Operating Deflection Shapes for the Space Shuttle Partial Stack Rollout

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ABSTRACT

In November of 2003 a rollout test was performed to gain a better understanding of the dynamic environment for the Space Shuttle during transportation from the Vehicle Assembly Building to the launch pad. This was part of a study evaluating the methodology for including the rollout dynamic loads in the Space Shuttle fatigue life predictions. The rollout test was conducted with a partial stack consisting of the Crawler Transporter, Mobile Launch Platform, and the Solid Rocket Boosters with an interconnecting crossbeam. Instrumentation included over 100 accelerometers. Data was recorded for steady state speeds, start-ups and stops, and ambient wind excitations with the vehicle at idle. This paper will describe the operating deflection shape analysis performed using the measured acceleration response data. The response data for the steady state speed runs were dominated by harmonics of the forcing frequencies, which were proportional to the vehicle speed. Assuming a broadband excitation for the wind, analyses of the data sets with the vehicle at idle were used to estimate the natural frequencies and corresponding mode shapes. Comparisons of the measured modal properties with numerical predictions are presented.

INTRODUCTION

The Space Shuttle Orbiter is mated to the External Tank (ET) and Solid Rocket Boosters (SRBs) on top of a Mobile Launch Platform (MLP) in the Vehicle Assembly Building (VAB). A Crawler Transporter (CT) [1] is used to lift the nearly 12 million pound MLP-Space Shuttle assembly and carry it to one of the two launch complexes, which are approximately 3 to 4 miles away. The average duration of the transportation process is 6.4 hours with the CT reaching top speeds of 0.9 miles per hour.

A test was conducted in November of 2003 to gain a better understanding of the dynamic environment and to evaluate the methodology used to develop load spectra associated with the rollout mission phase for certification of Space Shuttle Orbiter life. Figure 1 shows the partial stack test configuration used in the November 2003 test. This configuration has the MLP with the loaded SRBs and External Tank (ET) cross beam on the CT. Acceleration, strain, wind, and hydraulic pressure measurements were acquired during the transport process. Data was collected for variations in CT operations including starts, stops, turns, speed variations, and ambient wind excitations with the CT at idle to evaluate the sensitivity of the response to the input forcing frequency. This report will focus on the operating deflection shape (ODS) analysis of the 111 channels of accelerometer data. Assuming a broadband wind excitation for the CT idle data sets, the ODS analyses were used to estimate the natural frequencies and mode shapes for numerical model validation. The test setup, CT operating conditions, ODS results, and comparisons with the numerical predictions are presented.

