Feasibility Study to Extract Artemis-1 Fixed Base Modes While Mounted on a Dynamically Active Mobile Launch Platform

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ABSTRACT

There are several challenges associated with the scheduled integrated modal test (IMT) of the Space Launch System (SLS) Artemis-1 flight vehicle mounted on the mobile launcher (ML). While the goal of the test is to characterize the Artemis-1, the inclusion of the ML as the support stand for the test means that the entire system must be well characterized. A considerable amount of effort and schedule will have to be devoted to understanding both the test stand (the ML) and the Artemis-1 flight vehicle, and there is a risk that the effort may not be completed in time for a successful launch.

NASA has requested that alternative methods be investigated to generate test results that can remove the effects of the ML from the test. ATA Engineering, Inc., (ATA) was given a reduced model f the Artemis-1 flight vehicle's IMT configuration containing the candidate set of accelerometers and interface degrees of freedom (DOF). The model was used to determine how well ATA's fixed base correction technique is able to estimate fixed base modes from test data collected on the IMT. This paper presents the fixed base correction method results.

Keywords: modal testing, boundary conditions, frequency response functions

ACRONYMS

ATA	ATA Engineering, Inc.
CMIF	complex mode-indicator function
DOF	degree of freedom
FRF	frequency response function
IMT	integrated modal test
ML	mobile launcher
SLS	Space Launch System

INTRODUCTION AND BACKGROUND

ATA Engineering, Inc., (ATA) proposed to use our fixed base correction method to estimate fixed base modes of the Artemis-1 flight vehicle while it is mounted to the mobile launcher (ML) in the Vehicle Assembly Building at Kennedy Space Center. The fixed base correction method is a proven method that has been applied to a number of structures with flexible bases. The method derives from the fact that frequency response functions (FRFs) that use accelerations as references correspond to structures with modes that are fixed at those same reference accelerometer locations and directions. In this case, the accelerations are associated with the interface between the Artemis-1 flight vehicle and the ML. Since the motion at every degree of freedom (DOF) at a structure interface is truly independent at lower frequencies, a smaller number of generalized DOF, hereafter called constraint shapes, are used as references. This assumption is valid as long as the constraint shapes can capture the motion of the interface. The key to implementing this method is that at least as many independent sources must be applied to the ML as there are constraint shapes used to construct an invertible reference autospectral matrix (which is required for high-quality FRFs). A full mathematical investigation of the technique is provided in reference [1], and several examples of its implementation are provided in references [2] through [6].

In this paper, however, the drive point accelerometers at the interface DOF were used as references instead of constraint shapes. The different shaker combinations were selected to ensure that rigid or flexible body motion of each set of interface points could be excited. One can think of a given set of drive point accelerometers as a linear combination of the same number of calculated constraint shapes using the same accelerometers.

The actionable results from using this method are FRFs associated with the Artemis-1 flight vehicle mounted to a fixed base. These FRFs can be used as inputs into standard modal analysis software tools to extract fixed based modes. The resulting fixed base modes can then be compared to fixed base analysis modes of the Artemis-1 flight vehicle, both visually and mathematically, to make decisions about the validity of the analysis model.

For the assessment of this method’s feasibility, ATA was given a reduced model of the integrated modal test (IMT) setup using 3,926 DOF associated with the full candidate set of accelerometers, as well as all 24 interface DOF consisting of all three translational degrees at eight locations where the Space Launch System (SLS) connects to the ML. This 3,926-DOF model is assumed in this study to be the truth model, and the FRFs generated from this model are considered to be truth data associated with the full system. The model was reduced to the SLS DOF by eliminating all rows and columns not associated with the Artemis-1 flight vehicle. The interface DOF were not included in the SLS DOF set. This reduced model, containing 2,720 DOF, is considered the truth model associated with fixed base modes.

This paper uses the ATA fixed base correction technique to transform FRFs associated with the system model to FRFs associated with the fixed base model. Five locations on the Artemis-1 analysis model were selected as shaker locations and were used to generate both the system-level FRFs and the fixed base FRFs. The analysis models are discussed below.

