MODEL VALIDATION OF AN RSRM TRANSPORTER THROUGH FULL-SCALE OPERATIONAL AND MODAL TESTING

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ABSTRACT

The Reusable Solid Rocket Motor (RSRM) segments, which are part of the current Space Shuttle system and will provide the first stage of the Ares launch vehicle, must be transported from their manufacturing facility in Promontory, Utah, to a railhead in Corinne, Utah. This approximately 25-mile trip on secondary paved roads is accomplished using a special transporter system which lifts and conveys each individual segment.

ATK Launch Systems (ATK) has recently obtained a new set of these transporters from Scheuerle, a company in Germany. The transporter is a 96-wheel, dual tractor vehicle that supports the payload via a hydraulic suspension. Since this system is a different design than was previously used, computer modeling with validation via test is required to ensure that the environment to which the segment is exposed is not too severe for this space-critical hardware. Accurate prediction of the loads imparted to the rocket motor is essential in order to prevent damage to the segment.

To develop and validate a finite element model capable of such accurate predictions, ATA Engineering, Inc., teamed with ATK to perform a modal survey of the transport system, including a forward RSRM segment. A set of electrodynamic shakers was placed around the transporter at locations capable of exciting the transporter vehicle dynamics. Forces from the shakers with varying phase combinations were applied using sinusoidal sweep excitation. The relative phase of the shaker forcing functions was adjusted to match the shape characteristics of each of several target modes, thereby customizing each sweep run for exciting a particular mode. The resulting frequency response functions (FRF) from this series of sine sweeps allowed identification of all target modes and other higher-order modes, allowing good comparison to the finite element model. Furthermore, the survey-derived modal frequencies were correlated with peak frequencies observed during road-going operating tests. This correlation enabled verification of the most significant modes contributing to real-world loading of the motor segment under transport. After traditional model updating, dynamic simulation of the transportation environment was compared to the measured operating data to provided further validation of the analysis model.

KEYWORDS

Validation, correlation, modal test, rocket motor, transporter

THE NEED FOR A CORRELATED MODEL

ATK Launch Systems (ATK) manufactures the Reusable Solid Rocket Motor (RSRM) segments which are part of the current Space Shuttle system. The RSRM segments will also be used for the Ares launch vehicle first stage. The segments require transportation from the manufacturing facility to a railway transportation center on their way to the launch site in Florida. Each portion of the transportation path subjects the segments to vibration which must be evaluated for its effect on the segment fitness. Recently, ATK obtained a new set of transporters from Scheuerle, a German company, to provide the transportation from the manufacturing site to the railhead. Since this transportation system was a modification from the prior system, an evaluation of its performance was required to validate the vibration loads environment to ensure that no damage would be done to the segments. The transporter is a 96-wheel, dual tractor vehicle that supports the RSRM segment payload via a hydraulic suspension. Figure 1 shows the RSRM Scheuerle transporter vehicle with the RSRM segment installed on the cradle frame.

ATK developed a finite element model (FEM) of the transporter which was used to predict initial transportation vibration levels. Validation of that finite element model was a requirement for the new hardware, so a series of tests were planned which included dynamic modal testing and operational vibration testing. The testing was conducted to measure the dynamic characteristics of the transporter vehicle with an RSRM installed in order to satisfy requirements for a test-verified finite element model of the vehicle assembly. Consideration was given to the use of hydraulic exciters for conducting the modal test simply due to the size of the transporter and its payload and to analysis prediction of large required forces at specific locations. The amount of time available for the test program was limited, so ATK collaborated with ATA Engineering to help identify the best approach for the modal testing as well as to help in the correlation and model updating process.

The intent of the modal test was to confirm the predicted natural frequencies and mode shapes of the transportation system with the RSRM installed. This confirmation would allow the FEM to then be used to predict the responses occurring during the actual transportation process. These predictions would be combined with data from the transporter loads road test, to verify that the experienced segment transportation loads would be less than those specified for truck transportation of the RSRM.

SIMPLIFIED PRETEST PREPARATION

In preparation for the testing program, the FEM was used to predict the dynamic behavior of the transporter configuration. The modeling allowed estimates to be developed of the number of measurement locations and the excitation types and levels necessary for a successful test program. A normal test-analysis-model (TAM) development program (Brillhart et al. 1988 and Brillhart et al. 1998) was conducted. This activity identified a primary frequency range of interest to 5 Hz with about eight modes below that frequency and predictions of about twenty modes to 10 Hz. A detailed FEM, shown in Figure 2, was used to derive a set of measurement locations and locations where excitation might be applied during the modal test portion of the program.

The initial set of planned instrumentation was kept to a minimum, but it was anticipated that hydraulic exciters would be required to apply sufficient excitation to the test article. The use of hydraulic exciters complicated the planned testing in that substantial fixturing would be required to install the shakers at the desired locations. Since there was minimal time available in which to conduct the testing, an alternative approach was sought which would still meet the objectives of the overall program.

The first step in simplifying the test approach was to make an assumption that electrodynamic shakers, though less powerful than hydraulic units, could be used in sufficient number to excite the entire transporter system. It was anticipated that between eight and ten shakers would provide enough excitation to allow the modes of interest to be excited. In order to confirm these assumptions and to develop an alternative approach, the FEM predictions were used to assess a simplified set of measurements using modal assurance criteria (MAC) (Allemang 2002). A selection of measurement locations were assessed starting with a minimal set that included vertical responses on the corners of each transporter trailer (forward and aft). The MAC was assessed for any proposed measurement set in the same way that orthogonality would be used later, i.e., minimizing the off-diagonal elements. This approach, using the analysis mode shapes, allowed for very rapid iteration (a few minutes) of the proposed sensor placement, and quickly converged on a set of sixteen measurement locations which included the four corners of each transporter trailer, the four corners of the transporter cradle, and four locations on the RSRM segment. For simplicity, each of the sensor locations included three axes of measurement. The measurement locations can be seen in Figure 3.

Next, the proposed excitation locations were selected and again the model was used to evaluate the anticipated success. Frequency response functions (FRF) were predicted at each of the sensor locations with an eight-shaker configuration providing only vertical excitation at the transporter trailer corners. Damping assumptions were made, and the resulting FRF predictions provided an assessment of how much force would be required to develop reasonable, observable acceleration levels during the test. Further, the FRF were used to derive mode indicator functions (MIF) in various forms to verify whether the modes of interest would be excited by the proposed shaker locations. The various MIF techniques applied were complex (CMIF), multivariate (MMIF), power (PMIF), and normal (NMIF). All of the resulting functions lend insight into which modes may be excited, to what extent, and by which shaker locations.