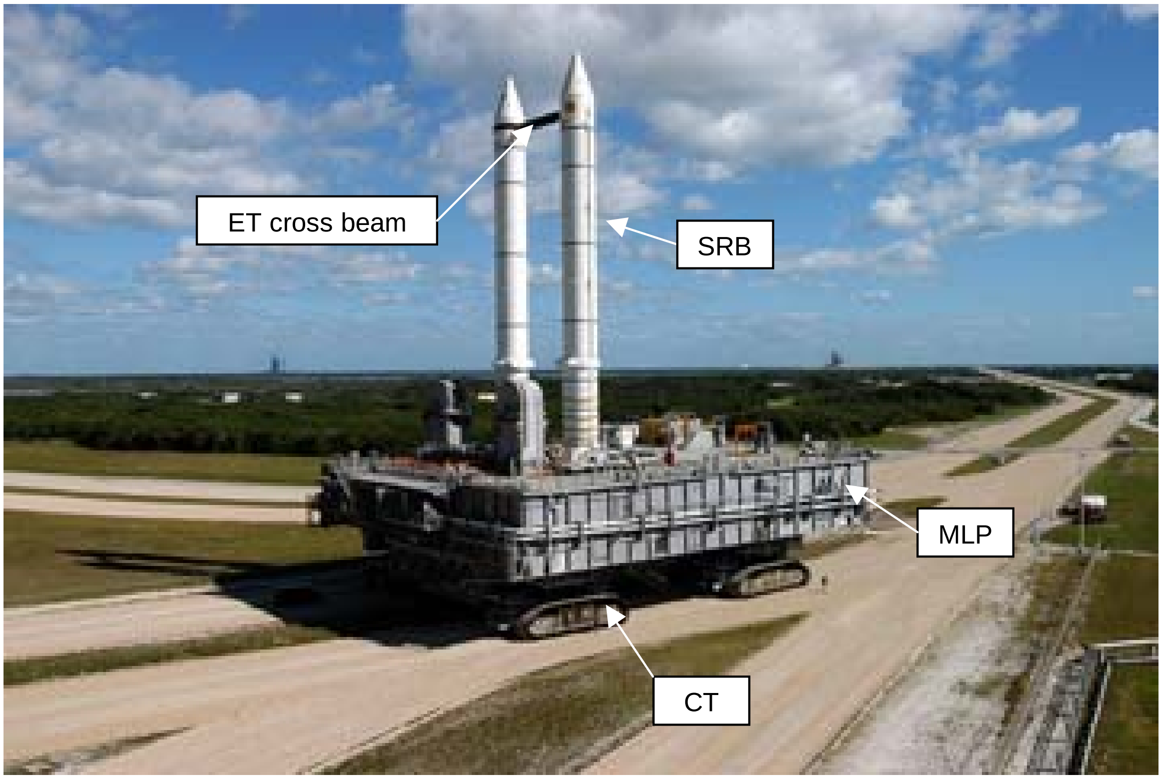

Figure 1. Partial stack rollout test.

