully true.**
  - Harmonics such as shoe/roller interaction
  - Trucks are attached to each other via the CT chassis.
- **CT speeds 1, 2, and 5 have the least correlation and appear to be best suited for an attempt using an EMA MIMO approach for extracting modal parameters.**
- **Assuming the GRFF's closely resemble the actual forcing functions, this analysis shows there are speeds of the CT that will have more correlation in the forcing functions than others.**

Least Correlated: CT Speed 1

CT Speed 1		Truck A			Truck B			Truck C			Truck D		
		X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
Truck A	X	1.00	0.00	0.01	0.20	0.07	0.01	0.01	0.03	0.05	0.09	0.02	0.12
	Y	0.00	1.00	0.04	0.08	0.29	0.07	0.02	0.11	0.05	0.01	0.14	0.08
	Z	0.01	0.04	1.00	0.05	0.04	0.13	0.00	0.05	0.13	0.03	0.08	0.17
Truck B	X	0.20	0.08	0.05	1.00	0.07	0.14	0.14	0.01	0.05	0.08	0.00	0.09
	Y	0.07	0.29	0.04	0.07	1.00	0.04	0.06	0.10	0.04	0.05	0.16	0.09
	Z	0.01	0.07	0.13	0.14	0.04	1.00	0.00	0.04	0.34	0.03	0.03	0.09
Truck C	X	0.01	0.02	0.00	0.14	0.06	0.00	1.00	0.04	0.08	0.14	0.10	0.02
	Y	0.03	0.11	0.05	0.01	0.10	0.04	0.04	1.00	0.04	0.01	0.02	0.05
	Z	0.05	0.05	0.13	0.05	0.04	0.34	0.08	0.04	1.00	0.01	0.03	0.12
Truck D	X	0.09	0.01	0.03	0.08	0.05	0.03	0.14	0.01	0.01	1.00	0.03	0.09
	Y	0.02	0.14	0.08	0.00	0.16	0.03	0.10	0.02	0.03	0.03	1.00	0.13
	Z	0.12	0.08	0.17	0.09	0.09	0.09	0.02	0.05	0.12	0.09	0.13	1.00

Most Correlated: CT Speed 3

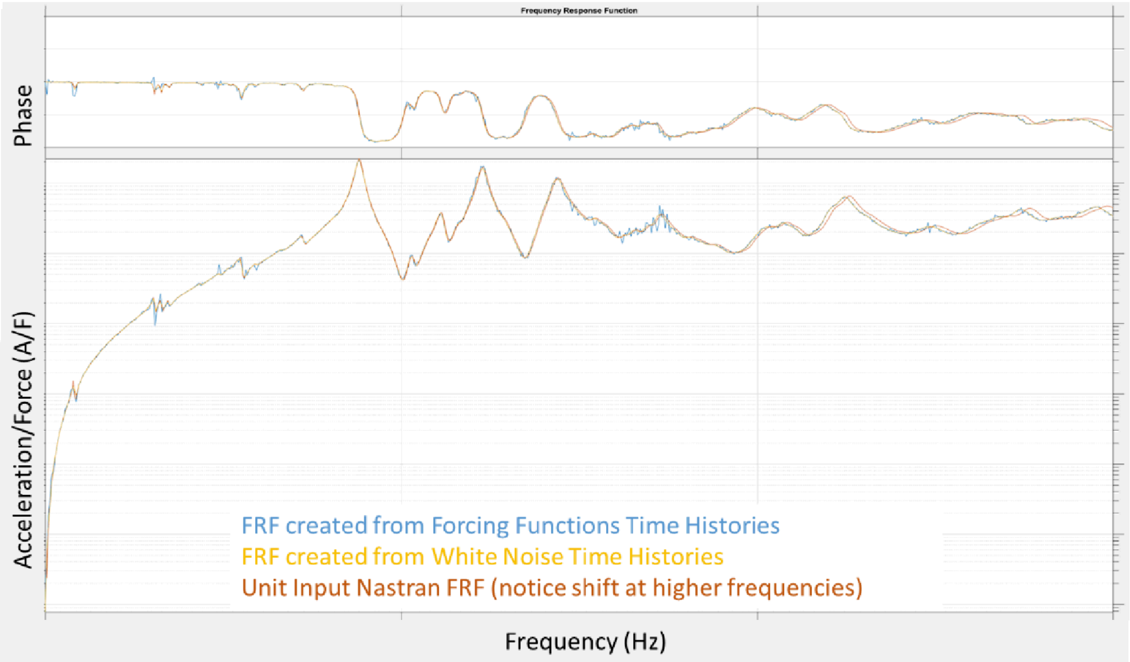
CT Speed 3		Truck A			Truck B			Truck C			Truck D		
		X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
Truck A	X	1.00	0.03	0.07	0.13	0.00	0.03	0.05	0.12	0.04	0.03	0.03	0.08
	Y	0.03	1.00	0.13	0.08	0.47	0.05	0.06	0.32	0.09	0.09	0.38	0.00
	Z	0.07	0.13	1.00	0.01	0.13	0.04	0.00	0.12	0.06	0.07	0.13	0.35
Truck B	X	0.13	0.08	0.01	1.00	0.12	0.18	0.08	0.05	0.01	0.06	0.06	0.13
	Y	0.00	0.47	0.13	0.12	1.00	0.09	0.04	0.30	0.07	0.00	0.37	0.11
	Z	0.03	0.05	0.04	0.18	0.09	1.00	0.02	0.03	0.40	0.09	0.08	0.02
Truck C	X	0.05	0.06	0.00	0.08	0.04	0.02	1.00	0.12	0.20	0.01	0.09	0.05
	Y	0.12	0.32	0.12	0.05	0.30	0.03	0.12	1.00	0.08	0.07	0.36	0.02
	Z	0.04	0.09	0.06	0.01	0.07	0.40	0.20	0.08	1.00	0.01	0.08	0.06
Truck D	X	0.03	0.09	0.07	0.06	0.00	0.09	0.01	0.07	0.01	1.00	0.00	0.22
	Y	0.03	0.38	0.13	0.06	0.37	0.08	0.09	0.36	0.08	0.00	1.00	0.13
	Z	0.08	0.00	0.35	0.13	0.11	0.02	0.05	0.02	0.06	0.22	0.13	1.00

