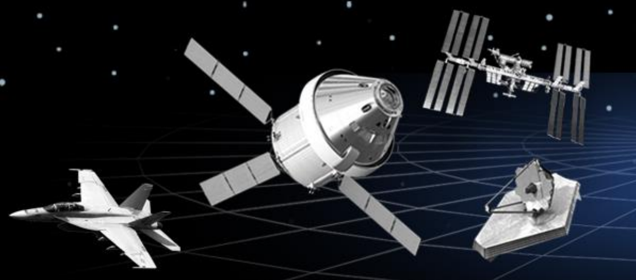
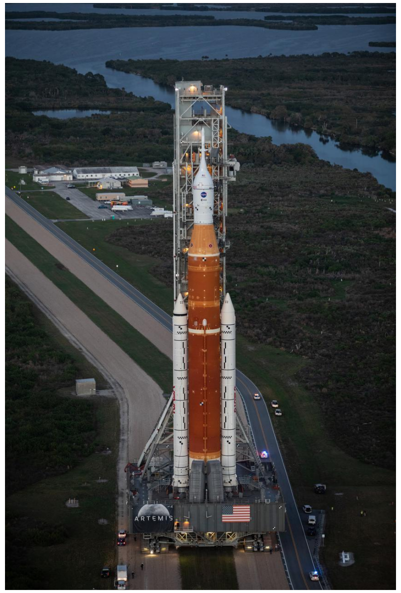


NESC Support of the Operational Modal Analysis (OMA) Of Artemis I Dynamic Rollout Test (DRT) & Wet Dress Rehearsal (WDR)



Dexter Johnson, NESC Lead, NASA LaRC

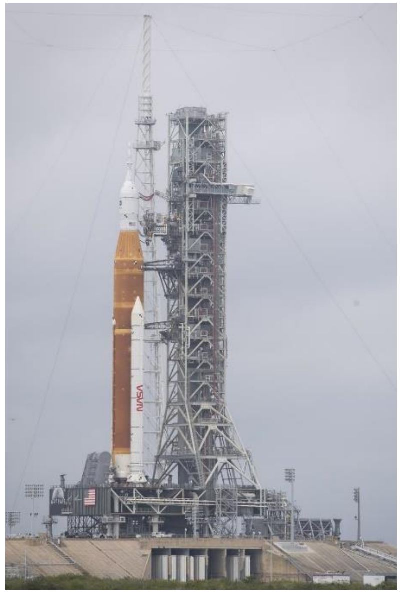
Teresa Kinney, Technical Lead, NASA KSC

James Akers, NASA GRC Structural Dynamics Branch

James Winkel & Alexander Chin, NASA LaRC Structural Dynamics Branch

Matt Allen: BYU Mechanical Engineering

May 10, 2023



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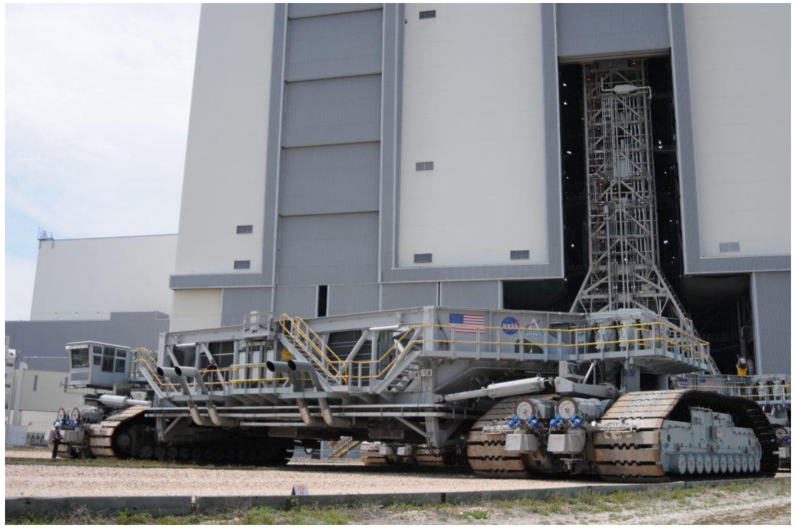
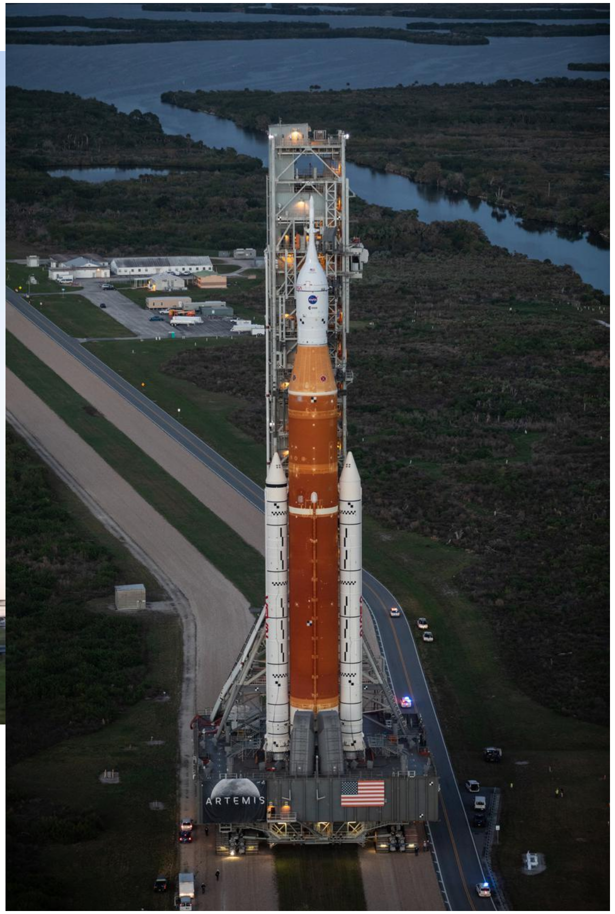
- Artemis I Dynamic Rollout Test (DRT) & Wet Dress Rehearsal (WDR) Background
- Crawler Transporter (CT) Truck Harmonics
- Applying Operational Modal Analysis (OMA) to DRT & WDR
- NESC Support of and Contributions to OMA Analysis of DRT & WDR
- OMA Best Practices
- Looking Forward

Artemis I Rollout from VAB to Launch Pad 39B

- The Artemis I Dynamic Rollout Test (DRT) recorded accelerations on Artemis I and the Mobile Launcher (ML), which were transported by the Crawler Transporter (CT), during its rollout from the Vehicle Assembly Building (VAB) to Launch Pad 39B and back.
- The dynamic characteristics extracted from DRT will be used to support Space Launch System (SLS) Integrated Modal Test (IMT) math model correlation efforts, Exploration Ground System (EGS) ML model verification and validation (V&V), and development of generic rollout forcing functions.



Artemis I Rollout from VAB to Launch Pad 39B (cont)

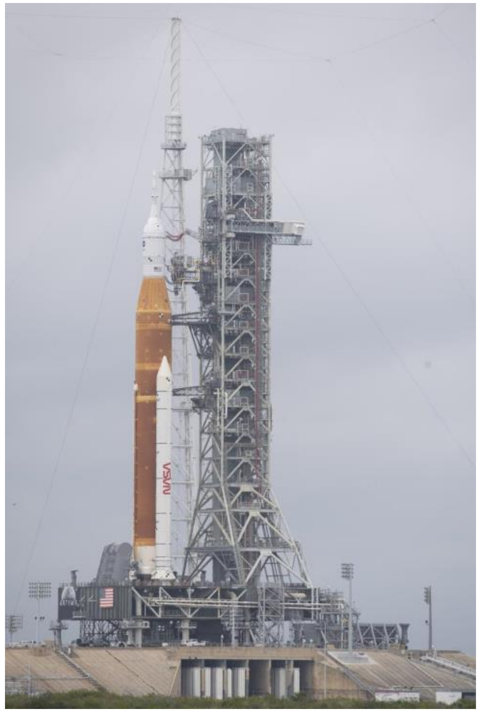


Crawlerway

- The Crawlerway is the specially prepared surface the CT drives on to transport the SLS from the VAB out to Launch Pad 39B and back that is 4.2 miles long.
- Takes the CT transporting the ML approximately 8 hours to cover this distance (~ avg speed 0.5 mph).

Artemis I At Launch Pad 39B WDR

- While Artemis 1 was at Launch Pad 39B, between the DRT rollout and rollback, the Wet Dress Rehearsal (WDR) was performed to demonstrate launch readiness, which was to include running through the planned launch countdown timeline and automated sequences all the way down inside of T-10 seconds before stopping.



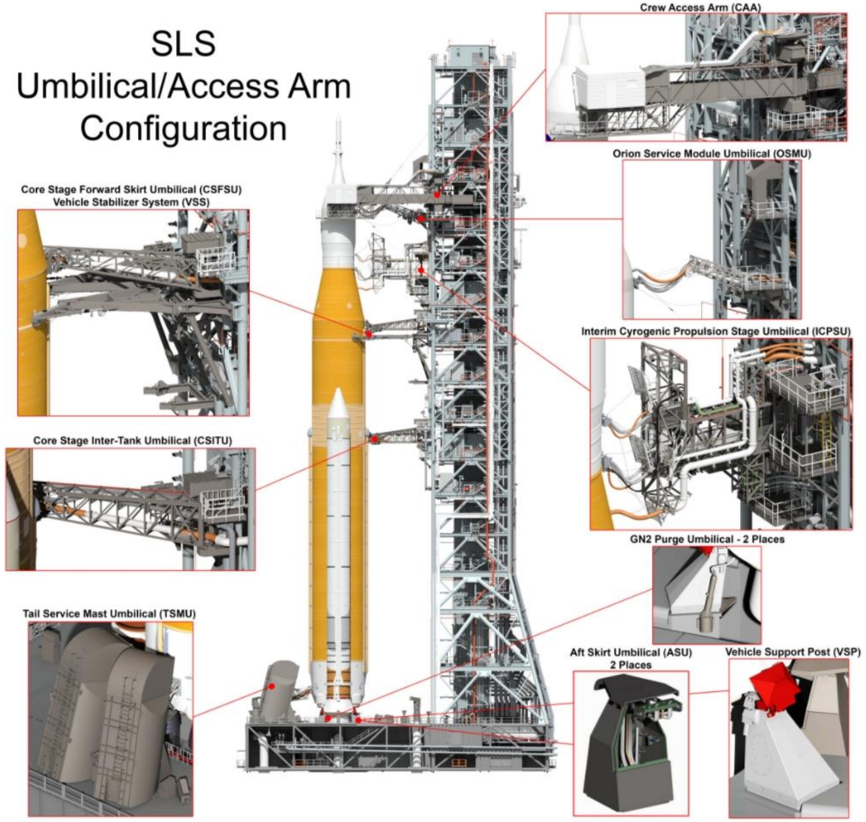
Artemis I At Launch Pad 39B WDR

Artemis I At Launch Pad 39B WDR (cont)

- ML supported on the six Vertical Support Posts at Launch Pad 39B with four Extensible Columns positioned near the perimeter of the flame hole providing additional vertical support to the ML Deck.
  - Extensible Columns provide additional vertical support to the ML Deck.