This approach to the pretest activity allowed development of a set of measurement locations which provided very good MAC results for target modes below 5 Hz and good results for the first twenty predicted modes. Moreover, the FRF predictions indicated that the eight proposed shaker locations would adequately excite the test article for observation of all modes of interest, and that the excitation levels could be in the 10s to 100s of pounds of force. Based on these predictions, completed in about a day, a more rigorous TAM development was completed using the proposed locations. It was also noted that the locations selected would minimize the instrumentation time required since the proposed locations would allow easy identification and access.

TEST IMPLEMENTATION

The test was conducted using the approach defined and evaluated during the pretest evaluation. Eight shakers were installed, one at each corner of the transporter trailers, as shown in Figure 4. As described earlier, each shaker was oriented vertically, normal to the surface of the trailer deck. This approach was selected for simplicity in that there would be no special fixtures required to hold the shakers and it would allow the maximum force to be imparted to the trailer frames. Figure 5 shows one of the shakers installed on a work stand to position it under the trailer frame. Each shaker included a load cell installed at the trailer frame to measure the amount of force applied to the test article. In addition, an accelerometer was installed in line with the shaker so that a drive point FRF could be obtained at each of the shaker locations. These measurements combined with the 48 response accelerometers yielded a total of 64 data channels.

Accelerometers were attached to the test article using magnetic mounting bases. This allowed the sensors to be quickly installed and oriented on the steel components, including the RSRM case.

The transporter system was configured in a standard road transportation arrangement with a live RSRM segment. All tires were serviced to confirm proper air pressure of between 120 and 140 psi. This service was important since the tires provide a significant amount of the vertical stiffness to the transportation system. Once all of the instrumentation was ready to go, the transporter cradle was raised into its normal operating height where it was held in place with a lock pin, and the shakers were installed and attached.

Testing was conducted using two modes of shaker excitation. Random excitation was applied initially using all eight shakers. This was followed by sinusoidal excitation using the same eight shakers. The sine excitation was applied using a variety of different phase combinations between the shakers. This approach allowed the excitation to concentrate on particular modes of interest, eventually deriving all modes of interest. For instance, the trailer roll mode (both trailers in phase) was excited by common phasing of all right-side shakers and opposite phasing of all left side shakers. The shaker phase combinations employed for the excitation of each mode are provided in Table 1.

As the modes were identified, a complete evaluation was developed and the shaker phase modified until all modes of interest were extracted. The random excitation was successful for identifying modes within some of the frequency range of interest, but it was not as effective below approximately 2 Hz, where the force spectrum was substantially lower. Therefore, testing relied primarily on sine testing, which was conducted using a log sweep covering the frequency range of 0.5 to 20 Hz.

Excitation levels were typically below 50 pounds of peak force. This level of excitation was consistent with that applied during the entire test program and made the most effective use of some of the highest output available from these shakers. This approach simplified the test setup and conduct at the expense of limiting extremely high force levels that might have been available with hydraulic shakers. While quite linear response with increased input force was apparent, it can be reasonably expected that some nonlinearity might be observed at much higher excitation forces. Nonetheless, the excitation levels were quite effective for the modal survey testing.

As the data system allowed all data to be acquired simultaneously, multiple test runs were able to be conducted efficiently. This led to rapid overall test completion, with the entire setup and testing being accomplished over a two-day period.

COMPARISON TO ANALYSIS

Comparisons to analysis predictions were started while the testing was ongoing. This assessment used the pretest analysis results that had originally helped develop the test approach. As soon as data was collected, it was processed to yield the test modes shapes. The shapes were evaluated for quality and then checked against the model predictions to help verify that all modes of interest had been extracted.

It was found that the test results were quite good using both MAC and orthogonality criteria as quality checks for the target modes below 5 Hz. Further, all of the target modes were identified and reasonable comparison to analysis predictions achieved to 5 Hz.

Although there was reasonable agreement between the test and analysis results, it was observed that test and analysis frequencies were not in agreement for some of the target modes. So, the validation – one of the primary reasons for conducting the test in the first place – was undertaken to achieve a better match between the test results and analysis predictions. The correlation effort focused on adjusting the model to match the first ten test modes. The modal survey results showed significant differences for these modes compared to the pretest FEM. The FEM was revised to better match the test hardware geometry, and adjustments were made to material properties and spring stiffness representing components not explicitly modeled. The result of the model updates was an excellent correlation to the first ten test-derived mode shapes, as shown in Table 2. All frequencies match within 5%.

The correlation activity identified 24 design variables that influenced the characteristics of the target modes. These model properties were then modified by optimization studies in ATA's Attune software (Indermuehle and Kaplan 2005). As the design variables were modified, predicted improvements in frequency and shape error were shown which ultimately resulted in an improved model. The correlation updates were weighted to adjust the spring properties representing the tires and cradle interface (Figure 6) above all other properties, as these were shown to be critical to correlation improvement, but other element properties were modified as well. Further, there were some model modifications performed outside of Attune's automated optimization routines. These changes included adjustments to the locations of lumped masses as well as geometric changes to place springs such as the tires in proper position relative to the overall vehicle. All of these modifications served to improve the overall model correlation.

FINAL VALIDATION

Ultimately, the verification of the environment that is experienced by the RSRM segments during use of the new transporter was demonstrated through road testing. Instrumentation of the RSRM and transporter system allowed measurement of the frequencies and response levels during operation.

Very good agreement was confirmed in the dominant responses observed in the operational road testing. Figure 7 shows a typical acceleration response from the analysis of road test data. The waterfall plot shows FFT spectral analysis of 300 seconds of data with 0.1 Hz resolution from 0 to 15 Hz. The contour plot helps to identify the natural response of the transporter and segment as it moved along the road. The 1.1 Hz vertical response observed was closely aligned with the fundamental vertical mode that was identified in the modal survey at 1.22 Hz (Table 2). The next significant vertical response, around 3.7 Hz, was closely matched to the 4.0 Hz mode observed in the modal survey. Correlation to modes in other directions was not attempted here. However, the close correlation of the fundamental vertical mode frequency indicated that the FE model correlation was good and that confidence could be placed in other modes.