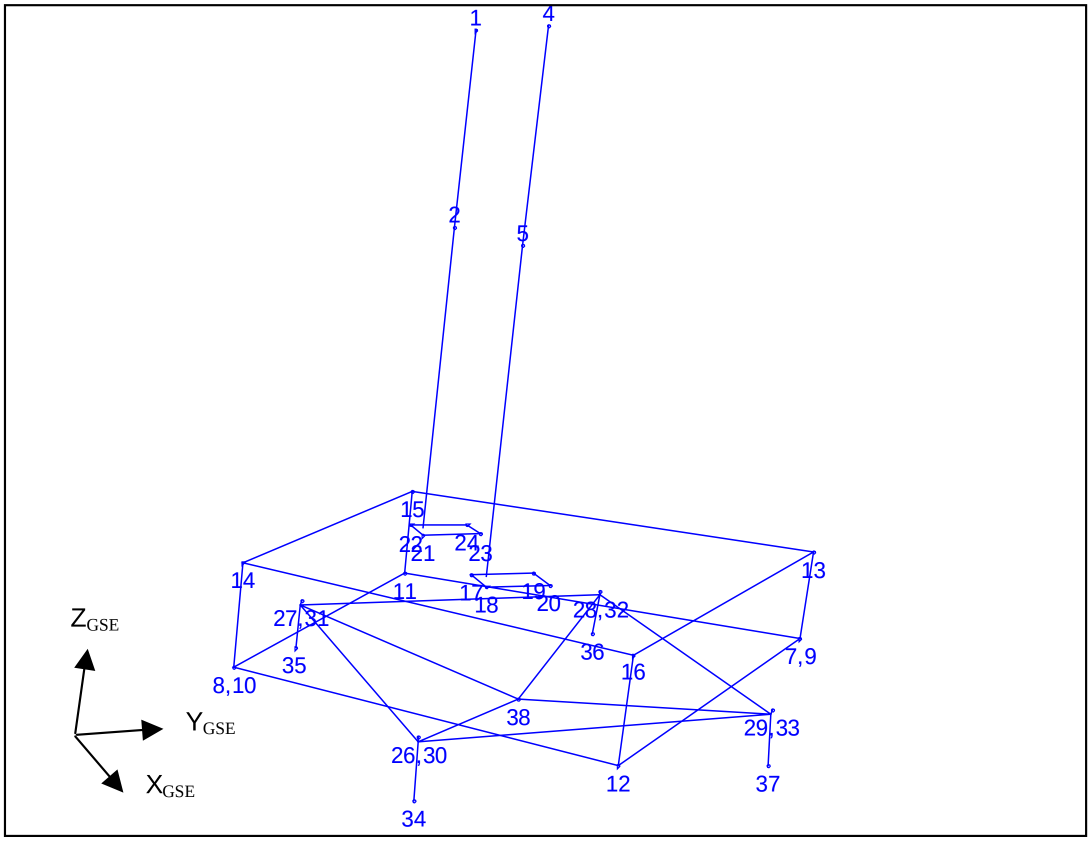

Figure 2. ODS measurement model.

MEASUREMENT MODEL

The locations of the 37 triaxial sets of accelerometers are shown in Figure 2. For reference, the measurement model in Figure 2 is approximately aligned with the photograph in Figure 1. The ground support equipment (GSE) coordinate system is shown in Figure 2, which has X_{GSE} in the lateral direction, Y_{GSE} in the direction of travel, and Z_{GSE} in the vertical direction. Three triaxial sets of accelerometers were located on each of the SRBs. The left hand (LH) SRB has measurement position 1 at the tip and 3 at the base. Points 21-24 are located on the four hold down attachments for the LH SRB. Similarly, for the right hand (RH) SRB, measurement point 4 is at the tip and 6 at the base with points 17-20 on the hold down attachments. Measurement points 13-16 are at approximately the midpoints between corners of the MLP upper level and measurement points 7-12 are located on the MLP lower level. Points 7 and 8 are duplicates of points 9 and 10, respectively. The accelerometers at points 9 and 10 are part of the nominal transducer set used during actual Space Shuttle rollouts. At the four MLP to CT interface points, measurement points 26-29 are on the MLP side and points 30-33 are on the CT side of the interface. Measurement point 38 is at the center of the CT chassis. At each of the CT to MLP interfaces, the CT has four hydraulic cylinders that are used for jacking, equalizing and leveling (JEL) during the transport process. The measurement points 30-33 are located above the JEL cylinders and points 34-37 are located at the base of the cylinders. Point 25 refers to the SRB hold down post strains and is not included in the accelerometer based measurement model.

ROLLOUT TESTS

Data was acquired during two days of rollout testing for the partial stack configuration. This included a series of steady state speeds from 0.5 to 0.9 miles per hour (mph), transient start-ups and stops, and ambient wind excitations with the CT at idle. For the steady state and ambient excitation conditions, data was typically recorded for 600 seconds with a time step of .00195 seconds. All accelerometer data used in the ODS analyses were simultaneously sampled and recorded using a 128-channel data acquisition system.

As will be illustrated in the results, the response spectra for the steady state data were dominated by the forcing frequencies [2] and harmonics associated with the CT speed. Therefore, for the purpose of estimating modal properties, ODS analyses concentrated on the ambient data sets. The ambient excitation data sets are described in Table 1. For the ambient data acquisition periods, the CT system was in an idle condition. A random excitation is assumed for these data sets.

Table 1. Ambient Excitation Data Sets

Test File	Test Day	Description
T020201	2	0-310 seconds; in VAB prior to motion, CT idle
T021401	2	600 seconds; ambient wind data set, CT idle
T021801	2	400-600 seconds; CT idle after stop from 0.9 mph
T031401	3	600 seconds; ambient wind data set, CT idle
T031901	3	600 seconds; ambient wind data set, CT idle
T034001	3	600 seconds; ambient wind data set, CT idle

ODS ANALYSIS

Operating Deflection Shapes (ODS) [3] can be defined as the deflection of a structure at a particular frequency or time. This is often used to evaluate the absolute dynamic behavior of a machine or structure under operating conditions. At or near a resonant frequency, the ODS is dominated by the corresponding resonant mode shape. However, the response measurements may also contain strong forced response components associated with the operating conditions. This can make it difficult to distinguish between the resonant and forced response components. Since the input forces are not measured, estimation of the modal properties from response only measurements is generally restricted to cases where the input force can be assumed to be broadband. Assuming a broadband excitation, the modal properties can be estimated by applying parameter estimation routines refined for the response only data [4,5]. This analysis procedure is sometimes referred to as Operational Modal Analysis (OMA) [5].