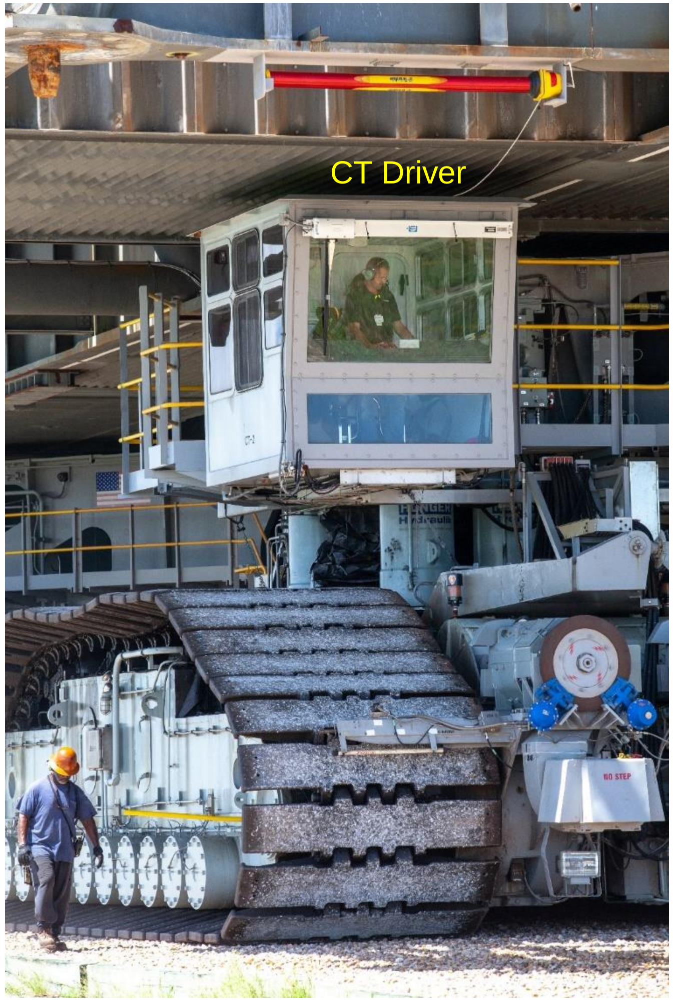
Mobile Launcher

- ML supported the integration of the Artemis 1 launch vehicle inside the VAB and served as the IMT modal test fixture.
- ML Deck supports the SLS at eight attachment points located at the bottom of its two boosters, which connect to the ML Vehicle Support Posts (VSP).
- ML Tower provides lateral support to the integrated SLS launch vehicle via the Vehicle Stabilization System (VSS) and supports the fuel, power, and data umbilicals running to SLS and MPCV.
- ML Tower also provides crew access to the MPCV Crew Module (CM) via the Crew Access Arm (CAA).



Crawler Transporter (CT)

ML on CT-2 Rollout Sept 10, 2019



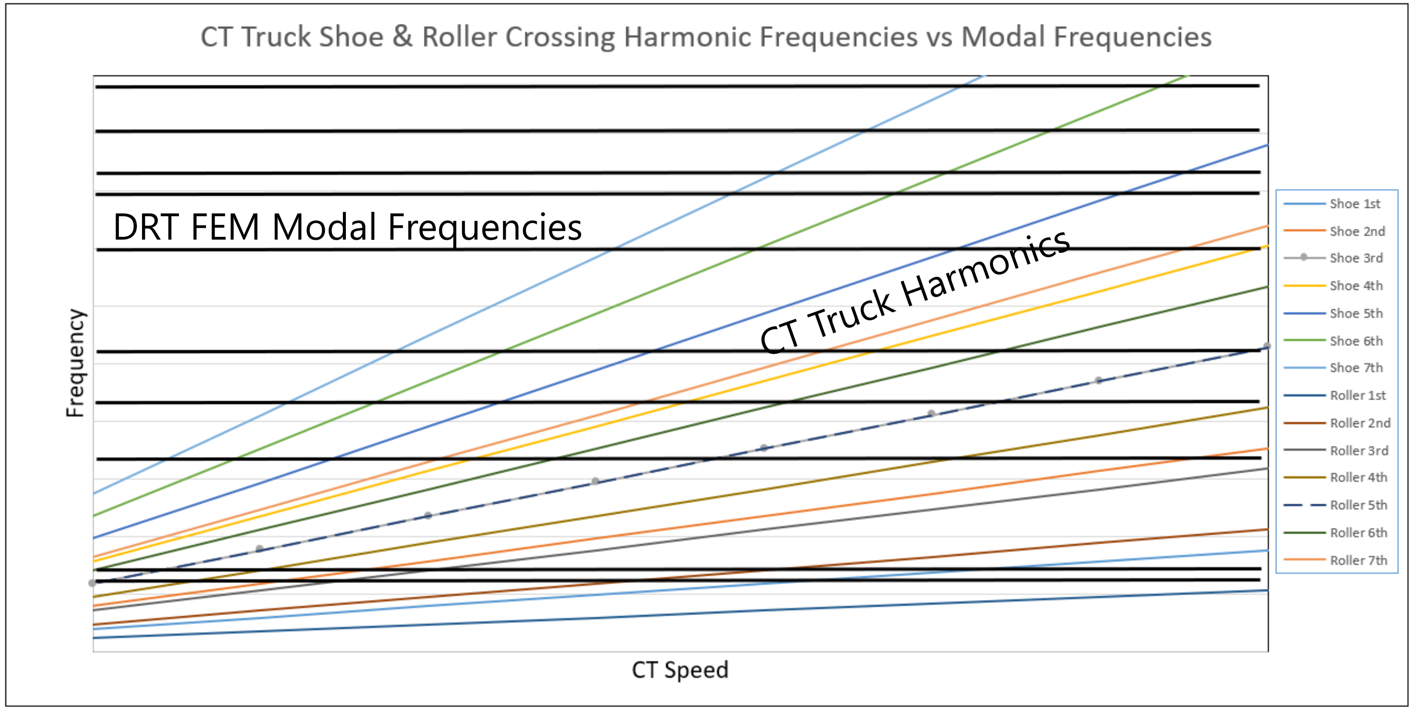
Crawler Transporter (cont)

- When the CT is moving, the primary low frequency excitation comes from the rollout ground forces generated by the CT.
  - Major contributors being the impulsive forces generated by the CT Truck track Shoes making initial contact with the ground and when they pass under the CT Truck rollers.

- When the CT is stopped or when the ML and Artemis I are at the launch pad, the primary excitation consists of wind loading on the ML Tower and the Artemis I integrated vehicle.

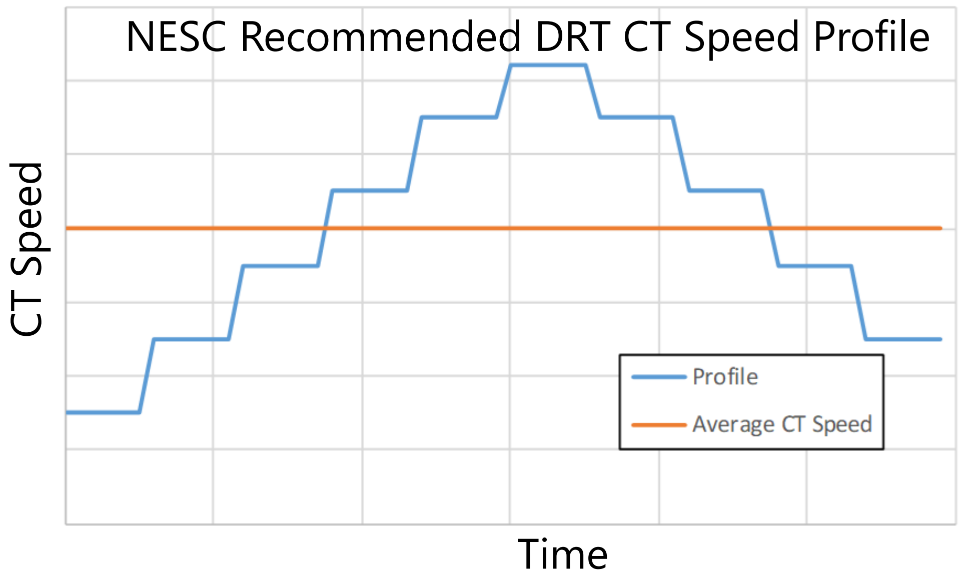
CT Truck Harmonics

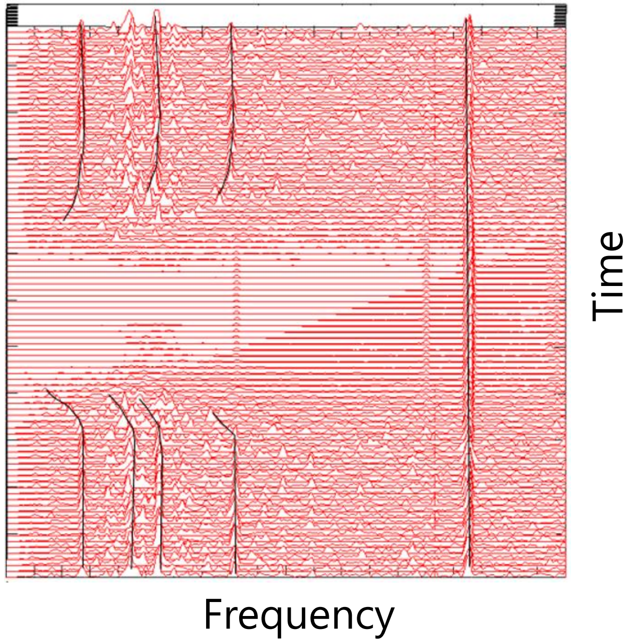
- A dominant CT harmonic excitation is produced by the impulsive forces generated by the initial slap of the track shoes making contact with the ground, referred to as the shoe slapping harmonics, which are a function of CT speed and shoe spacing.
- Another dominant CT harmonic excitation is produced by the track shoes passing underneath the 11 support rollers of each track, referred to as the roller crossing harmonics, which are also a function of the CT speed and the spacing between the support rollers.



CT Harmonics (cont)

- Amplitudes and frequencies of the CT Truck track shoes and roller crossing harmonics depend on CT speed.
  - Amplitudes increase with increasing speed.
  - CT speeds that vary from slow to fast (or vice versa) either continuously or in a stair step fashion does not replicate a constant amplitude sine sweep excitation.





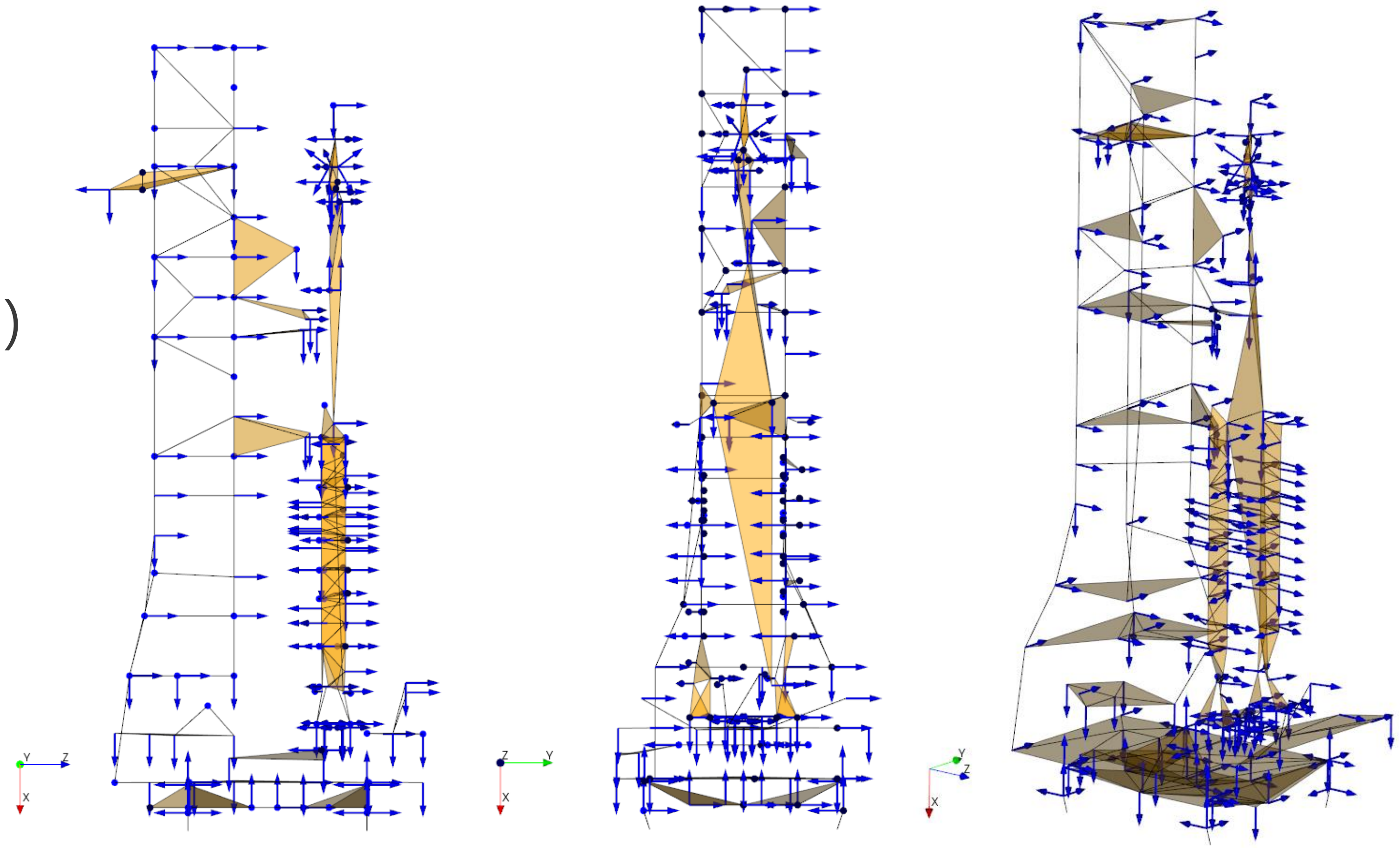
Challenges Applying OMA to DRT and WDR

- OMA relies upon four assumptions:
  - Structure: Linear time invariant.
  - Excitation: spatially distributed, uncorrelated, stationary, broadband (i.e., no harmonics or tones) excitation.
  - Data: sufficient duration (i.e., ~1,000 x T).