It is clear that not all modes identified in the modal test and the model correlation process were obvious in the operating test data. This behavior is not unexpected since the road inputs may be such that particular modes are not as well excited as others. Those frequencies which were observed could be matched well against the modal results. With the selection of appropriate road profile input, the model can predict transporter and segment responses and validate that the truck transportation load levels are not exceeded.

SUMMARY

A complete test and analysis program was undertaken in order to validate the model of a new RSRM segment transporter system. This validation program allowed verification that the loads which would be applied to the segment during the transportation from the manufacturing facility to the railhead would not exceed specified truck transportation loads.

The approach used for the modal testing portion of this program was selected for efficiency and speed as well as its high level of reliability. The use of many electrodynamic shakers, along with a limited instrumentation set, allowed testing to be configured more readily than trying to implement a hydraulic excitation approach. The distribution of the shakers around the structure allowed the energy to be distributed throughout the structure, similar to a road input, while applying specific shaker phase combinations allowed target modes to be readily identified. The drawback to the electrodynamic shaker system was that measurements with large displacements could not be achieved. However, this did not hinder successful mode identification. Further, road test data verified that the measured responses were relatively small, usually less than 0.05 g, whereas the modal testing was conducted with levels around 0.01 g. Large displacements were therefore not characteristic of actual transportation and could be reasonably approximated with those levels applied during the modal testing.

Successful test completion allowed an effective model correlation activity to be completed using automated software tools. The areas where model improvements were clearly needed were identified and implemented in an efficient manner. Overall model correlation achieved was excellent. The match achieved between the modal results and the updated model increased confidence in the model's predictive abilities and the comparisons achieved with actual road data.

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Figure 1. RSRM Scheuerle transporter.

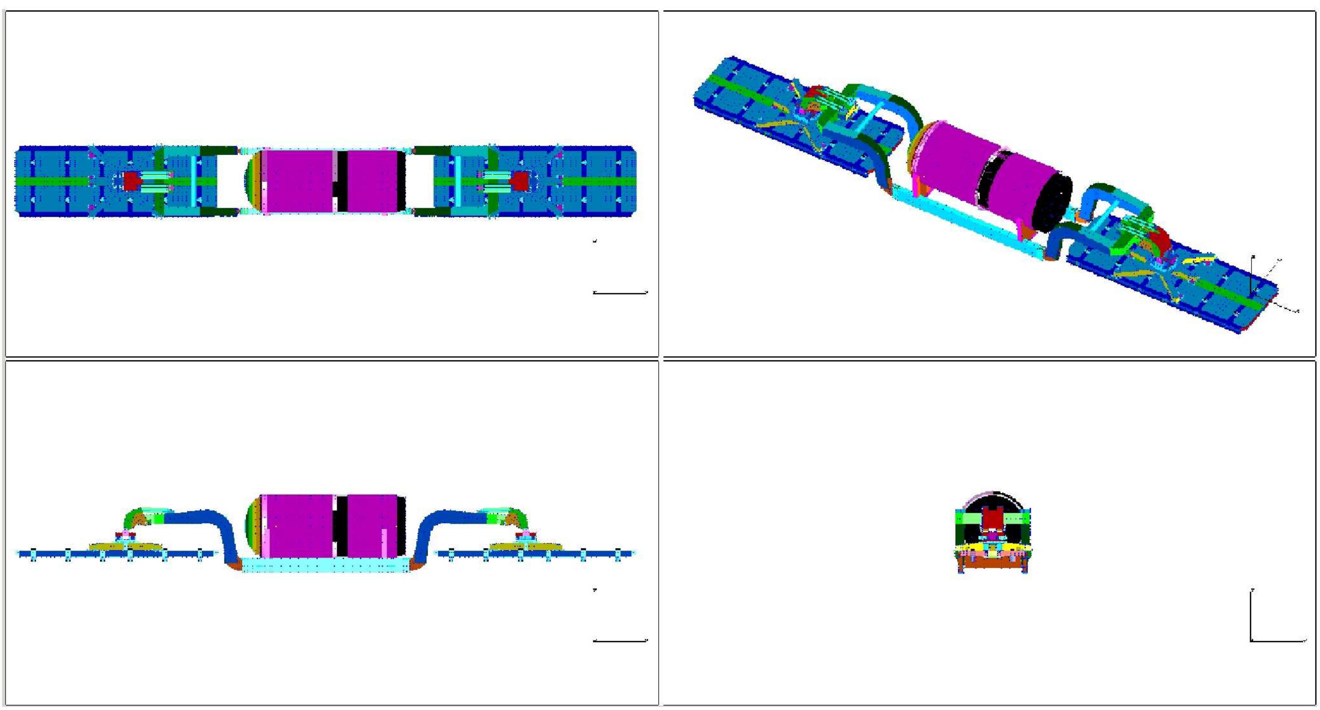


Figure 2. Detailed finite element model of the transporter, including RSRM.