As described in a companion paper [2], the acceleration response of the partial stack was dominated by strong forced response frequencies and harmonics associated with the crawler transporter (CT) speed. Therefore, the CT constant speed data were highly dependent on the forcing function and not representative of a broadband excitation. The ambient wind data sets with the CT at idle were assumed to have a broadband excitation. Two independent ODS (or OMA) analyses were used to estimate the modal properties from the ambient wind data sets.

One data analysis approach used the ODS techniques available in ME'scope from Vibrant Technology [4] to estimate the modal properties from individual ambient data sets. Universal files were read in and processed into ODS frequency response functions (FRFs). An ODS FRF consists of the autospectrum for the magnitude and the phase from the cross spectrum with the selected reference. For this data set, 16384 lines of resolution were used (delta-f=.015625 Hz). The mean response was removed from the time signals but no other filtering of the data was performed. Twenty linear averages were taken over a 600 second time record with a 56% overlap. A Hanning window was used for the assumed random data. The reference degrees of freedom (DOFs) were 4-X, Y, and Z (top of SRB). Peak picking was the predominant method for the ODS analysis of the individual ambient data sets.

For the second data analysis approach, the first four ambient data records from Table 1 were combined into a single 1710-second record. The data was lowpass filtered to 15 Hz and then resampled to a 30 Hz sample frequency. Then, a time domain parameter estimation technique available in the Bruel & Kjaer OMA software [5] was applied to estimate the modal parameters. Several references were investigated. The analysis was most successful when using measurements on top of the SRB's (1-X, Y, Z; 4-X, Y, Z) as references.

RESULTS AND DISCUSSION

The power spectral density for an accelerometer mounted on the MLP (point 7) in the direction of travel is shown in Figure 3 for crawler transporter (CT) speeds of 0.8 and 0.9 MPH. There was a dominant forcing frequency proportional to the speed of the crawler transporter [2], such that a 0.8 MPH CT speed would result in the excitation of the first three harmonics of 0.8 Hz. As shown, the steady state speed data is dominated by the forcing frequencies and harmonics making it difficult to separate out modal frequencies. As an illustration of the response motion, an ODS for the 2.7 Hz frequency is shown in Figure 4. In animation, this shape appears to have combined pitch and yaw motion of the MLP with SRB bending out-of-phase with the MLP motion.

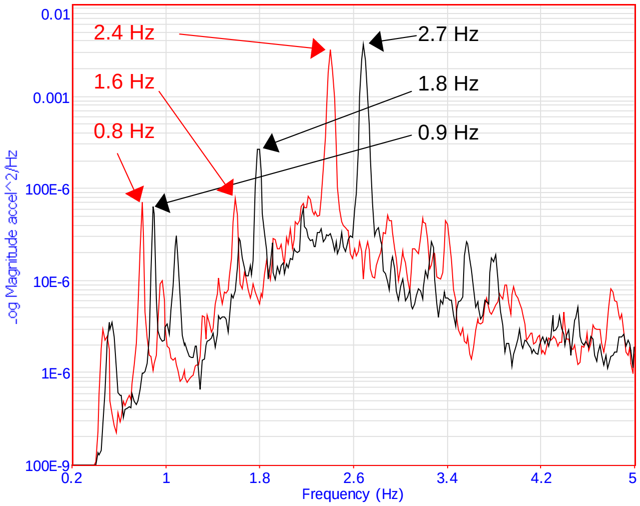

Figure 3. Power spectral density for point 7 in direction of travel for CT speeds of 0.8 MPH (red) and 0.9 MPH (black).