- DRT/WDR challenges all of these assumptions.
  - Structure: Nonlinear (e.g., Vehicle Stabilizing System and the umbilicals).
  - Excitation: when CT is moving the excitation is not spatially distributed (i.e., comes up from the CT), has a high density of harmonics, and not perfectly stationary.
  - Excitation: when the CT is stopped, wind acting on the ML and Artemis, which may be nonstationary, is the primary excitation. Possible vortex shedding.
  - Data duration: limited with respect to how closely spaced the modes are.

DRT Instrumentation & TDM

- ~ 350 low frequency highly sensitive accelerometers distributed over the CT, ML, and Artemis.
- Test Display Model (TDM) generated using trace lines and triangular plate elements to aid in depth perception.

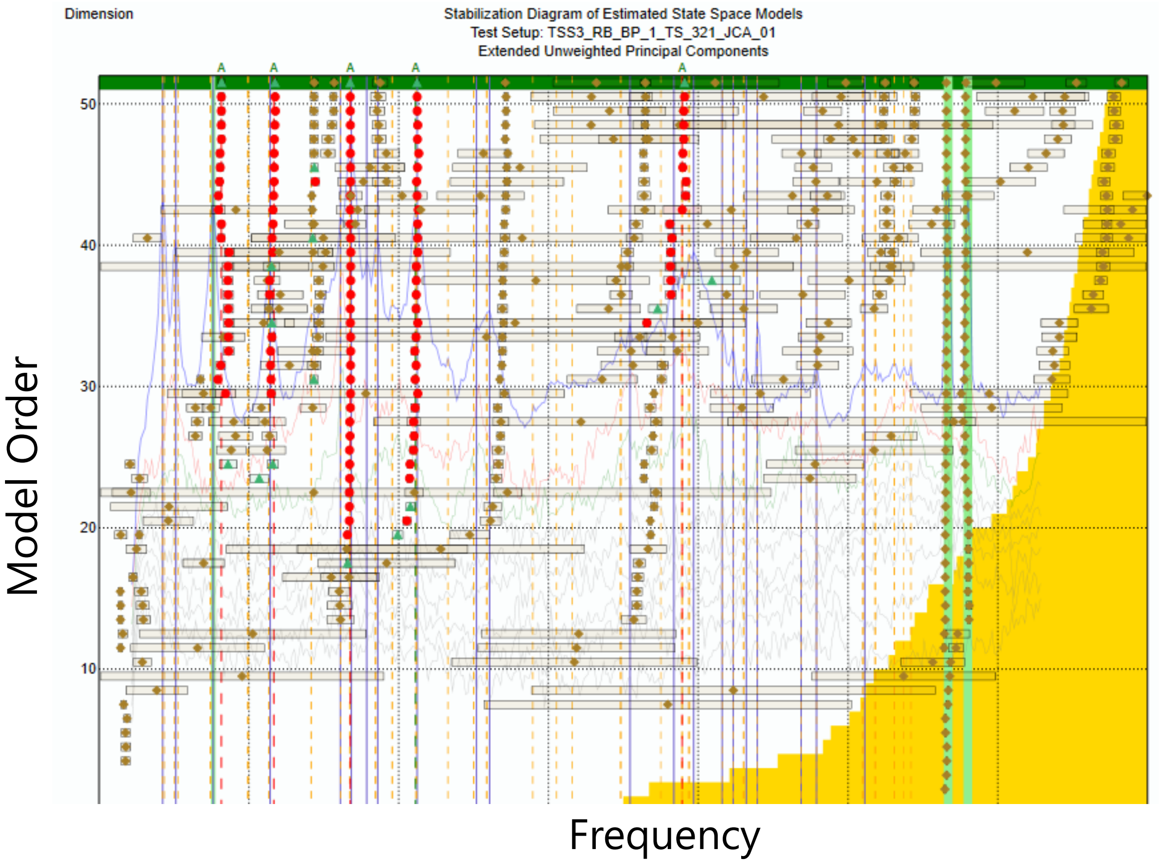


NESC Preparation For OMA Analysis of DRT & WDR

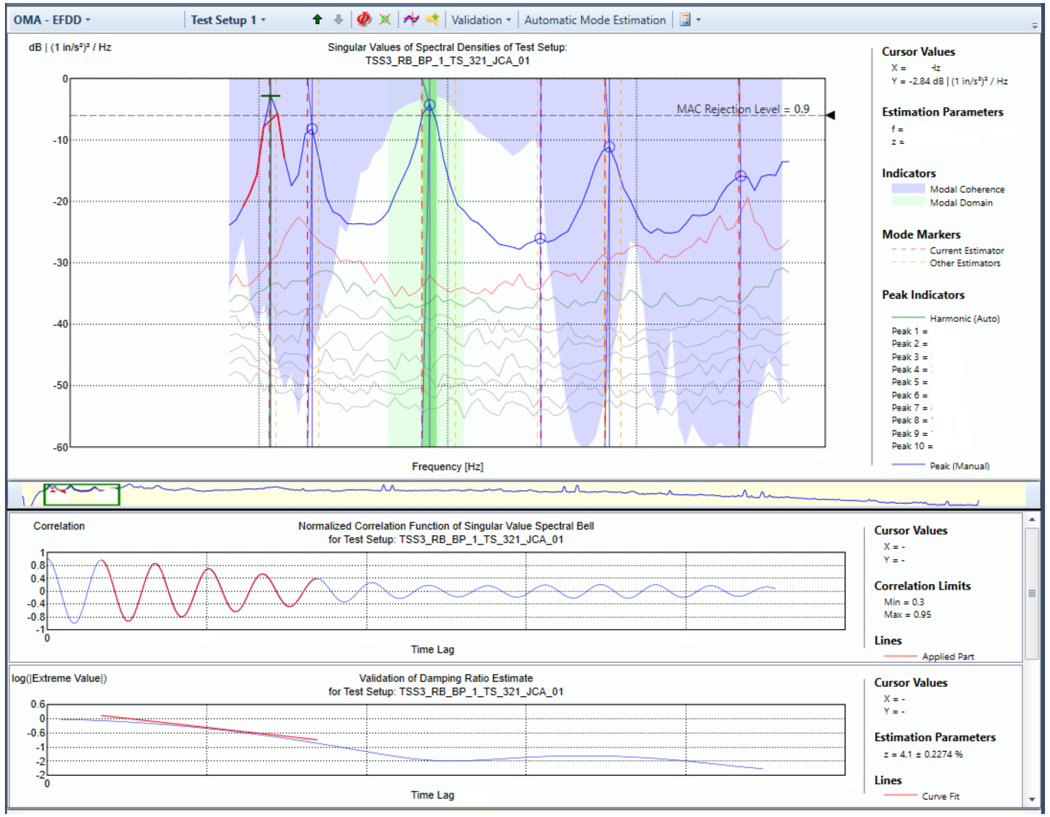
- Mentoring by Prof Carlos Ventura during on-site visit to NASA GRC in November 2019.
- NESC independent assessment (IA) of the OMA analysis of the ISVV-010 Rollout, which consisted of the CT transporting the ML from the VAB to Launch Pad 39B at the end of June 2019.
- NESC IA of the OMA analysis 2005 CT-1 and CT-1 + Mobile Launch Platform (MLP) data, 2017 CT-2 and CT-2 + MLP 2017 data.
- NESC IA of the ISVV-018 ML Only modal test pretest analysis and modal test.

OMA Modal Extraction

Time-domain Subspace Identification: Extended Unweighted Principal Component Method (SSI-UPCX)

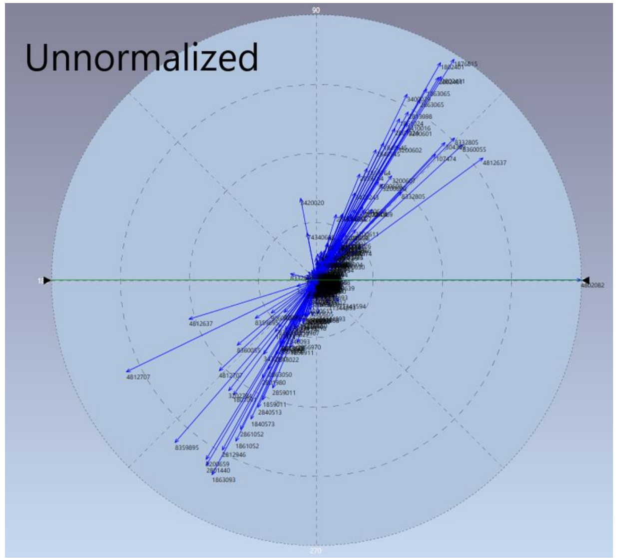


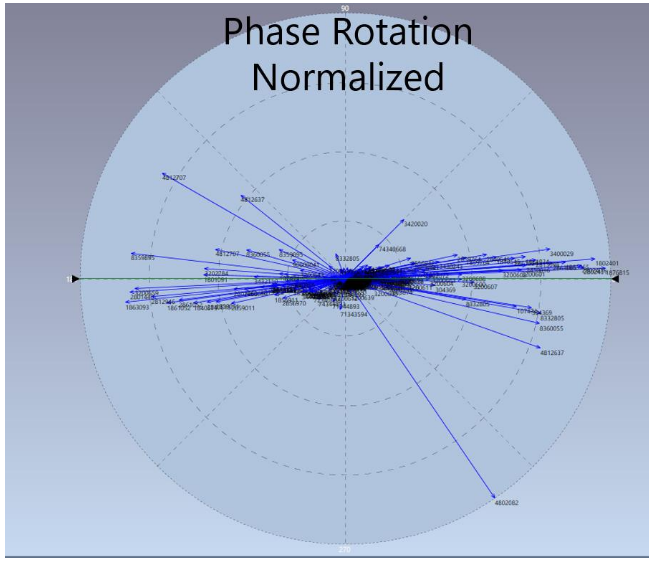
Frequency-domain: Extended Frequency Domain Decomposition Method (EFDD)

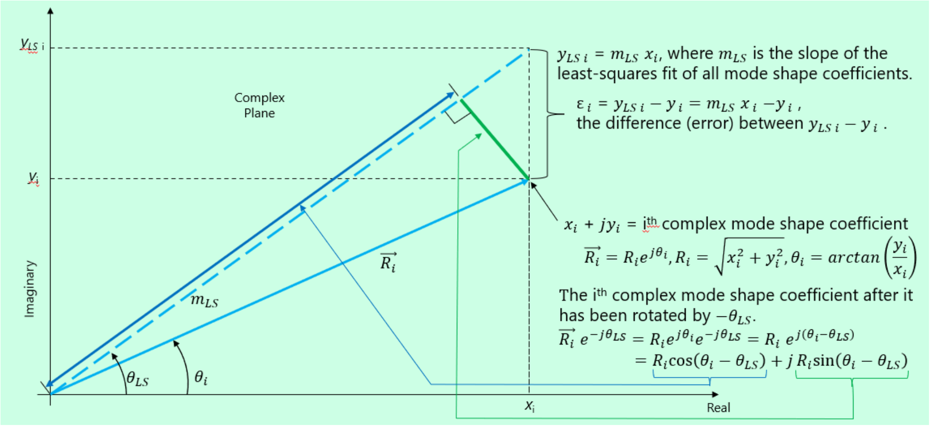


DRT & WDR Mode Shapes

- The DRT and WDR OMA identified mode shapes typically have some complexity (i.e., their mode shape coefficients do not lie on a line passing through the origin of the complex plane).
- Care needs to be followed on converting these complex modes shapes into real valued mode shapes.