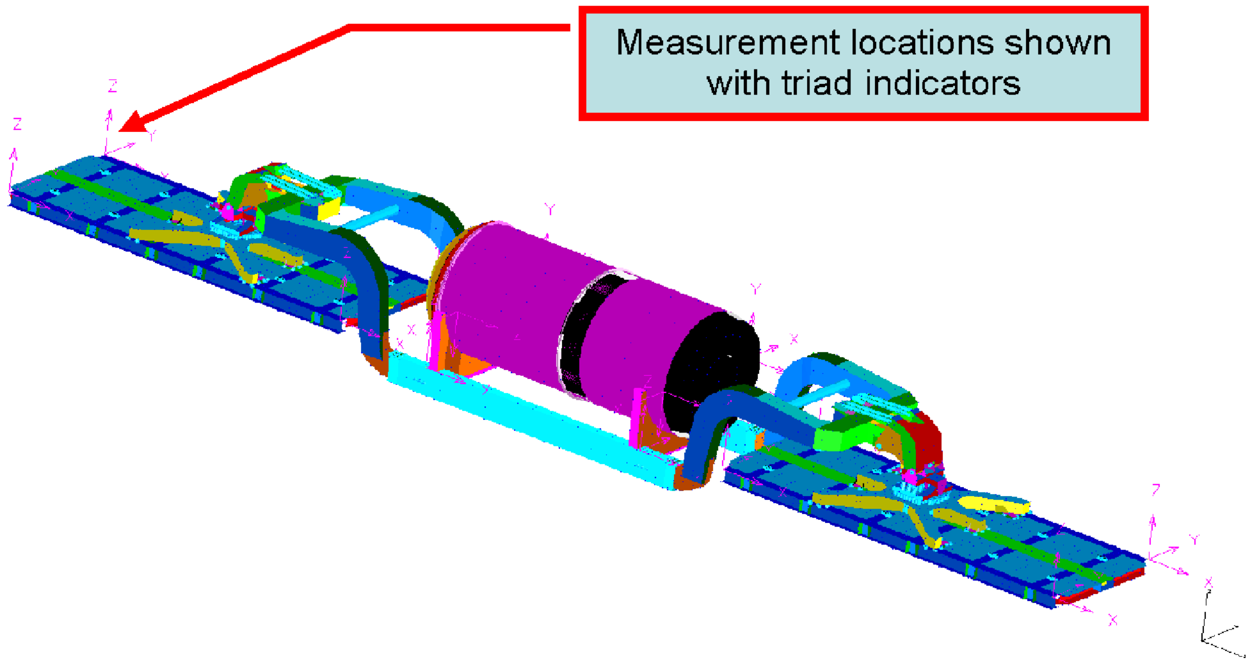


Figure 3. A simple set of sixteen locations were selected for the transporter.

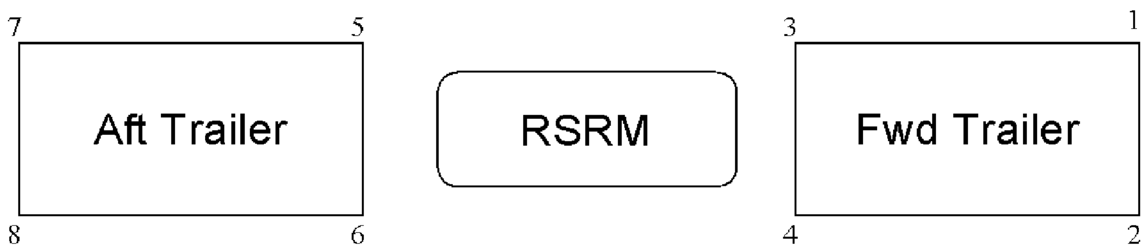


Figure 4. Shaker numbering scheme used for the modal test.

Figure 5. Shakers were installed atop stands under the trailer frame.

Table 1. A variety of sine sweep phase combinations was performed.

	Shaker Number							
Excitation Type	1	2	3	4	5	6	7	8
In-phase sine sweeps (All shakers)	+	+	+	+	+	+	+	+
Cradle Pitch	+	+	+	+	-	-	-	-
Trailer Roll	+	-	+	-	+	-	+	-
Trailer Roll - Opposite Phase	+	-	+	-	-	+	-	+
Trailer Torsion	+	-	-	+	+	-	-	+
Trailer Torsion - Opposite Phase	+	-	-	+	-	+	+	-
Trailer Pitch	+	+	-	-	+	+	-	-
Trailer Pitch - Opposite phase	+	+	-	-	-	-	+	+

+ and - are 180° out of phase

Table 2. Model updates resulted in excellent test versus analysis agreement.

Test Mode			Initial FEM					Correlated FEM				
#	Freq	Shape	#	Freq	Freq Error	Shape	Shape Error	#	Freq	Freq Error	Shape	Shape Error
1	0.91	1.00	1	0.97	6.83%	0.89	-11.33%	1	0.92	0.59%	0.97	-2.54%
2	1.22	1.00	2	1.23	0.24%	0.97	-3.11%	2	1.23	0.60%	0.96	-3.76%
3	1.46	1.00	3	1.37	-6.43%	0.86	-14.49%	3	1.40	-4.59%	0.89	-10.84%
4	1.61	1.00	4	2.18	35.90%	0.98	-1.93%	4	1.60	-0.10%	0.99	-0.68%
5	2.00	1.00	5	2.98	48.91%	0.98	-2.19%	5	1.99	-0.53%	0.91	-8.63%
6	2.77	1.00	8	3.58	29.34%	0.97	-3.38%	6	2.67	-3.65%	0.93	-6.78%
7	3.24	1.00	9	3.98	22.99%	0.98	-1.71%	7	3.30	1.99%	0.87	-13.03%
8	4.02	1.00	10	4.11	2.36%	0.87	-13.06%	9	4.15	3.19%	0.98	-2.03%
9	4.27	1.00	13	6.02	40.92%	0.80	-19.55%	8	4.10	-3.95%	0.84	-16.05%
10	4.61	1.00	6	3.48	-24.52%	0.96	-4.02%	11	4.73	2.69%	0.97	-3.43%