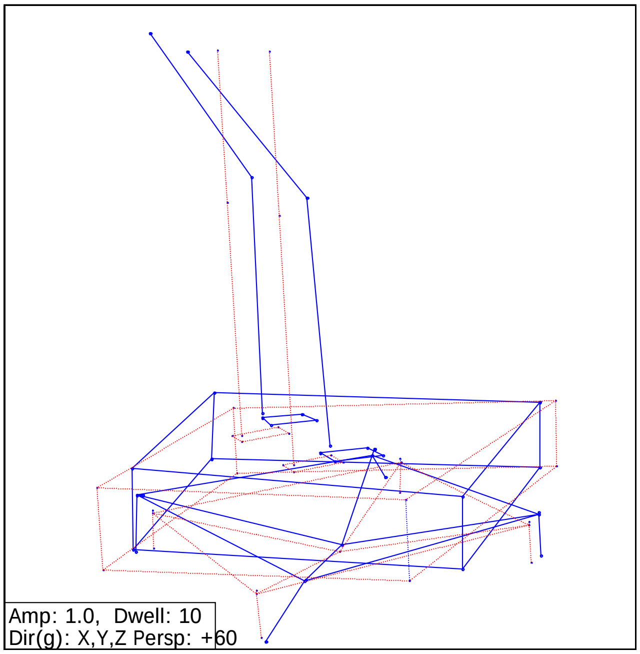

Figure 4. Operating deflection shape at 2.7 Hz for 0.9 MPH speed (blue-deformed; red–undeformed)

Figures 5 and 6 show sample power spectral density plots for the ambient wind data sets T021401 and T031401, respectively. The response is shown for the triaxial response transducer at the top of the right hand SRB. Assuming a broadband excitation, the dominant response peaks will correspond to natural frequencies of the system. The results of performing ODS analysis on the individual ambient data sets are presented in Table 2. All modes are not identified in each of the data sets indicating variations in the excitations and responses between data sets, as indicated in Figures 5 and 6. There are also closely spaced modal frequencies, which makes it difficult to resolve the modal properties.

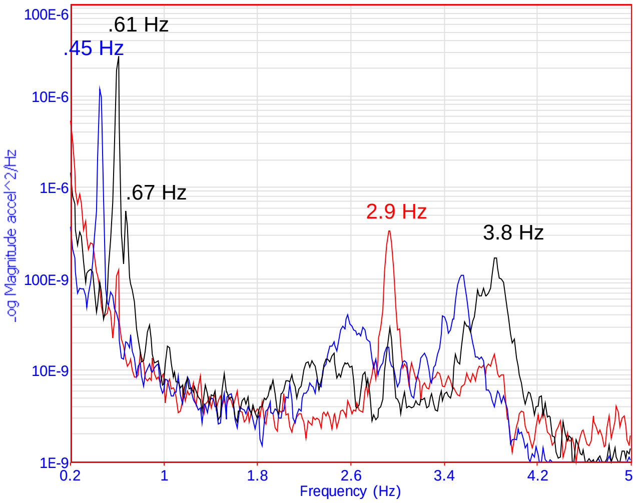

Figure 5. Power spectral density for point 4 in X_{GSE} (blue), Y_{GSE} (black), and Z_{GSE} (red) directions for ambient wind data set T021401.

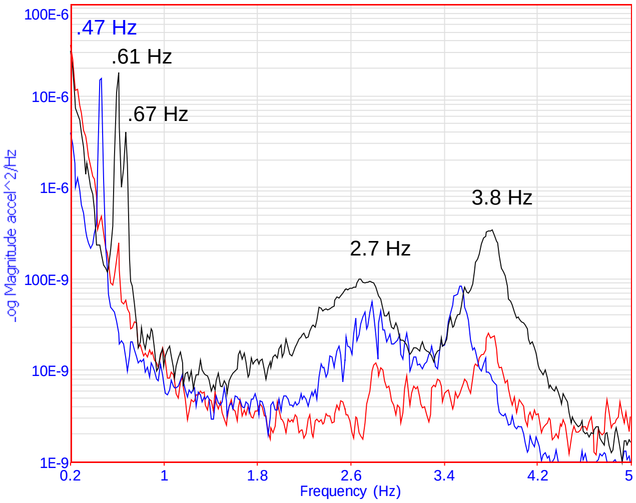

Figure 6. Power spectral density for point 4 in X_{GSE} (blue), Y_{GSE} (black), and Z_{GSE} (red) directions for ambient wind data set T031401.