Red > 0.2 Grey < 0.2

Note: In statistical methods, weakly correlated ~0.3

Data Quality Checks – FRF Generation (4 of 5)

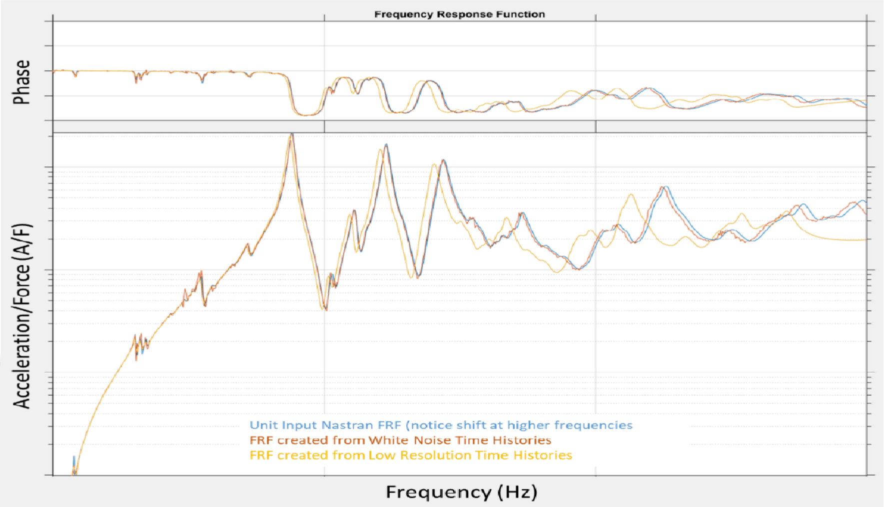
- **FRFs were generated using three different approaches with the expectation that they should all be identical to each other:**
  - FRF using Nastran Sol 112 and GRFFs as References
  - FRF using Nastran Sol 112 and Uncorrelated Forces
  - FRF using Nastran Sol 111 with Unit Input
- **The FRF generated by SOL 111 started to diverge from the other two as frequency increased.**
- **The following three potential sources of error were looked at:**
  - Round off error in the time domain data
  - Restarting the MSC NASTRAN decks
  - Differences in the residual vectors



Data Quality Checks – FRF Generation (5 of 5)

- **Round off error was investigated by lowering the resolution of the input forces**
  - Made frequency shift worse (Bottom Figure)
- **Restarts vs. No Restarts generated no difference**
- **Residual Vectors vs. No Residual Vectors only changed amplitude slightly**
- **Based on these checks, it is suspected that this frequency divergence is tied to the resolution of the time data.**
  - Large field format was already being utilized.