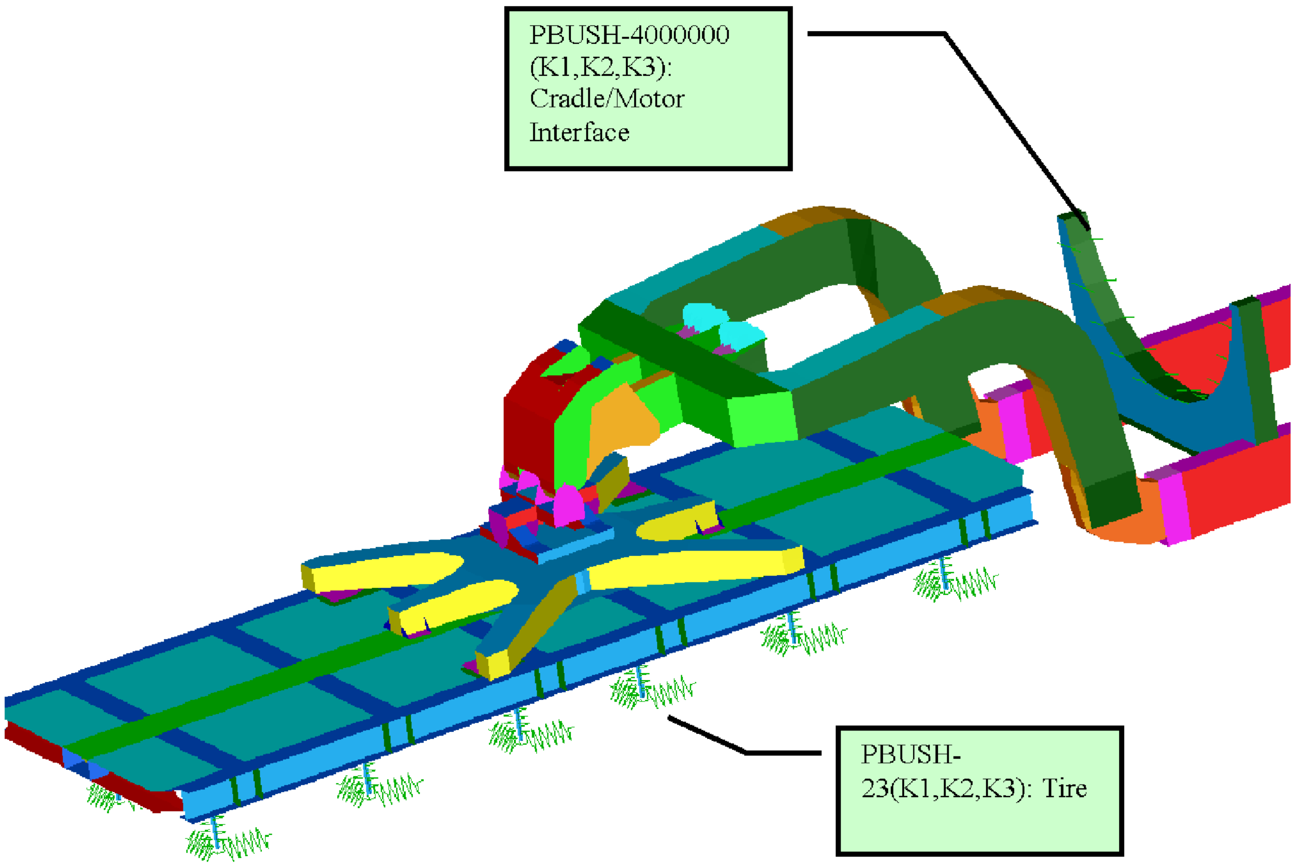


Figure 6. Stiffness of tires and cradle bushing interface had significant influence on correlation.

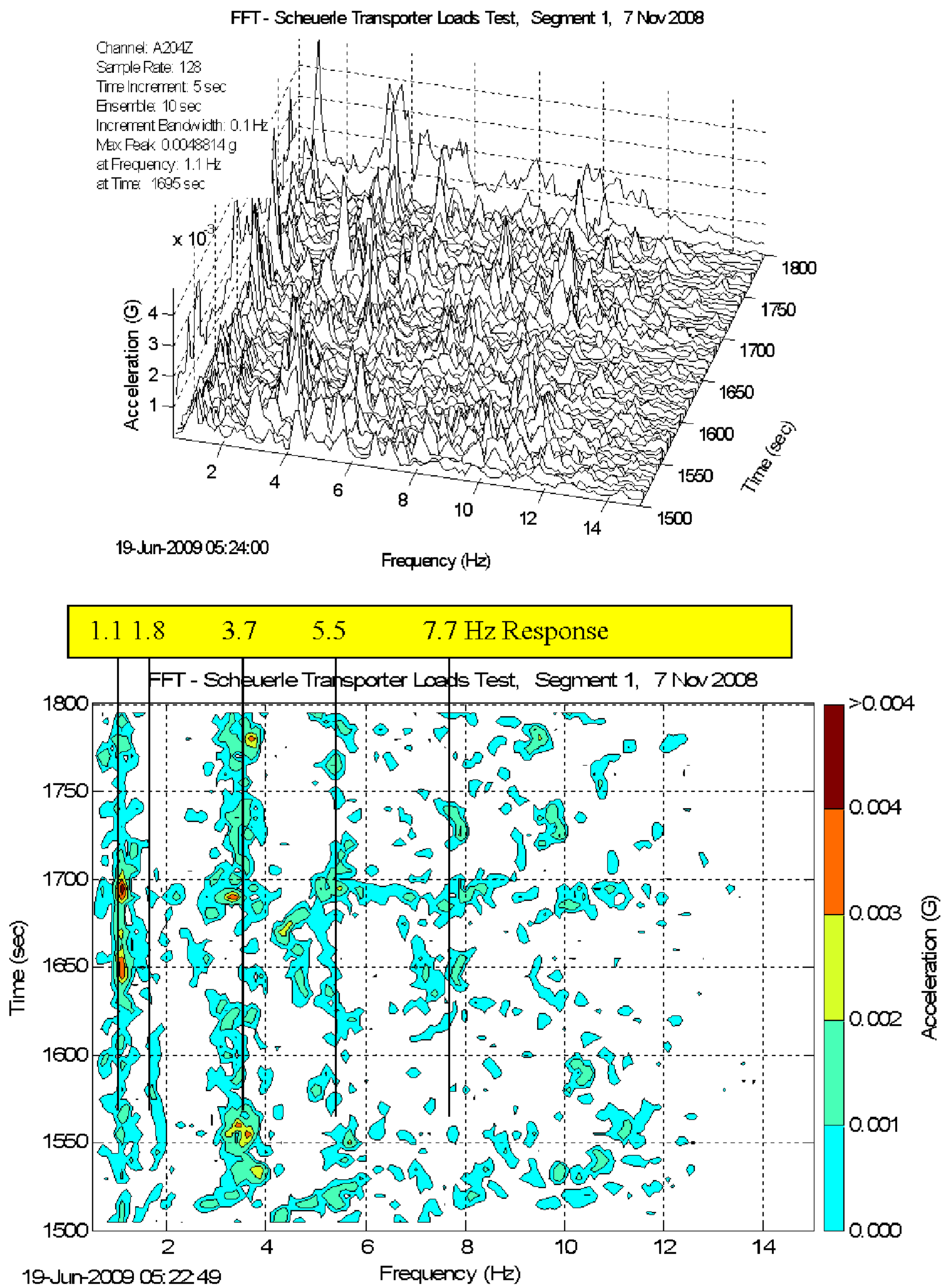


Figure 7. Typical road test data waterfall and associated contour plots.