Table 2. ODS Summary of Results

Description\Data Set	**T020201 Freq. (Hz)**	**T021401 Freq. (Hz)**	**T031401 Freq. (Hz)**	**T031901 Freq. (Hz)**	**Overall Freq. (Hz)**
SRB Bending (X_{GSE})	.47	0.45	.47	.45	.45-.47
SRB Bending (Y_{GSE})	0.59	0.61	.61	.61	.59-.61
SRB Bending out-of-phase (Y_{GSE})	0.67	0.67	.67		.67
System Lateral Mode SRB's out-of-phase with MLP (X_{GSE})		2.58		2.55-2.61	2.55-2.61
System Yaw Mode	2.7				2.7
System Vertical (Z_{GSE}) / Pitch Mode			2.7-2.78		2.7-2.78
System Vertical–"Bounce on JEL" (Z_{GSE})		2.92		2.88	2.88-2.92
System Vertical (Z_{GSE}) with SRB Bending (X_{GSE})	3.44	3.53	3.53	3.53	3.44-3.53
SRB 2nd Bending (Y_{GSE}) out-of-phase	3.69	3.7	3.67	3.64	3.64-3.7
SRB 2nd Bending (Y_{GSE}) in-phase	3.77	3.84	3.81	3.86	3.77-3.86

In Table 3, the frequency estimates from ODS analysis for the individual ambient data sets and the OMA for the combined ambient data sets are compared to the normal mode predictions [6]. The frequencies listed were based on visual comparisons with the numerical deflection shapes. For the OMA analysis, the mode at 2.0 Hz required a reference in the middle of an SRB and high model order in order to identify it. The highest confidence is in the frequencies estimated by both the ODS analysis for individual data sets and OMA for the combined data sets, which are highlighted in bold print. These are predominantly modes with significant SRB participation, as illustrated by the modes shown in Figures 7and 8. The system modes were difficult to identify from the ambient response data sets. It is important to note that two system modes were measured at 2.7 and 2.9 Hz that are not present in the results for the numerical model. The mode shapes for these frequencies are shown in Figures 9 and 10. The response of the system indicates relative motion across the CT hydraulic jacking, equalizing and leveling (JEL) system (see Figure 2, points 30-33 at top versus 34-37 at base of JEL system). These modes were not consistently excited/identified in all of the ambient data sets. However, the mode at 2.7 Hz may be critical since it is at the third harmonic of the forcing frequency for the 0.9 MPH CT speed. A comparison of Figures 4 and 9 indicates that the operating deflection shape at 2.7 Hz contains similar MLP pitch and SRB bending motions as the mode estimated at 2.7 Hz. However, the forced response shown in Figure 4 contains a significant amount of MLP yaw motion that is not observed in the 2.7 Hz mode shown in Figure 9. There is a 2.58 Hz yaw mode predicted by the numerical model which may be contributing to the forced response.