TAKEAWAY: This underscores the importance of ensuring the forcing function time domain resolution is set to a value that minimizes this difference as well as always performing sanity checks of analytical processes!!



Parameter Sensitivity – CT Speed (1 of 3)

- CT speed variations primarily impacted first three target modes.
- CT speed 5 appeared to give the best chance of extracting cleanly the first three target modes.
- Otherwise, it had an insignificant impact on the extraction.

FEM Shapes

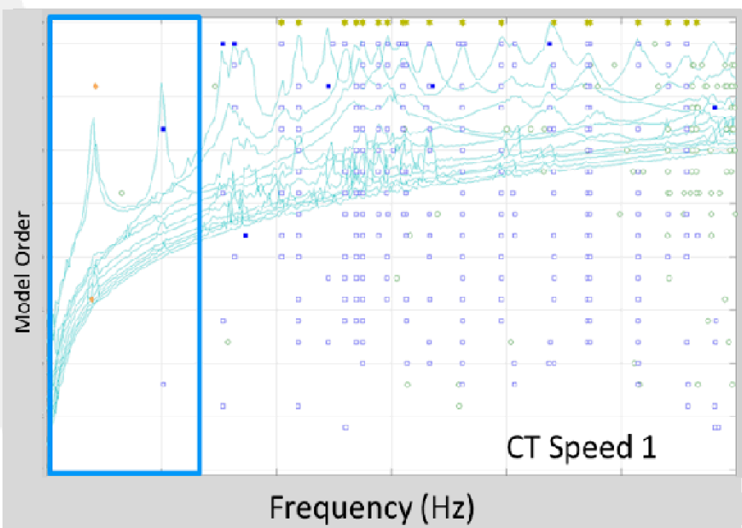
TAM Shapes	1	2	3	4	5	6
1	0.78					
2		0.48				
3				0.24	0.30	
4				1.00		
5					1.00	
6						0.98

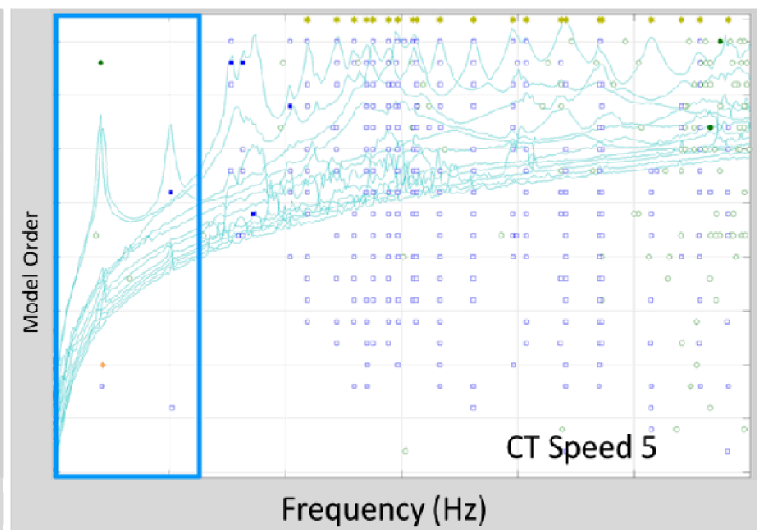
CT Speed 1

FEM Shapes

TAM Shapes	1	2	3	4	5	6
1	0.85					
2		0.94				
3			0.90			
4				1.00		
5					1.00	
6						1.00

CT Speed 5





Parameter Sensitivity – Damping (2 of 3)

- **Increasing damping behaved like expected, making the closely spaced modes much more difficult to extract.**
- **When the damping increased above 3%, the software's ability to select pole estimates was cut in half.**

FEM/Test Cross Orthogonality Table

FEM shapes

TAM Shapes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1		0.69																										
2		0.61																										
3			0.89																									
4				1.00																								
5					1.00																							
6						1.00																						
7							0.96																					
8								0.99																				
9									1.00																			
10										0.98																		
11											0.97																	
12												0.86	0.40	0.20														
13															0.99													
14													0.48			0.83												
15																0.23	0.96											
16																	0.20	0.96										
17																			1.00									
18																				1.00								
19																					1.00							
20																						1.00						
21																							0.96	0.30				
22																								1.00				
23																									0.99			
24																										1.00		
25																											1.00	
26																												0.97