Model Validation Of An RSRM Transporter Through Full Scale Operational And Modal Testing

25th Aerospace Testing Seminar

October 13-15, 2009

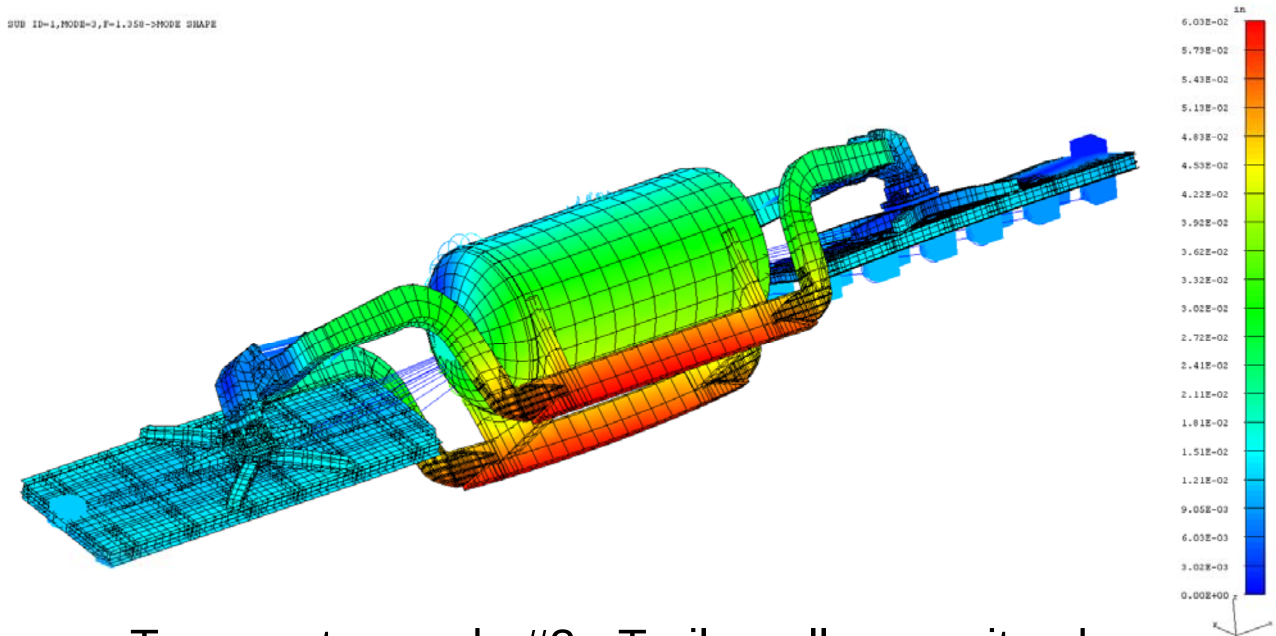
Ralph Brillhart – ATA Engineering
Joshua Davis – ATA Engineering
Bradley Allred – ATK Space Systems

ATK's Scheuerle Transport System Moves RSRM from Manufacturing to Railhead

- 96-wheel, dual tractor vehicle supports a single Reusable Solid Rocket Motor (RSRM) segment via hydraulic suspension.
- Modal test performed to validate finite-element model (FEM) for accurate load predictions – ensuring motor safety.
- Road test data integrated with modal results to further enhance predicted load accuracy.

Pretest Preparation Was Important for Test Success

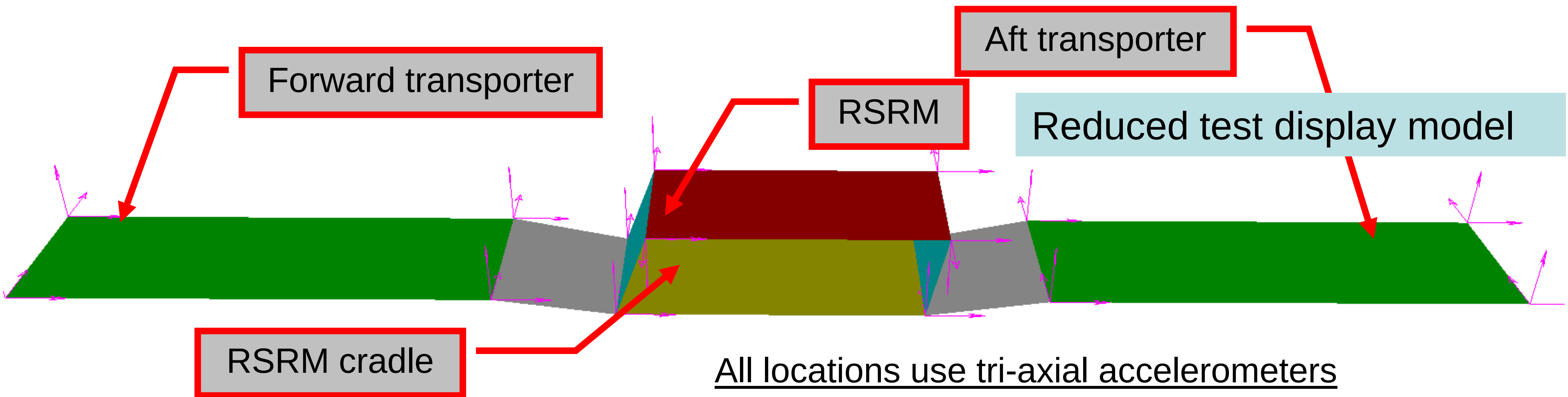
- Pretest planning relied on an existing detailed transporter-motor segment model.
- A normal test-analysis-model (TAM) development program identified eight target modes below 5 Hz.



Transporter mode #3 - Trailer roll, opposite phase

- Candidate measurement locations were evaluated by computing the modal assurance criteria (MAC) of the analysis modes, parsed to the candidate DOF set.