$$(\lambda_i + \lambda_k)\psi_k^T M \psi_i + \psi_k^T C_D \psi_i = 0; \text{ i,k} = 1,\ldots, \text{n}$$

$$(\lambda_i \lambda_k)\psi_k^T M \psi_i - \psi_k^T K \psi_i = 0; \textbf{ i,k} = \textbf{1,...,}\text{n}$$

DRT Rollback CT Stopped Modes

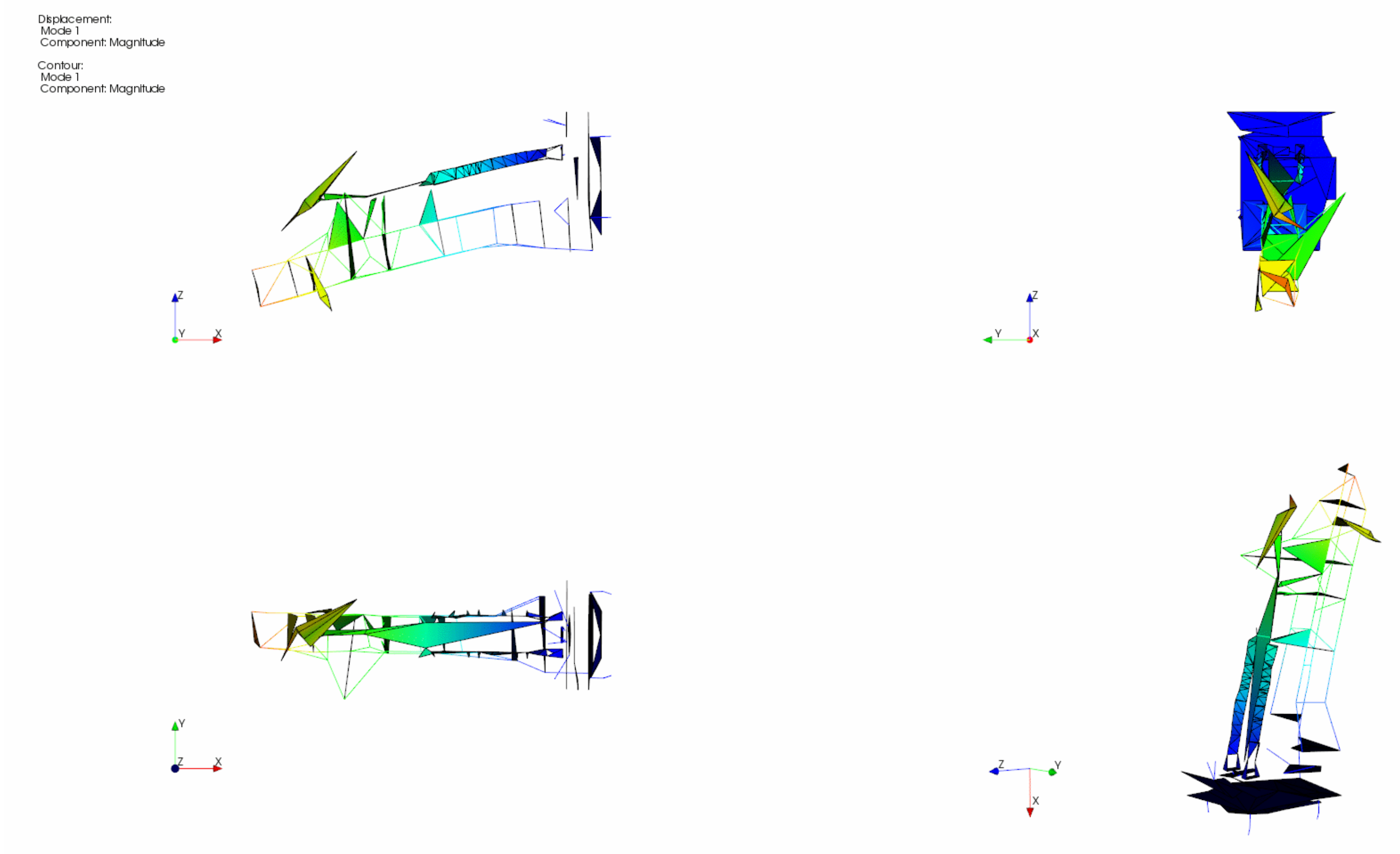
(green)	= High Confidence Mode (i.e. identified by SSI-UPCX, CDFF, and EFDD methods).	5
(blue)	= Medium Confidence Mode (i.e. identified by both CFDD and EFDD methods).	13
(yellow)	= Low Confidence Mode (i.e. only identified by CFDD, EFDD, or SSI-UPCX method).	5
(pink)	= Very Low Confidence Mode (i.e. only identified by FDD method).	9
		32

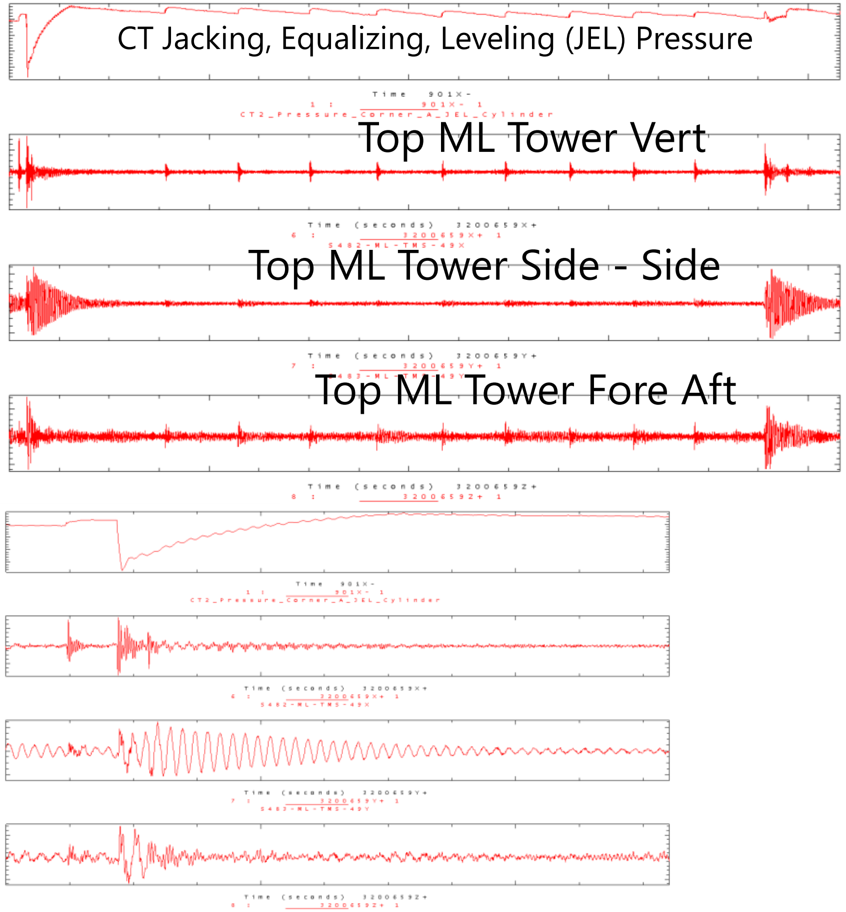
Preliminary Final Mode Set

Mode #	Method	Normalized Freq	Mode Shape Description	SSI-UPCX Freq (Hz)	CFDD Freq (Hz)	EFDD Freq (Hz)	FDD Freq (Hz)
1	EFDD	1.00	ML Deck Bending, ML Tower & SLS 1st Lateral Bending Z-Axis.	NF	0.99	1.00	NF
2	EFDD	1.19	ML Deck Rotation About Z-Axis, ML Tower & SLS 1st Lateral Bending Y-Axis.	NF	1.19	1.19	NF
3	CFDD	1.76	ML Tower & SLS 1st Lateral Bending Y-Axis Out-of-Phase, ML Tower & SLS 1st Torsion In-Phase.	1.93	1.76	1.77	NF
4	EFDD	2.36	ML Deck Rotation About Z-Axis, SLS 1st Lateral Bending Y-Axis, ML Tower & SLS 1st Lateral Bending Y-Axis In-Phase, ML Tower & SLS 1st Torsion In-Phase.	NF	2.35	2.36	NF
5	EFDD	2.68	ML Tower & SLS 1st Lateral Bending Z-Axis In-Phase, CSITU Y-AxisTranslation.	2.77	2.68	2.68	NF
6	EFDD	3.36	ML Tower & SLS 1st Torsion Out-of-Phase, Boosters 1st Lateral Bending Z-Axis.	NF	3.35	3.36	NF
7	FDD	3.82	ML Tower 1st Torsion & SLS 1st Lateral Bending Y-Axis In-Phase.	NF	NF	NF	1.61
8	EFDD	3.97	ML Tower 1st Torsion & SLS 1st Lateral Bending Z-Axis Out-of-Phase.	3.97	3.96	3.97	NF
9	EFDD	4.38	ML Tower 1st Torsion & SLS 1st Lateral Bending Y-Axis Out-of-Phase.	NF	4.37	4.38	NF
10	EFDD	4.64	ML Deck Rotating About Y & Z Axes, ML Tower 1st Torsion & 1st Lateral Bending Y-Axis, SLS 1st Latral Bending Y-Axis In-Phase.	NF	4.64	4.64	NF
11	EFDD	5.03	ML Deck Bending Along Z-Axis, ML Tower % SLS 1st Lateral Bending Z-axis, Boosters 1st Lateral Bending Z-Axis.	5.01	5.01	5.03	NF

DRT Rollback CT Stopped Mode Shapes (cont)

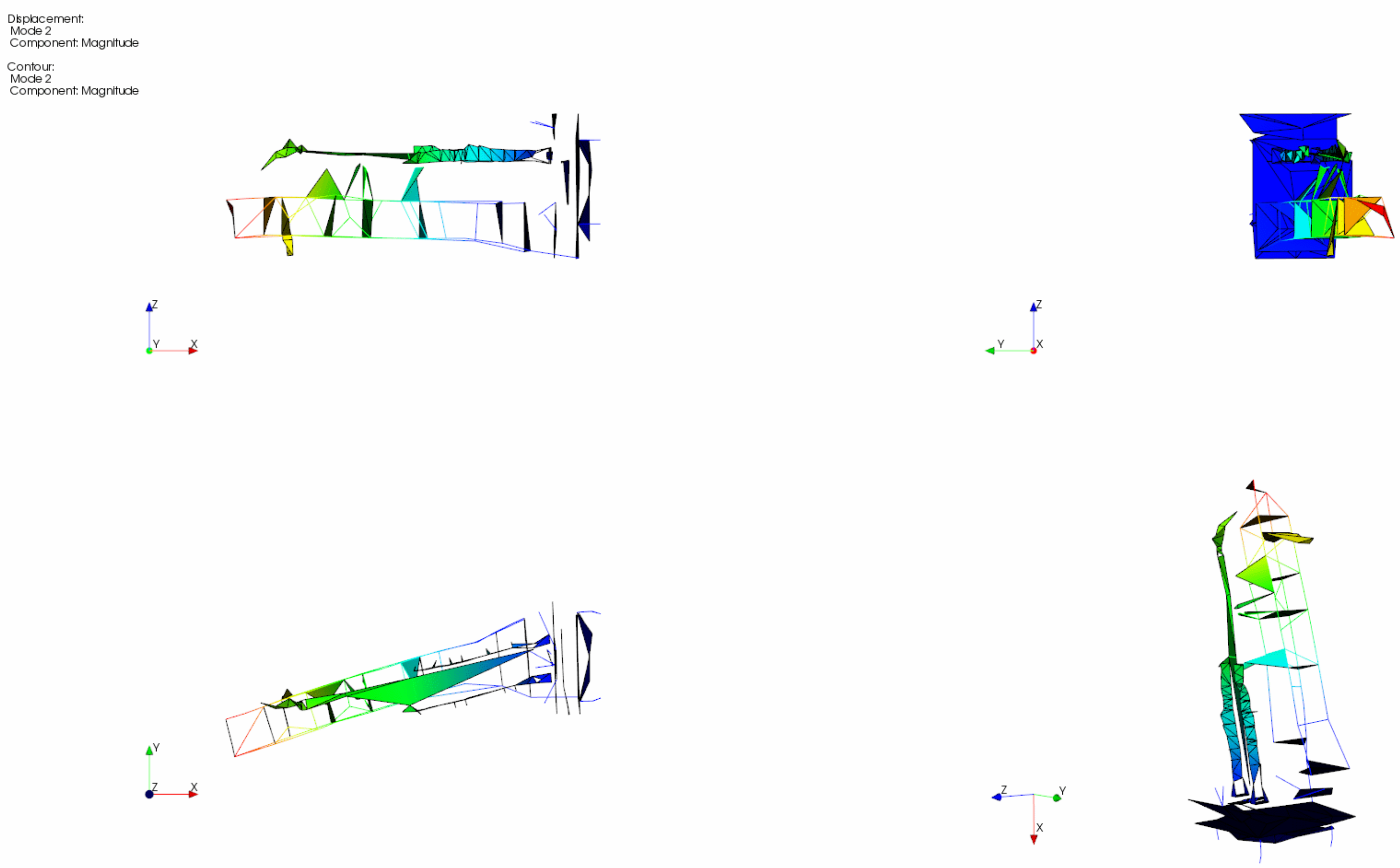
- Mode #1: ML Deck Bending, ML Tower & SLS 1st Lateral Bending Z-Axis.