1% Damping – CT Speed 2

FEM/Test Cross Orthogonality Table

FEM shapes

TAM Shapes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	0.87																											
2		0.51																										
3			0.73																									
4				1.00																								
5					1.00																							
6						0.99																						
7							0.89																					
8								0.98																				
9									1.00																			
10										0.98																		
11											0.97																	
12												0.86	0.40	0.20														
13															0.98													
14													0.49			0.83												
15																	0.95	0.23										
16																	0.27	0.95										
17																			1.00									
18																				1.00								
19																					1.00							
20																						1.00						
21																							1.00					
22																								1.00				
23																									1.00			
24																										1.00		
25																											1.00	

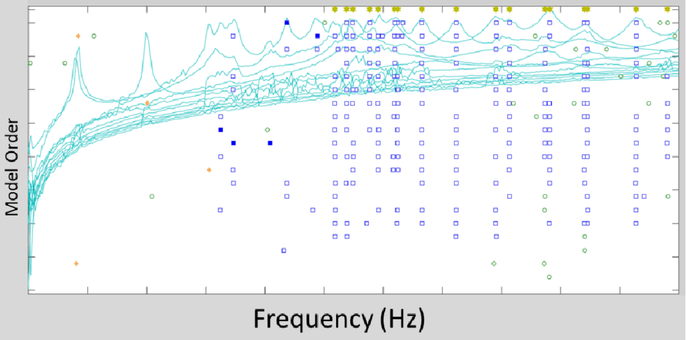
3% Damping – CT Speed 2

FEM/Test Cross Orthogonality Table

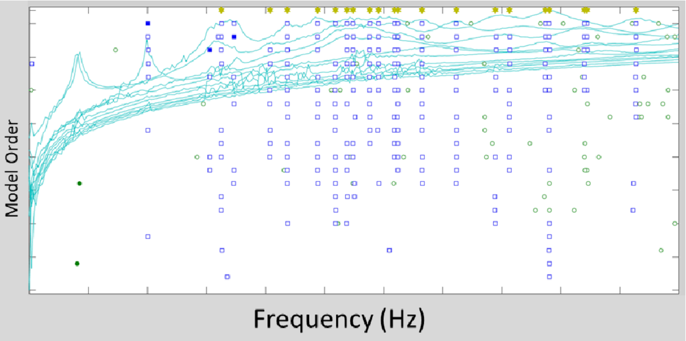
FEM shapes

TAM Shapes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	0.82																									0.23		
2		0.59																										
3			0.71																									
4					1.00																							
5						0.99																						
6							0.84																					
7								0.98																				
8									1.00																			
9										0.98																		
10															0.94	0.23												
11													0.50			0.82												
12																			1.00									
13																								1.00				

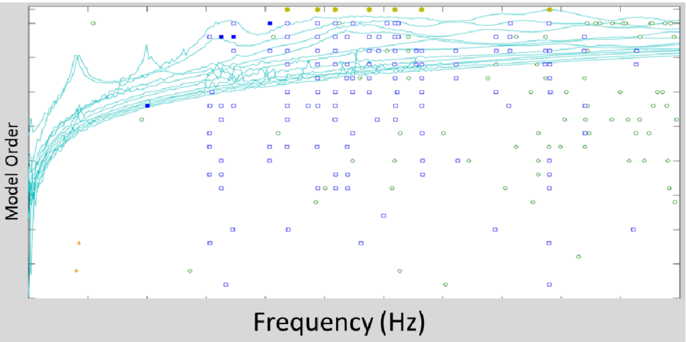
5% Damping – CT Speed 2



1% Damping – CT Speed 2



3% Damping – CT Speed 2



5% Damping – CT Speed 2

Parameter Sensitivity – Sensor Broadband Noise (3 of 3)

- **Created and added uncorrelated broadband noise to each generated time history before frequency processing.**
- **Sensor ambient noise levels much higher than 30 μgrms significantly hinder the ability to extract target modes.**

Orig	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1			1.00																									
2				1.00																								
3					1.00																							
4						1.00																						
5								0.99																				
6										0.98																		
7											0.96																	
8													0.47			0.83												
9																0.21	0.96											
10																		0.98										
11																			1.00									
12																				1.00								
13																					1.00							
14																						1.00						
15																								1.00				
16																									0.99			
17																											1.00	