Analysis FEM Reduced to 48 Measurement DOF



<u>All locations use tri-axial accelerometers</u>

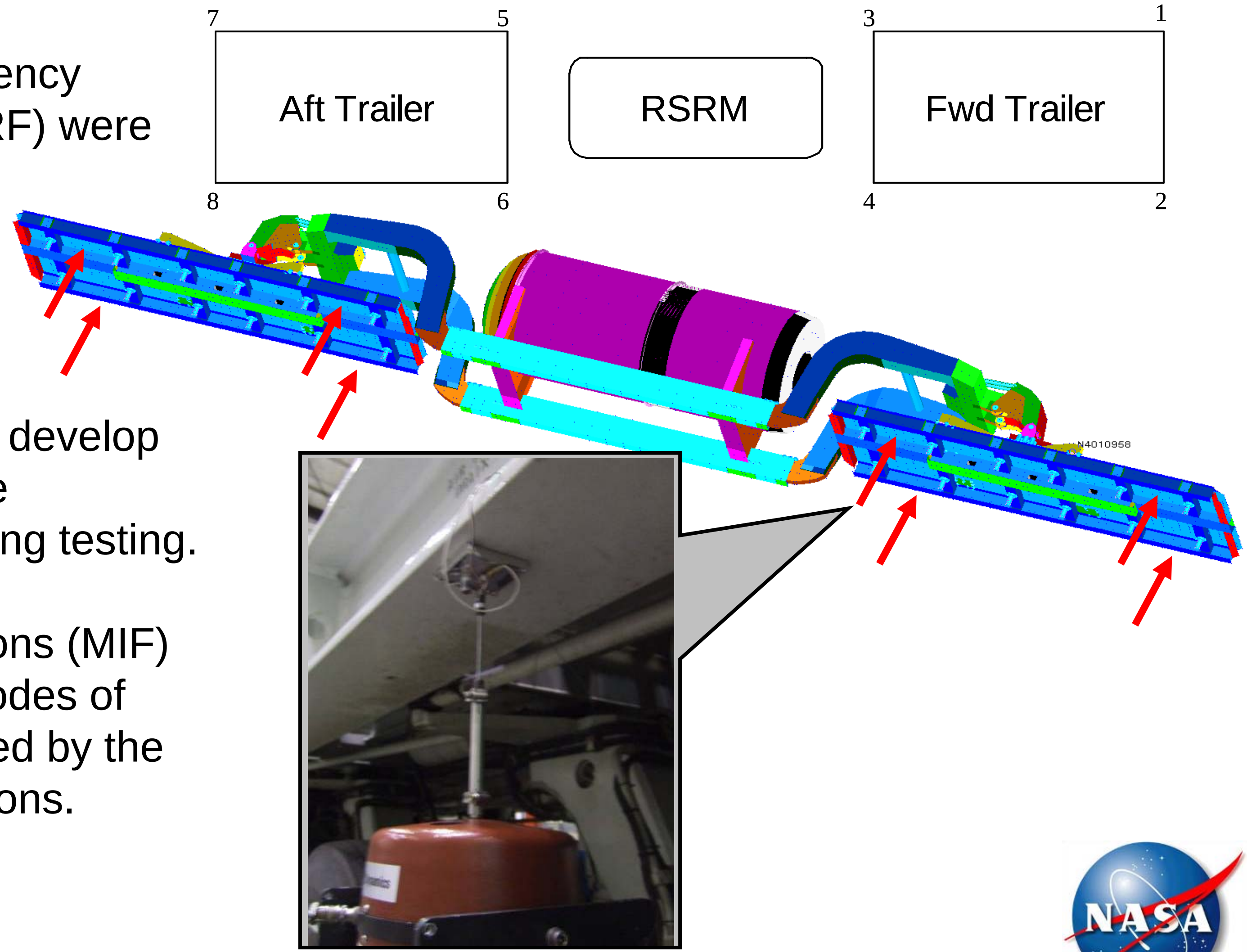
- 4 locations on RSRM segment
- 4 locations on RSRM cradle
- 4 locations on each of the two transporter trailers

Eight Shakers were Installed at Transporter Corners

- Before testing, Frequency response functions (FRF) were predicted for an eight shaker, vertical drive configuration.

- These FRF assessed force levels required to develop reasonable, observable acceleration levels during testing.

- Mode indicator functions (MIF) verified whether the modes of interest would be excited by the proposed shaker locations.



Unique Input Force Phase Combinations Enabled Excitation of All Target Modes

- Modal survey utilized both random and sinusoidal force excitation.
- Sine excitation was applied using a variety of different phase combinations between the shakers - allowing each run to concentrate on particular modes of interest; eventually deriving all modes.
- For instance, the trailer roll mode (both trailers in phase) was excited by common phasing of all right side shakers, and opposite phasing of all left side shakers.

	Shaker Number							
Excitation Type	1	2	3	4	5	6	7	8
In-phase sine sweeps (All shakers)	+	+	+	+	+	+	+	+
Cradle Pitch	+	+	+	+	-	-	-	-
Trailer Roll	+	-	+	-	+	-	+	-
Trailer Roll - Opposite Phase	+	-	+	-	-	+	-	+
Trailer Torsion	+	-	-	+	+	-	-	+
Trailer Torsion - Opposite Phase	+	-	-	+	-	+	+	-
Trailer Pitch	+	+	-	-	+	+	-	-
Trailer Pitch - Opposite phase	+	+	-	-	-	-	+	+

+ and - are 180 out of phase

Test Results Showed Original Analysis Model to be a Good Baseline

- All target modes identified.
- Test results were quite good using both MAC and orthogonality criteria as quality checks for the target modes below 5 Hz.
- However, test and analysis frequencies were not in agreement for some of the target modes.
- A model correlation effort was undertaken to adjust the model to match the first 10 modes.

FEM Mode No.	Test Mode No.	FEM Freq Hz	Test Freq Hz	%Freq Diff	Cross MAC	CRS XMAC	Cross Ortho	CRSS XOrtho
1	1	1.0	0.9	-6.4	58.9	99.5	76.7	99.8
2	2	1.2	1.2	-0.2	82.1	89.0	90.6	94.4
3	3	1.4	1.5	6.9	85.6	99.5	92.5	99.8
4	4	2.2	1.6	-26.4	87.3	99.6	93.4	99.8
5	5	3.0	2.0	-32.8	90.4	98.8	95.1	99.4
6	10	3.5	4.6	32.5	93.0	99.8	96.4	99.9
7	11	3.5	4.8	35.9	78.4	99.7	88.6	99.9
8	6	3.6	2.8	-22.7	90.9	99.5	95.3	99.7
9	7	4.0	3.2	-18.7	94.3	99.0	97.1	99.5
10	8	4.1	4.0	-2.3	52.6	99.5	72.5	99.7