Table 3. Comparison of Results

Description	Numerical Model Frequency (Hz)	OMA Combined Data Sets Frequency (Hz)	ODS for Separate Data Sets Frequency (Hz)
SRB Bending (X_{GSE})	**0.47**	**0.46**	**.45-.47**
SRB Bending (Y_{GSE})	**0.58**	**0.58**	**.59-.61**
SRB Bending out-of-phase (Y_{GSE})	**0.78**	**0.67**	**.67**
System Longitudinal Mode (Y_{GSE})	2.10	0.92	
SRB Bending out-of-phase (X_{GSE})	2.12	2.01	
System Lateral Mode SRB's out-of-phase with MLP (X_{GSE})	**2.38**	**2.44**	**2.55-2.61**
System Yaw Mode	2.58		2.7
System Vertical (Z_{GSE}) / Pitch Mode		2.71	2.7-2.78
System Vertical Mode–"Bounce on JEL" (Z_{GSE})			2.88-2.92
System Vertical (Z_{GSE}) with SRB Bending (X_{GSE})	**3.40**	**3.40**	**3.44-3.53**
SRB Bending (X_{GSE})	3.51		
System Pitch Mode	3.66		
SRB 2nd Bending (Y_{GSE}) out-of-phase	**3.70**	**3.61**	**3.64-3.7**
SRB 2nd Bending (Y_{GSE}) in-phase	**3.87**	**3.80**	**3.77-3.86**

Notes: X_{GSE} -lateral, Y_{GSE} -direction of travel, Z_{GSE} –vertical.

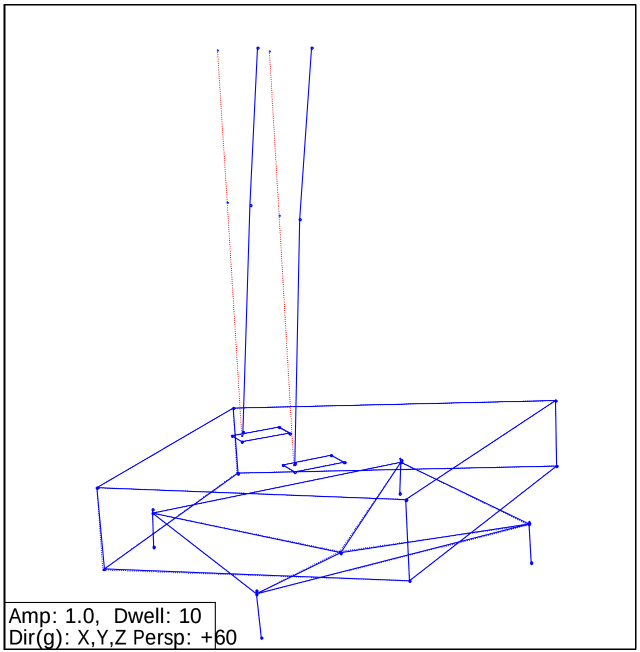

Figure 7. Measured mode shape at 0.61 Hz, SRB 1st bending in Y_{GSE}. (blue-deformed; red–undeformed)

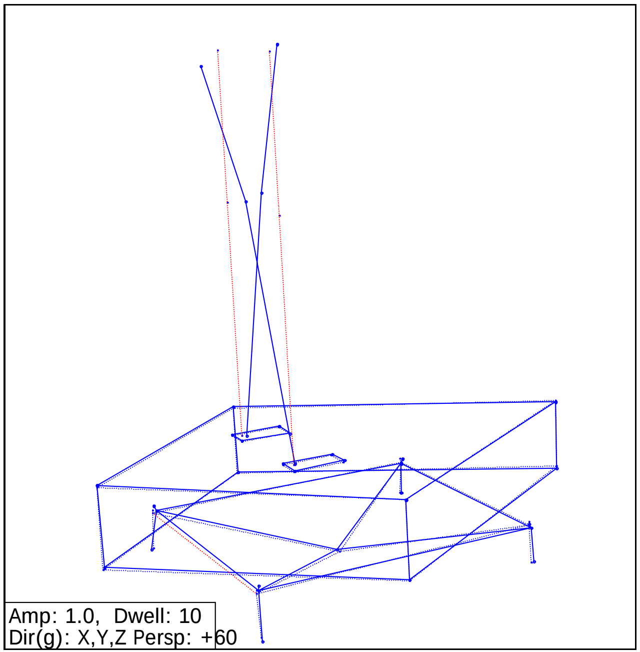

Figure 8. Measured mode shape at 0.67 Hz, SRB 1st bending in Y_{GSE} (LH SRB out-of-phase with RH SRB). (blue-deformed; red–undeformed)