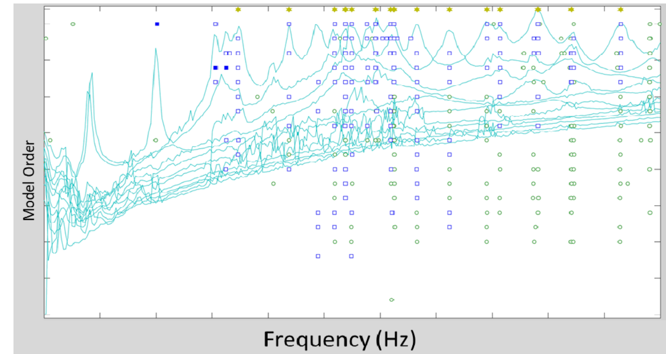
30 μgrms Ambient Noise, 1% Damping, CT Speed 2

Orig	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1				1.00																								
2					1.00																							
3						1.00																						
4								0.99																				
5									1.00																			
6										0.98																		
7															0.99													
8													0.47			0.84												
9																0.27	0.95											
10																		0.97										
11																			1.00									
12																				1.00								

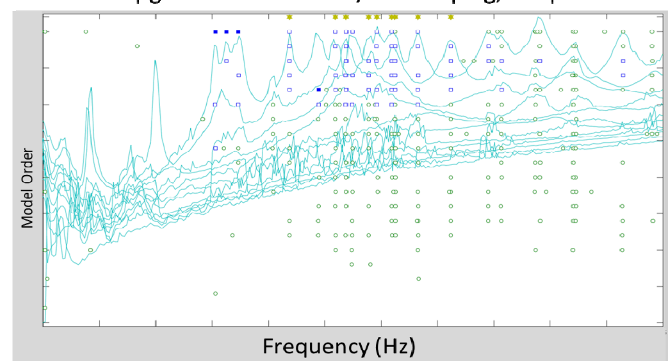
100 μgrms Ambient Noise, 1% Damping, CT Speec 2

Orig	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1				1.00																								
2					1.00																							
3						0.99																						
4								0.99																				
5									1.00																			
6										0.98																		
7											0.96																	
8															0.99													
9													0.47			0.84												
10																0.26	0.95											
11																			1.00									
12																				1.00								

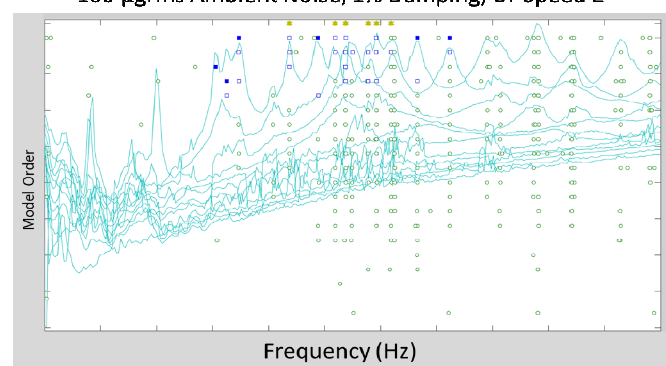
200 μgrms Ambient Noise, 1% Damping, CT Speed 2



30 μgrms Ambient Noise, 1% Damping, CT Speed 2



100 μgrms Ambient Noise, 1% Damping, CT Speed 2



200 μgrms Ambient Noise, 1% Damping, CT Speed 2

Summary

- All cases studied (5 speed settings, 3 different damping values, 3 noise levels) showed an ability to extract a subset of target modes, but specific values can improve or hinder the efforts
- This analytical approach can be utilized as a tool to help inform test engineers prior to a test which parameters might be problematic or helpful in their testing.
- It's important to make sure and take the appropriate steps to anchor any analysis in reality by using standard model checkouts and simplifying assumptions early on in the process.
- This work relies heavily upon the FEM behaving dynamically similar to the actual as-built hardware.
- Test data is always more challenging to extract modes from than the "perfect" analytical data.

Percentage of Target Modes Extracted					
	CT Speed				
Damping	1	2	3	4	5
1%	93%	93%	93%	89%	93%
3%	75%	89%	75%	79%	82%
5%	36%	46%	43%	36%	39%
	CT Speed				
Broadband Noise (1% Damping)	1	2	3	4	5
30 ugrms		61%			
100 ugrms		43%			
200 ugrms		43%			

> 75% Target Mode Extraction

> 50% Target Mode Extraction

< 50% Target Mode Extraction