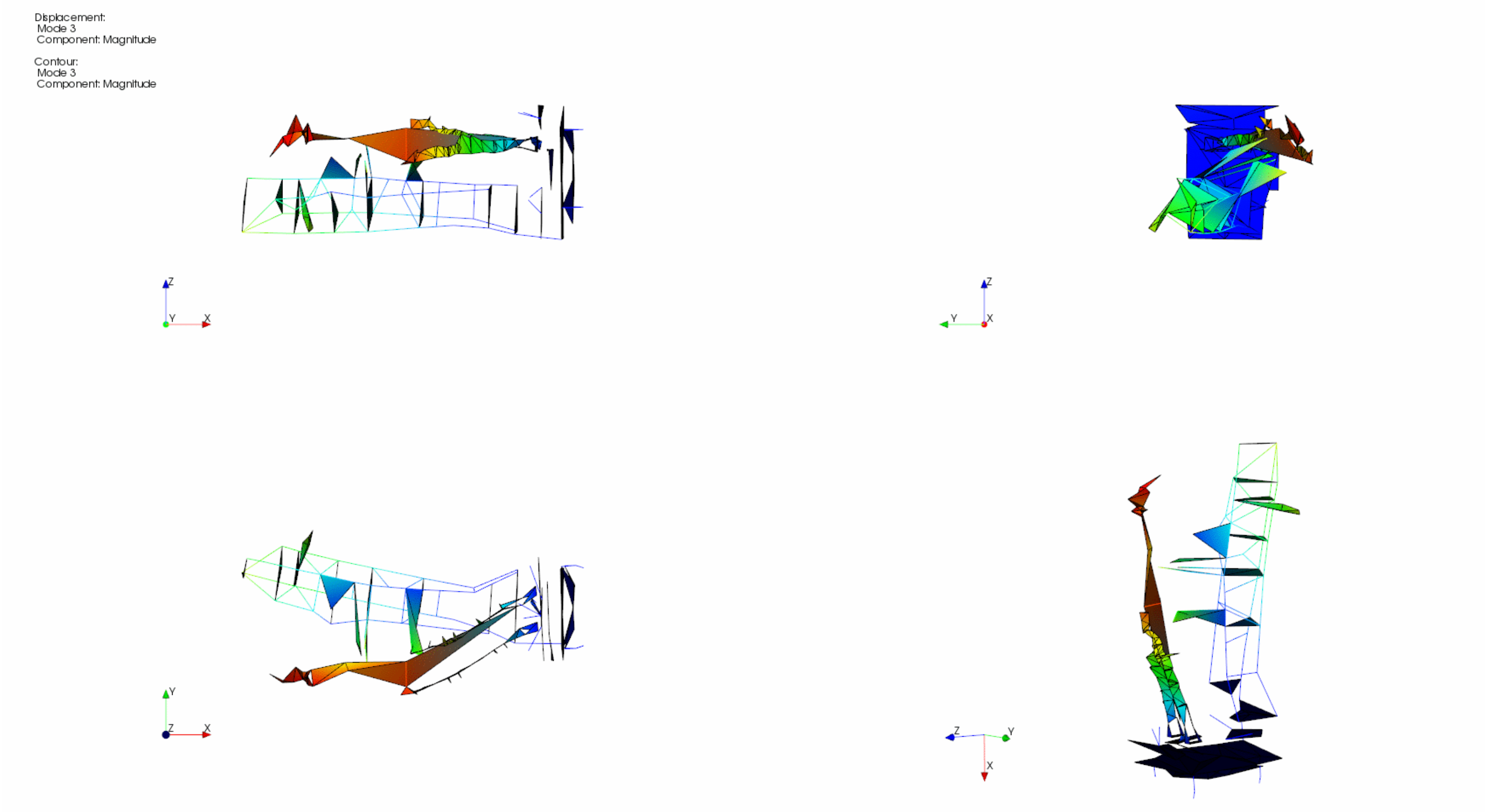
DRT Rollback CT Stopped Mode Shapes (cont)

- Mode #2: ML Deck Rotation About Z-Axis, ML Tower & SLS 1st Lateral Bending Y-Axis.



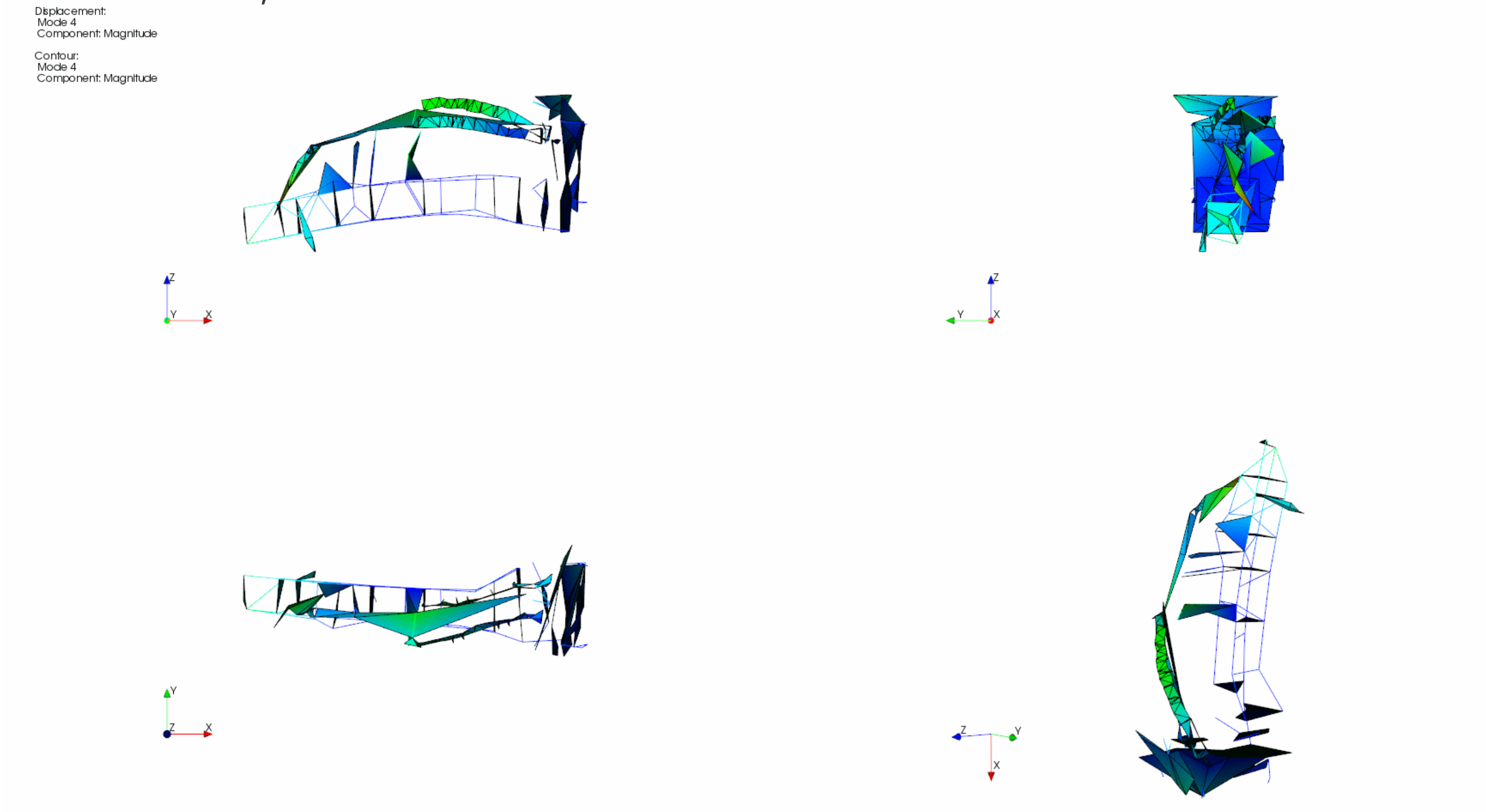
DRT Rollback CT Stopped Mode Shapes (cont)

- Mode #3: ML Tower & SLS 1st Lateral Bending Y-Axis Out-of-Phase, ML Tower & SLS 1st Torsion In-Phase.



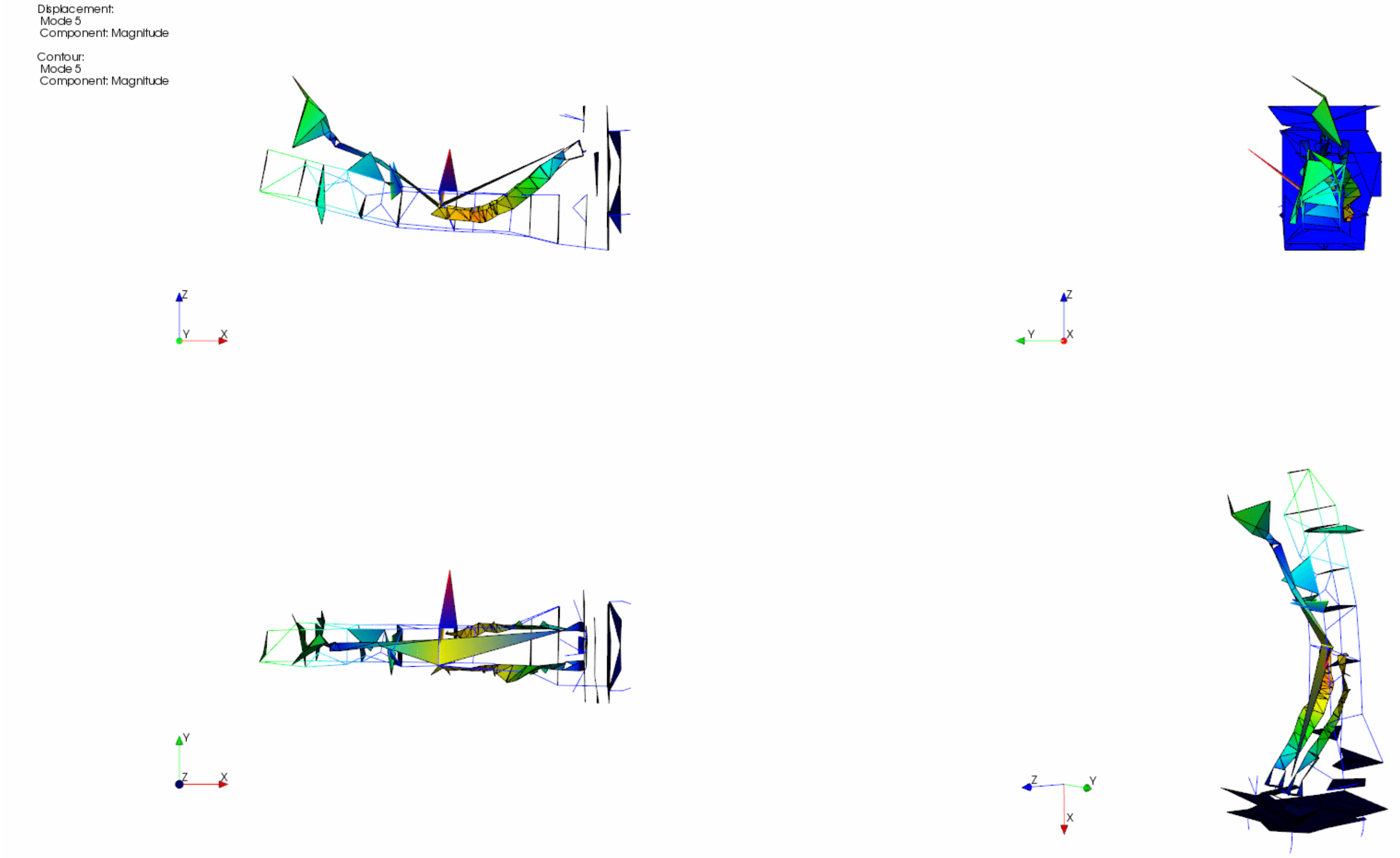
DRT Rollback CT Stopped Mode Shapes (cont)

- Mode #4: ML Deck Rotation About Z-Axis, SLS 1st Lateral Bending Y-Axis, ML Tower & SLS 1st Lateral Bending Y-Axis In-Phase, ML Tower & SLS 1st Torsion In-Phase.