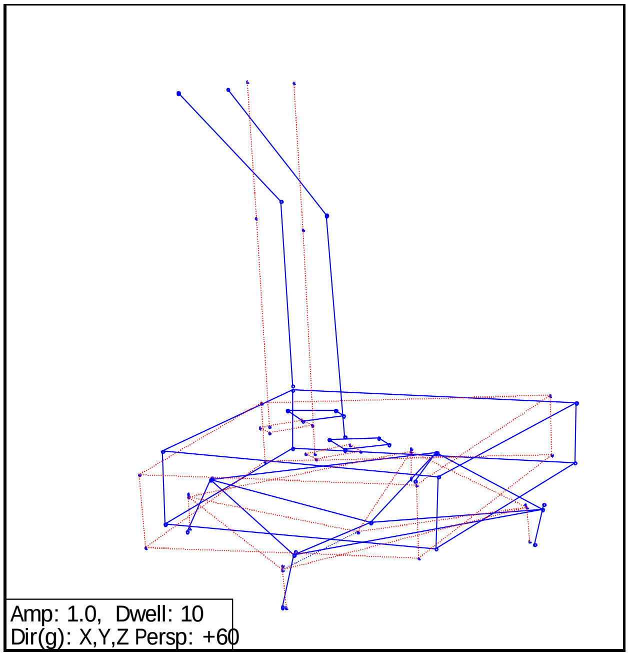

Figure 9. Measured mode shape at 2.7 Hz, MLP pitch with SRB bending out-of-phase with MLP. (blue-deformed; red–undeformed)

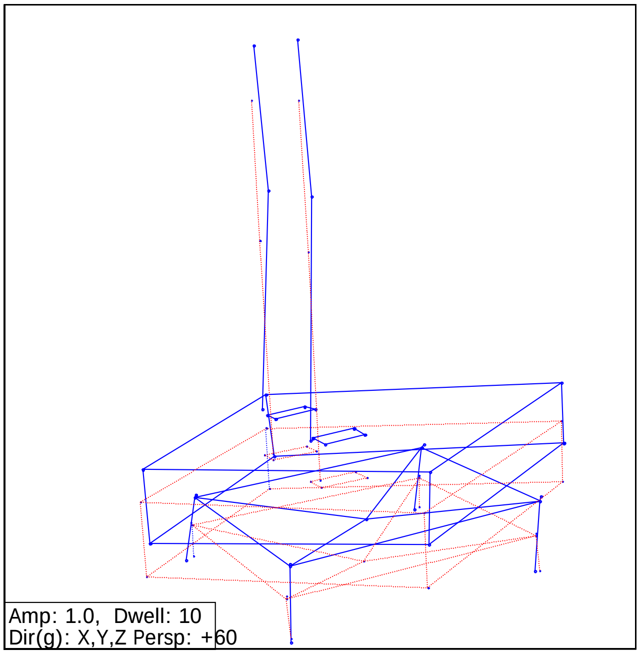

Figure 10. Measured mode shape at 2.9 Hz, vertical “bounce on JEL.” (blue-deformed; red–undeformed)

CONCLUSIONS

The steady state CT speed runs were dominated by the input frequencies and harmonics making it difficult to separate out modal frequencies. Therefore, ODS analyses concentrated on the ambient wind, CT idle, data sets. There is good agreement between the measured and predicted natural frequencies for the SRB bending modes. System modes of the overall CT, MLP, SRB assembly were more difficult to define. The overall system is a massive structure that is difficult to excite with ambient excitations associated with the wind and idling CT engines. Two system modes involving relative motion of the CT JEL system were measured at 2.7 and 2.9 Hz that are not present in the results for the numerical model. These modes were not consistently excited/identified in all of the ambient data sets. However, the mode at 2.7 Hz may be critical since it is at the third harmonic of the forcing frequency for the 0.9 MPH CT speed. Further investigation is required to define the system level modes with confidence.

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