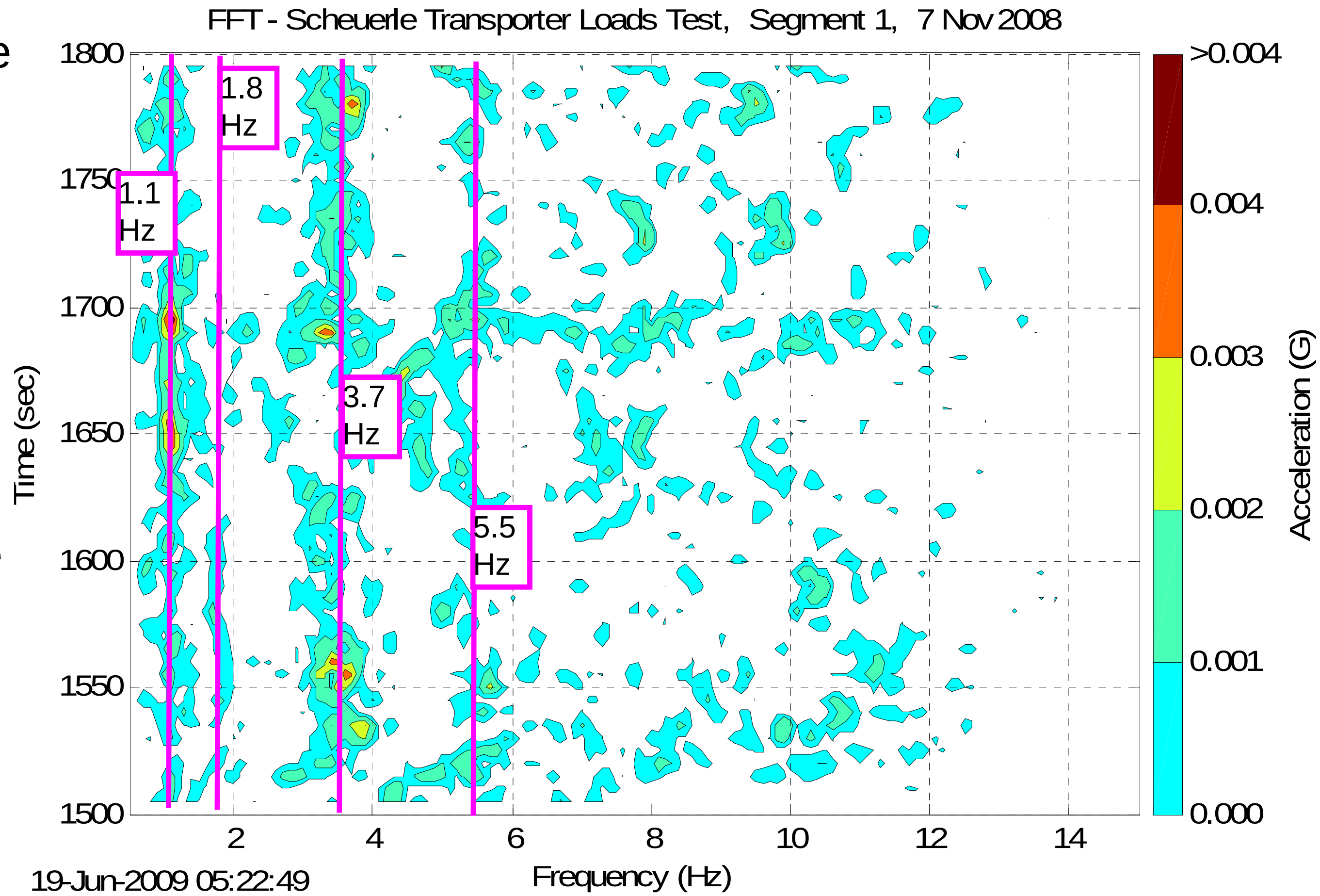
Model Correlation Effort Improved Test-Analysis Agreement

- 24 design variables were modified by optimization studies in ATA's Attune software
  - ➢ Design variables included: MAT1 elastic moduli, PBAR beam area and moment of inertia, PBUSH spring stiffness.
  - ➢ Optimization weighted to adjust the tire and cradle interface stiffnesses above all other properties.
- Other geometry changes performed outside of the optimization routine also improved correlation.
- Highest frequency error reduced from 20% to less than 5%.

Test Mode			Initial FEM					Correlated FEM				
#	Freq	Shape	#	Freq	Freq Error	Shape	Shape Error	#	Freq	Freq Error	Shape	Shape Error
1	0.91	1.00	1	0.97	6.83%	0.89	-11.33%	1	0.92	0.59%	0.97	-2.54%
2	1.22	1.00	2	1.23	0.24%	0.97	-3.11%	2	1.23	0.60%	0.96	-3.76%
3	1.46	1.00	3	1.37	-6.43%	0.86	-14.49%	3	1.40	-4.59%	0.89	-10.84%
4	1.61	1.00	4	2.18	35.90%	0.98	-1.93%	4	1.60	-0.10%	0.99	-0.68%
5	2.00	1.00	5	2.98	48.91%	0.98	-2.19%	5	1.99	-0.53%	0.91	-8.63%
6	2.77	1.00	8	3.58	29.34%	0.97	-3.38%	6	2.67	-3.65%	0.93	-6.78%
7	3.24	1.00	9	3.98	22.99%	0.98	-1.71%	7	3.30	1.99%	0.87	-13.03%
8	4.02	1.00	10	4.11	2.36%	0.87	-13.06%	9	4.15	3.19%	0.98	-2.03%
9	4.27	1.00	13	6.02	40.92%	0.80	-19.55%	8	4.10	-3.95%	0.84	-16.05%
10	4.61	1.00	6	3.48	-24.52%	0.96	-4.02%	11	4.73	2.69%	0.97	-3.43%

Final Validation Obtained through Corroboration of Modal Frequencies in Road Test Data

- Acceleration response measured on RSRM and transporter measured during on-road operation.
- Notably, 1.1 and 3.7 Hz spectral peaks observed in vertical response – closely matching vertical mode frequencies.
- Not all modes participated significantly in system response.



Summary

- A complete test and analysis program was undertaken in order to validate the model of a new RSRM segment transporter system.
- Excitation of large structure modes accomplished with phase combinations of multiple shakers.
- Correlated model capable of accurately predicting transporter and segment responses given a road profile input.