DRT Rollback CT Stopped Mode Shapes (cont)

- Mode #5: ML Tower & SLS 1st Lateral Bending Z-Axis In-Phase, Core Stage Intertank Umbilical (CSIT) Y-Axis Translation.



DRT Rollback CT Stopped Test Modes Self ORTHO

Test Self Orthogonality Table

Test 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	29	30	31	32
Ott	Test Shapes		1.00	1.19	1.76	2.36	2.68	3.36	3.82	3.97	4.38	4.64	5.02	5.52	5.93	6.14	6.86	7.48	8.25	8.88	9.22	9.34	9.85	10.02	10.19	10.19	10.41	11.10	11.34	12.09	12.28	12.57	12.71	12.83
100	1	1.00	100				11						7	7	5			5																
95	2	1.19		100	13									6				5				5		6										
90	3	1.76		13	100	40			8		7	8																						6
85	4	2.36			40	100	69	13	11			15	7	19	19	8	23	18	24	15	13	9		6	9	7		6			7	11		5
80	5	2.68	11			69	100	7				9	6																					
75	6	3.36				13	7	100	9	16		9		12	6	7	7	7	11		7	10	12	13	10		7							
70	7	3.82			8	11		9	100		17	7							6	11	21	22	15	24	21		9							
65	8	3.97						16		100	13	14		13					9	8	15	20	18	25	23		7		8					5
60	9	4.38			7				17	13	100	58	13				8			17	27	25	18	28	28	5	25							
55	10	4.64			8	15	9	9	7	14	58	100	57	13	17	17	11	8	18	19	26	24	11	20	31	14	21	5				6	6	
50	11	5.02	7			7	6				13	57	100	67	8		10				10	15	18	17	18		17		6					
45	12	5.52	7	6		19		12		13		13	67	100	51	39	33	12	33	22	7	5	26	10		20	15	9	10	6	10	12	5	5
40	13	5.93	5			19		6				17	8	51	100	53	13	10	5		7		8	5	6									7
35	14	6.14				8		7				17		39	53	100	42	28	12	18	11			6	7	6	8			7				
30	15	6.86				23		7			8	11	10	33	13	42	100	21	57	43	25	8	23	7	21	39		15	16	12	12	15	16	6
25	16	7.48	5	5		18		7				8		12	10	28	21	100	74	25	13		17		13	27	6	10	9	9		7		
20	17	8.25				24		11	6	9		18		33	5	12	57	74	100	20	5	7	31	7	11	47		11	16				10	5
15	18	8.88				15			11	8	17	19		22		18	43	25	20	100	67	42		45	60	55	19	7	9				9	
10	19	9.22				13		7	21	15	27	26	10	7	7	11	25	13	5	67	100	80	34	84	91	42	29		10				7	5
5	20	9.34		5		9		10	22	20	25	24	15	5			8		7	42	80	100	57	89	82	15	48		9					
0	21	9.85						12	15	18	18	11	18	26	8		23	17	31		34	57	100	68	33	48	35				5		6	
	22	10.02		6		6		13	24	25	28	20	17	10	5	6	7		7	45	84	89	68	100	87	16	39		13	6	8	6		
	23	10.19				9		10	21	23	28	31	18		6	7	21	13	11	60	91	82	33	87	100	51	36	6			11	9		6
	24	10.19				7					5	14		20		6	39	27	47	55	42	15	48	16	51	100	6	24	8	21	28	26	5	8
	25	10.41						7	9	7	25	21	17	15		8		6		19	29	48	35	39	36	6	100	8	22	7			8	5
	26	11.10				6						5		9			15	10	11	7					6	24	8	100	39		5		8	
	27	11.34								8			6	10			16	9	16	9	10	9		13		8	22	39	100	7	18	16		
	28	12.09												6		7	12	9						6		21	7		7	100	30	43	23	17
	29	12.28				7								10			12						5	8	11	28		5	18	30	100	86	40	
	30	12.57				11						6		12			15	7						6	9	26			16	43	86	100	61	12
	31	12.71										6		5			16		10	9	7		6			5	8	8		23	40	61	100	61
	32	12.83			6	5				5				5	7		6		5		5				6	8	5			17		12	61	100

DRT Rollback CT Stopped
Test vs FEM Modes XORTHO

FEM/Test Cross Orthogonality Table

FEM Shapes

Otg	Test 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	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	Test CRSS 3%	Test CRSS All
			1.02	1.22	1.54	1.87	2.12	2.12	2.12	2.12	3.12	3.22	3.56	3.77	3.86	4.61	4.67	5.09	5.40	5.44	5.67	6.12	6.67	6.78	7.07	7.17	7.30	7.51	7.73	7.77	7.84	8.67	8.81	9.49	10.19	10.35	11.01	11.30	11.51	11.75	12.38	12.80	13.20	13.27	13.85	14.09	14.27		
100	1	1.00	98																																													98	99
95	2	1.19		99			34																																									99	100
90	3	1.76			97		80																																		21							97	100
85	4	2.36			38	63	33	68	67	68		32																																				77	96
80	5	2.68				89		97	98	98		38																																				98	100
75	6	3.36						20			94	23																																				94	100
70	7	3.82					54						96																																			96	100
65	8	3.97				31						85				33																																85	100
60	9	4.38					22							92																																		92	99
55	10	4.64				20								59		26	53		24																													59	99
50	11	5.02				20						21		23		83				32																												84	99
45	12	5.52										25				42				56	38									30			25															56	98
40	13	5.93																	25	28	90																				26							90	100
35	14	6.14														23			35	81	24		28	25																								83	99
30	15	6.86																		20			32		49	23				51			43															52	98
25	16	7.48																		21			20		23	48		32		40			49															49	98
20	17	8.25																										25	20	74			49															78	99
15	18	8.88																						22				23					80															80	99
10	19	9.22																		29			49	50	21								27															73	99
5	20	9.34																		24			38	39	22		57				24																	59	100
0	21	9.85																		22			25	28			31						34	54														54	99
	22	10.02																		31			44	46	26		38																					66	99
	23	10.19																		27			46	44			34						27															67	99
	24	10.19																												38			55	24	24	32	27											55	98
	25	10.41												26				57	31								37								42			21										57	100
	26	11.10																																	22		93											94	99
	27	11.34																																	24		26	80				24						85	99
	28	12.09																																				21	68					40			29	72	94
	29	12.28																																					37			29	26	40	32		34	47	86
	30	12.57																																						23	20		48	33			53	55	86
	31	12.71																																						64					21		37	64	84
	32	12.83																																					31	61	49	25						72	93
FEM	CRSS	3%	98	99	97	89	80	97	98	98	94	85	96	92	14	83	53	64	35	81	90	15	49	50	49	48	74	32	20	74	31	17	80	65	47	34	93	81	91	70	56	38	66	50	59	31	58		
FEM	CRSS	All	99	100	100	99	99	99	99	99	100	99	99	99	22	99	97	87	70	99	99	88	78	65	84	88	88	53	76	91	59	66	97	95	70	76	96	94	97	81	68	81	76	69	75	60	60		

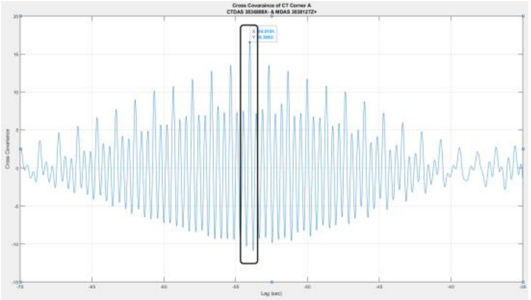
Legend
90 - 100
50 - 89
0 - 49

NESC Support of DRT and WDR

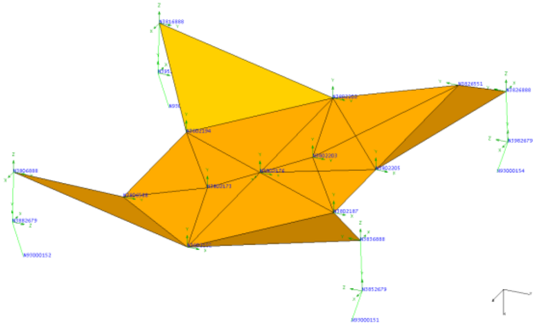
- NESC task originally scoped as an independent assessment (IA) of the Operational Modal Analysis (OMA) of the Artemis I Dynamic Rollout Test (DRT).
- Converted to an NESC Support Task (ST) and then was further modified to include OMA analysis of the Artemis I Wet Dress Rehearsal (WDR).
  - The dynamic characteristics extracted from DRT and WDR will be used to support Space Launch System (SLS) Integrated Modal Test (IMT) math model correlation efforts, Exploration Ground System (EGS) mobile launcher (ML) model verification and validation (V&V), and development of generic rollout forcing functions.

NESC Contributions

- Time synchronization of the time history data.
  - Accelerometer data on the ML and Artemis I was acquired by a data acquisition system (DAQ) separate from the DAQ used to collect accelerometer data on the Crawler Transporter (CT) .



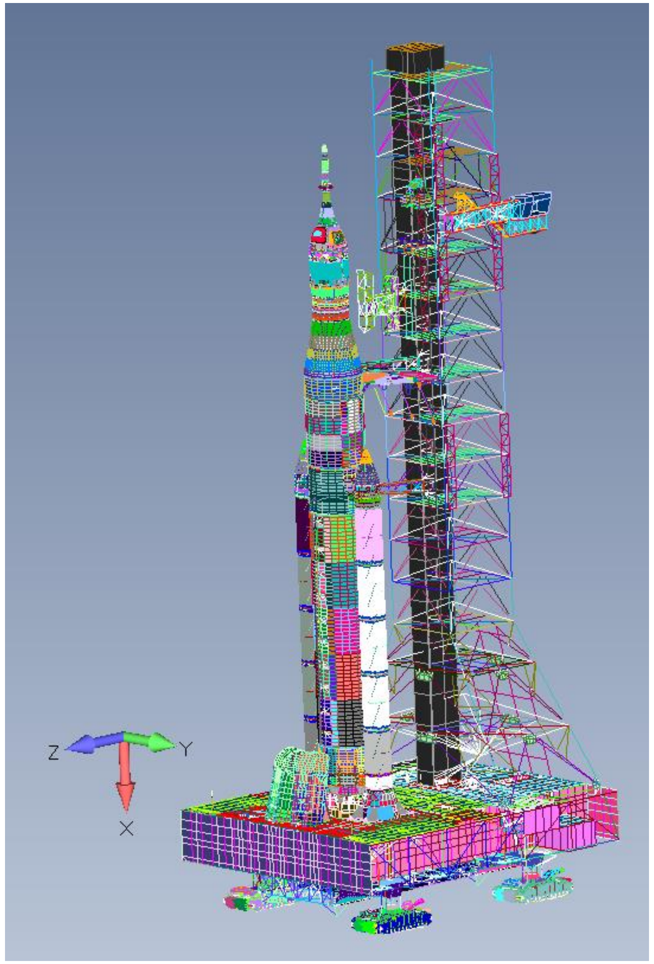
- Worked with Kennedy Space Center (KSC) EGS personnel to correctly identify the as-installed Crawler Transporter (CT) accelerometer instrumentation.
  - Revisiting the Integrated Modal Test 10-point configuration modal test results may be warranted.



- Performed time-domain and frequency-domain data quality assessments, which directly lead to identifying channel errors, some of which were not caught during IMT.

NESC Contributions (cont)

- Assembled SLS Program supplied FEM files to generate a WDR configuration FEM, performed standard model checks, and created the associated Test Analysis Model (TAM) needed to support OMA modal parameter identification.
  - Core Stage LOX tank 42% filled, LH2 tank 15% filled.
- Analyzed accelerometers located on the right booster aft struts during WDR and DRT Rollback to determine if free-play occurred at these joints.
- Provided guidance on OMA best practices, OMA theory, and the use of the SVS ARTeMIS OMA software.
  - Both time-domain and frequency-domain techniques.
- Provided guidance on the CT Truck's two dominant family of harmonics and their impact on identifying modes.



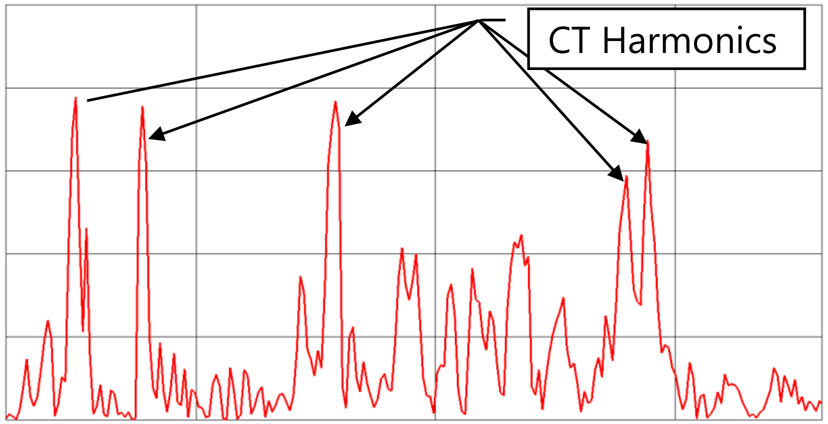
NESC Contributions (cont)

- Identified modal parameters for DRT and WDR time intervals selected by the SLS Program.
- Evaluated the viability of two supplemental OMA methods.
  - Unfortunately, the accelerations at the ML/CT Pickup Points were not sufficiently uncorrelated to be used as references from which frequency response functions could be estimate.
    - Accelerations on the CT below the Jacking, Equalizing, and Leveling (JEL's) are themselves correlated (CT harmonics are highly correlated). $\hat{H}_1(j\omega) = G_{yx}(j\omega)G_{xx}^{-1}(j\omega)$

Correlation coefficients computed between pairs of the TSS3_RB_BPC_TS_2_JCA_01.ati below CT JEL acceleration time histories.

Corner		A			B			C			D		
	Direction	3852679Y+	3852679Z-	3852679X+	3882679Y+	3882679Z-	3882679X-	3952679Y+	3952679Z-	3952679X-	3982679Y+	3982679Z-	3982679X+
A	3852679Y+	1	-0.1343	-0.1762	0.2108			0.1206			0.3288	-0.1565	-0.2324
	3852679Z-		1	-0.221		-0.8402			-0.1631			0.1912	
	3852679X+			1			-0.0464			0.0592			0.0697
B	3882679Y+				1	-0.0995	-0.3541						
	3882679Z-					1	-0.2186						
	3882679X-						1						
C	3952679Y+							1	-0.1907	-0.5607			
	3952679Z-								1	0.2805			
	3952679X-									1			
D	3982679Y+										1	-0.2356	-0.4418
	3982679Z-											1	0.1153
	3982679X+												1

Coherence Between CT Below JEL Accels



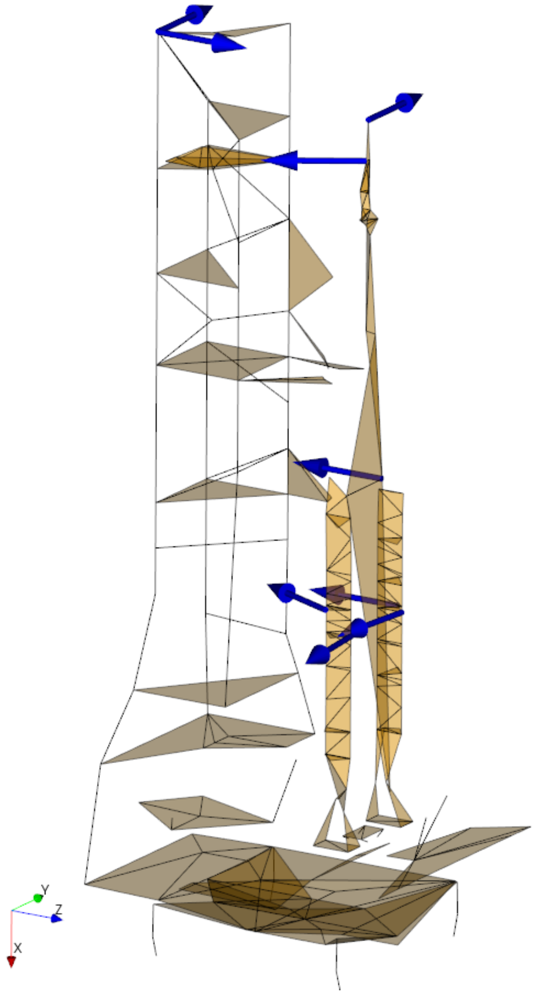
  - Selecting singular vectors based upon modal frequencies estimated with time-domain techniques does not guarantee identifying mode shapes.

OMA Best Practices

- OMA techniques will not replace traditional modal testing.
  - Does however provides important supplemental information and insights into the structural dynamics of hardware in its operational environment.
- Streamlining the data acquisition and transfer process, especially time synchronization of the data, plays a critical roll in the timeliness and effectiveness of analyzing rollout data.
  - Accurate logs of rollout event times are critical for understanding the rollout data.
- The effectiveness of OMA techniques is highly dependent on the quality of the rollout data.
  - Time-domain and frequency-domain data quality checks and “correcting” “bad” or “corrupted” acceleration time histories prior to starting an OMA analysis are critical to its success.

OMA Best Practices (cont)

- Selection of Projection Channels is important.
  - Poor selection of Projection Channels adversely effects both the time-domain and frequency-domain OMA analysis techniques.
- Accelerometers need to have sufficient sensitivity and sufficiently low noise floor.
  - Typical modal accelerometers may not be suitable.
- Important to appropriately apply bandpass filtering and decimation to obtain acceleration time histories that only have frequency content in the range of interest prior to performing OMA analysis.



OMA Best Practices (cont)

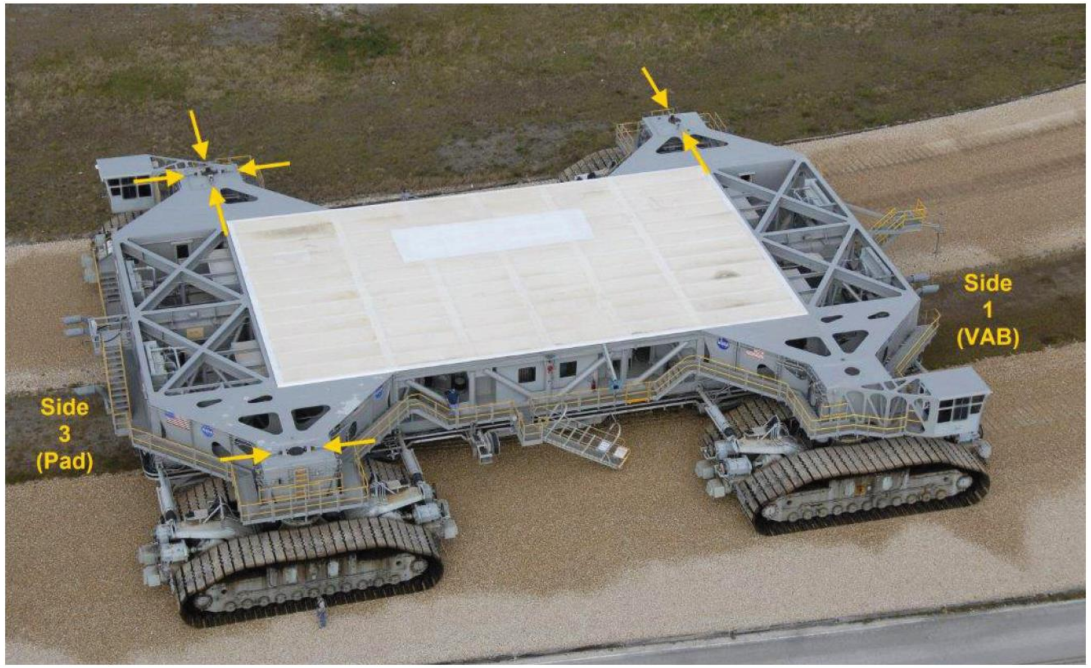
- Having a FEM, its predicted modal frequencies and mode shapes, and the associated Test Analysis Model (TAM) are tremendously helpful in identifying the target modes.
  - FEM mode shapes and modal frequencies help to focus the OMA Analysis.
  - TAM allows computing cross-orthogonalities for judging the similarity between FEM and test shapes.
  - TAM allows the test shapes to be back expanded to all three translational DOF at each accelerometer location (i.e., TDM grid point), which facilitates visual interpretation of the test mode shapes.

Looking Forward

- Increase Professor Ventura's involvement.
  - Work IT security issues to either provide access to the data or provide a secure computer at a NASA center with the appropriate software to allow independent analysis.
- Acquire ambient data on ML-2 as it is built up and perform OMA analysis to help inform and preliminarily "tune" its FEM.
  - Building block approach.
- Acquire rollout data when the ML-2 is transported by the CT and perform OMA analysis.
- Consider utilizing 6 DOF accelerometer sensors at the ML/CT Pickup Points and the Booster/VSP interfaces.

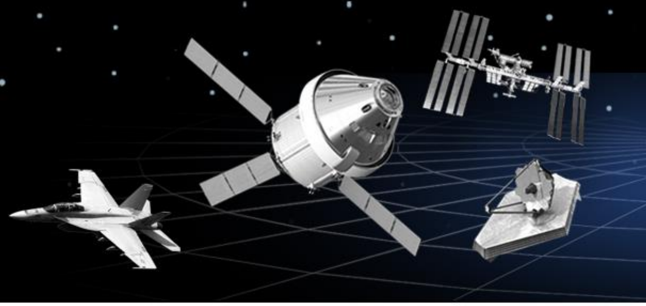
Looking Forward (cont)

- Look into the possibility of using the CT JEL's as an excitation source for a modal test of the CT, CT+ML-1, CT+ML-1+Artemis IV?



- Advocate and support Generic Rollout Forcing Function work.

Backup Slides



DRT Rollback CT Stopped Test MAC

Test Self MAC Table

Test 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	29	30	31	32
MACtt	Test Shapes		1.00	1.19	1.76	2.36	2.68	3.36	3.82	3.97	4.38	4.64	5.02	5.52	5.93	6.14	6.86	7.48	8.25	8.88	9.22	9.34	9.85	10.02	10.19	10.19	10.41	11.10	11.34	12.09	12.28	12.57	12.71	12.83
100	1	1.00	100							18		6	15	15																				
95	2	1.19		100	9				11		9	8																						
90	3	1.76		9	100	14			20		15	9																						
85	4	2.36			14	100	64	18		10			6	5						8	6			5	6									
80	5	2.68				64	100	5																										
75	6	3.36				18	5	100	10	28	14	18	21	22					9	12	14	14	16	18	19		8							
70	7	3.82		11	20			10	100		67	52	15		13				9	21	13	33	26	25	23		14							
65	8	3.97	18			10		28		100	7	26	53	63					11	17	25	16	20	27	31		6							
60	9	4.38		9	15			14	67	7	100	84	31	10	11				11	25	19	42	34	34	31		33		8					5
55	10	4.64	6	8	9			18	52	26	84	100	61	31	8				14	34	31	48	41	44	44		35		7					6
50	11	5.02	15			6		21	15	53	31	61	100	78	8	6			20	31	37	36	33	41	44		24							7
45	12	5.52	15			5		22		63	10	31	78	100	18	22			20	17	26	21	24	29	29		15							
40	13	5.93							13		11	8	8	18	100	24	6			9	7	13	11	10	9		5							
35	14	6.14											6	22	24	100	19	21		5	5									5				
30	15	6.86													6	19	100	11	20	7						15							5	
25	16	7.48														21	11	100	42													9	7	
20	17	8.25						9	9	11	11	14	20	20			20	42	100	14	29	33	38	35	29	8	17							6
15	18	8.88				8		12	21	17	25	34	31	17	9	5	7		14	100	76	67	51	71	71	14	34		14					14
10	19	9.22				6		14	13	25	19	31	37	26	7	5			29	76	100	72	67	85	86	8	32		10					12
5	20	9.34						14	33	16	42	48	36	21	13				33	67	72	100	87	91	81		60		18					18
0	21	9.85						16	26	20	34	41	33	24	11				38	51	67	87	100	90	77	5	59		11					13
	22	10.02				5		18	25	27	34	44	41	29	10				35	71	85	91	90	100	95		52		16					14
	23	10.19				6		19	23	31	31	44	44	29	9				29	71	86	81	77	95	100		46		10					13
	24	10.19															15		8	14	8		5			100	6	11						
	25	10.41						8	14	6	33	35	24	15	5				17	34	32	60	59	52	46	6	100							15
	26	11.10																								11		100						
	27	11.34									8	7								14	10	18	11	16	10				100			7		
	28	12.09														5														100		9	9	
	29	12.28																													100	23		
	30	12.57																9											7	9	23	100	68	
	31	12.71															5	7												9		68	100	28
	32	12.83									5	6	7						6	14	12	18	13	14	13		15						28	100

DRT Rollback CT Stopped Test vs FEM XMAC

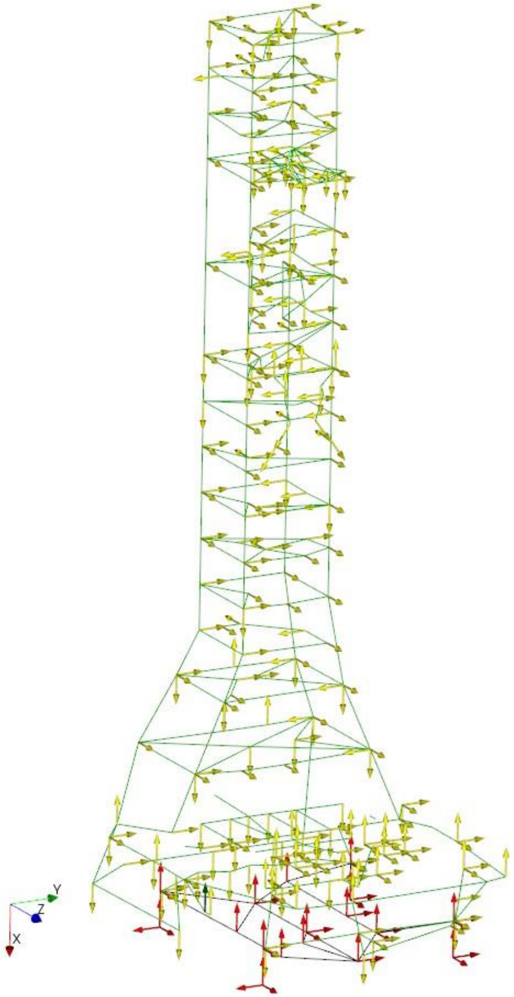
FEM/Test Cross MAC Table

FEM Shapes

																																															Test	Test	90 - 100
			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	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	CRSS	CRSS	50 - 89
MACtg	Test Shapes		1.02	1.22	1.54	1.87	2.12	2.12	2.12	2.12	3.12	3.22	3.56	3.77	3.86	4.61	4.67	5.09	5.40	5.44	5.67	6.12	6.67	6.78	7.07	7.17	7.30	7.51	7.73	7.77	7.84	8.67	8.81	9.49	10.19	10.35	11.01	11.30	11.51	11.75	12.38	12.80	13.20	13.27	13.85	14.09	14.27	3%	All	0 - 49
100	1	1.00	84																																														92	94	
95	2	1.19		98																																												99	100	
90	3	1.76			92								22																																			96	99	
85	4	2.36						58	57	58																																						77	96	
80	5	2.68				41		89	92	92																																						96	99	
75	6	3.36									63	22																																				79	97	
70	7	3.82			21		72						96	60							29					22	45																					98	100	
65	8	3.97				22						62								33																												79	89	
60	9	4.38			22		60						59	92							32					26	48																					96	99	
55	10	4.64					43						44	69							27					20	44																					83	98	
50	11	5.02										35								37							20																					61	95	
45	12	5.52										40								52																												72	92	
40	13	5.93																			75																											87	99	
35	14	6.14																		40																												63	98	
30	15	6.86																																														41	96	
25	16	7.48																																														38	96	
20	17	8.25																									21			26																		54	98	
15	18	8.88																									38																					64	98	
10	19	9.22																		28							27																					53	97	
5	20	9.34					24						33	36							35					35	77														23							88	99	
0	21	9.85											25	26							26					27	63														22							80	99	
	22	10.02											24	23							23					23	58														21							77	99	
	23	10.19											21														48																					71	99	
	24	10.19																																														38	95	
	25	10.41												33							24					32	58														23							77	100	
	26	11.10																																			65											82	98	
	27	11.34																																				59										79	99	
	28	12.09																																					46									71	92	
	29	12.28																																														44	87	
	30	12.57																																									56		46		55	80	92	
	31	12.71																																									39		45	27	40	72	89	
	32	12.83																																						26	39					21		63	90	
FEM	CRSS	3%	92	99	96	64	85	94	96	96	79	79	98	96	8	44	23	53	22	72	87	74	45	33	43	70	98	16	29	51	39	46	41	27	64	32	81	77	85	52	66	58	82	47	86	58	82			
FEM	CRSS	All	93	100	99	91	99	98	98	98	99	86	99	99	21	95	93	93	70	95	98	92	52	43	54	78	99	25	83	64	75	73	86	88	85	72	91	92	93	69	79	82	89	68	91	73	89			

NESC OMA Experience/Background

- NESC independent assessment (IA) of the OMA analysis of the ISVV-010 Rollout, which consisted of the ML being transported by the CT.
  - Preliminary OMA analysis on the 2005 CT-1 and CT-1 + Mobile Launch Platform (MLP) data, 2017 CT-2 and CT-2 + MLP 2017 data, and 2003 Partial Stack Rollout.
  - Mentoring by Professor Carlos Ventura, University British Columbia Civil Engineering, during his GRC on-site visit November 2019.
    - NESC sponsored Professor Ventura to provide an OMA analysis training course during the DTaMSS off-site meeting held near MSFC in August 2018.
  - Tabletop review with stakeholders in April 2020 and provided a data packet of training material to elevate the issues to the community with performing OMA analysis on rollout data.

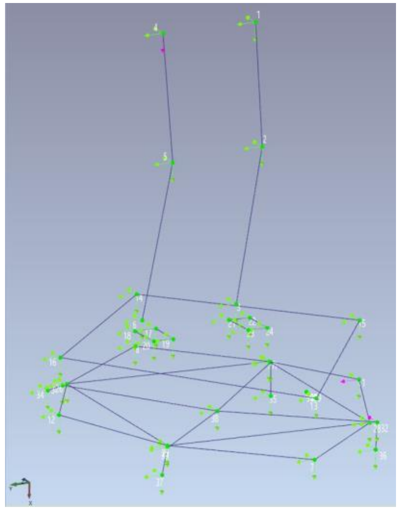


ISVV-010 Rollout

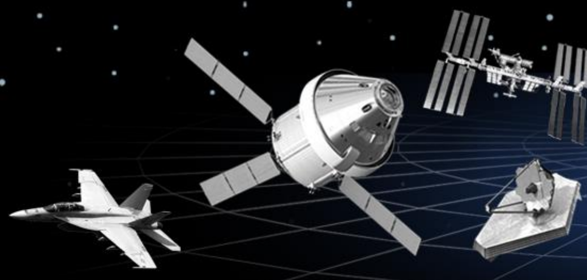
- ML being transported by the CT rolled out of the VAB at midnight June 28, 2019, following the completion of the ISVV-018 ML Only modal test.
  - Viewed as a pathfinder for DRT.

NESC OMA Experience/Background (cont)

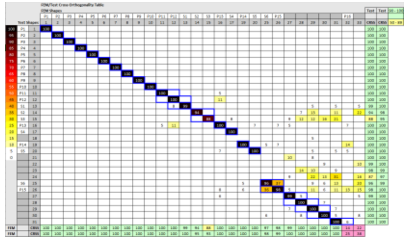
- Subsequent NESC IA of the OMA analysis 2005 CT-1 and CT-1 + Mobile Launch Platform (MLP) data, 2017 CT-2 and CT-2 + MLP 2017 data.
  - Tabletop review with stakeholders in September 2020.
  - Identified key relationships between CT speed and the amplitudes and frequencies of the CT harmonic force.
    - Determined that the CT speed profile recommended for DRT coming out of the IA of the OMA analysis of ISVV-010 was not valid.

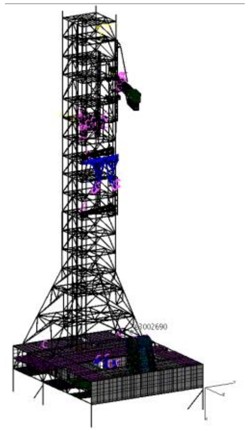


NESC ML/IMT Experience/Background

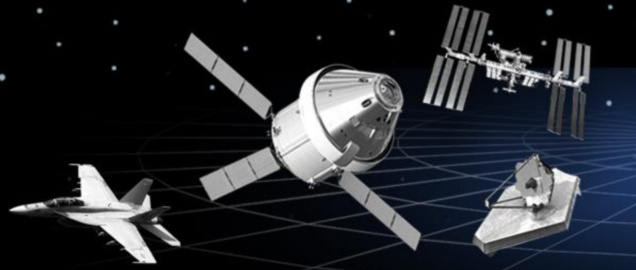


- NESC IA of the ISVV-018 ML Only modal test pretest analysis, May 2019, and modal test, February 2021.
  - In addition to performing standard pretest analyses verifying shaker and accelerometer layout an “as-run end-to-end” MIMO simulation taking into account sensor noise, ambient vibration levels, and shaker random force capabilities was performed to ensure a high likelihood of successfully identifying the primary target modes.
- NESC IA of the IMT ML Shaker Checkout & Pretest Analysis, May 2021.
  - Helped to rectify issues with preliminary shaker installation.
  - Provided confidence that multi-point sine sweeps could provide sufficient excitation to identify primary target modes.





References



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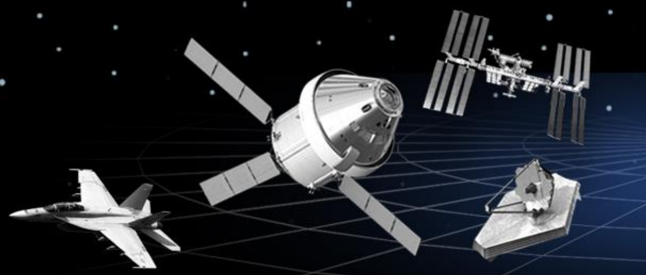

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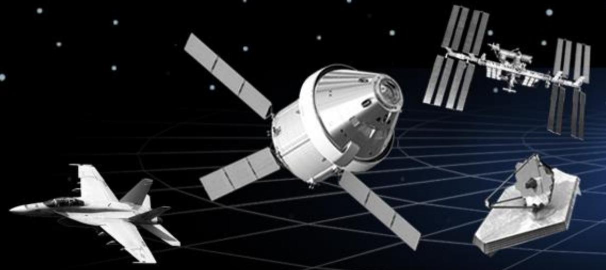

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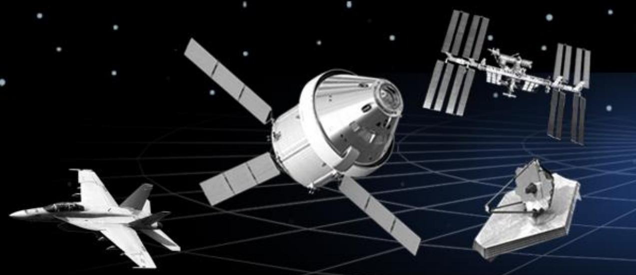

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