ANALYSIS MODEL

The DOF associated with a 4,000-DOF system model and the 2,200-DOF Artemis-1 fixed base model are presented in Fig. 1. The 2,200-DOF fixed base model was created by fixing all DOF not associated with the Artemis-1 portion, including the 24 interface DOF associated with the interface, shown in Fig. 2. The interface DOF were also used as candidate shaker locations for shakers mounted to the ML. In addition, five shaker locations were selected on the SLS to excite the structure primary modes. These five locations, listed in Fig. 3, represent shakers that could be used for the overall modal survey. The objective of this effort was to convert system FRFs from these five shakers into fixed base FRFs. These shaker locations are not the specific shakers that will be used in the overall modal survey, but the effect of the ATA fixed base correction method will be the same for these shakers as they will be for other shakers mounted on the structure.

Lists of the first 33 modes of the system and fixed base model are presented in Fig. 4. A comparison table between the two sets of modes is also presented. The comparison table maps the fixed base mode in column 1 to the analysis mode with the cross-orthogonality derived from the mass matrix of the fixed base model with 2,720 DOF. The percent frequency difference and cross-orthogonality between the two modes are also presented. The cross-orthogonality calculation was performed using the fixed base model mass matrix. The modes with high effective mass and large frequency shifts are highlighted.

Fig. 1 Left panel shows 3,926-DOF system model and right panel shows 2,720-DOF fixed base model

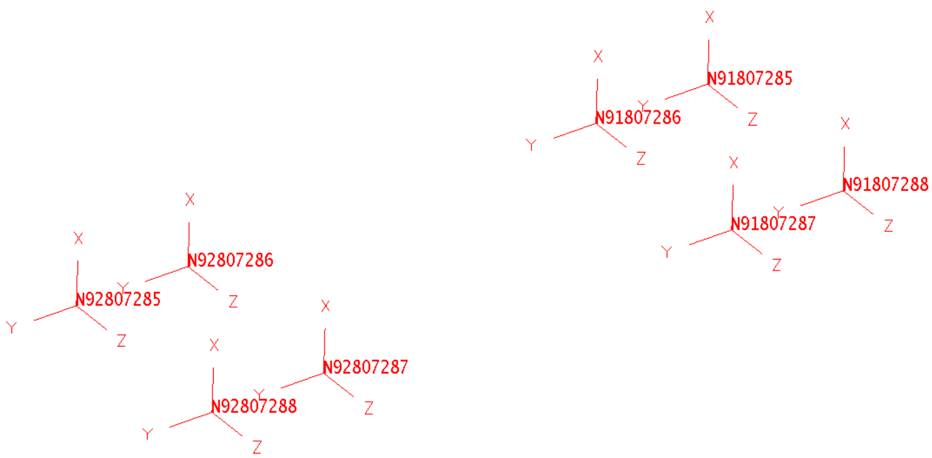
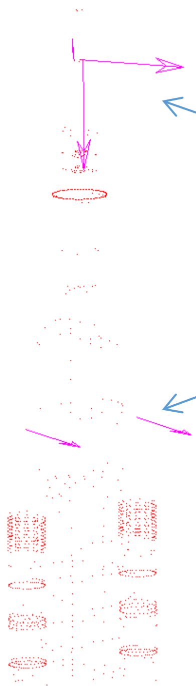


Fig. 2 Interface DOF that define the fixed base of the SLS model[1]

[1] The analysis in this paper assumes that the base shakers are applied to these DOF. However, the base shakers can be applied at nearby locations if those are more readily accessible.



DOF	Description	Purpose
'4812597Y+'	Near top of vehicle	Excite Lateral Modes
'4812633Z+'	Near top of vehicle	Excite Vertical Modes
'4812743Y+'	Near top of vehicle	Excite Lateral Modes
'1880067Y+'	Y- SRB, Lateral	Excite Torsion Modes
'2880067X+'	Y+ SRB, Lateral	Excite Torsion Modes

Fig. 3 Shaker locations on the SLS portion of the analysis model

Fixed Mode No.	System Mode No.	% Freq Diff	Cross Ortho
1	3	-12.40	100
2	6	-9.36	100
3	8	-8.73	94
4	10	-6.85	99
5	12	-2.14	97
6	14	-3.43	100
7	18	1.39	98
8	19	-1.59	97
9	21	-2.21	99
10	23	0.64	90
11	25	-2.07	99
12	32	-2.16	99
13	34	-6.28	99
14	38	-1.60	85
15	37	-6.54	89
16	28	-35.22	88
17	53	-0.11	90
18	48	-9.49	81
19	55	-1.52	93
20	52	-6.90	98
21	64	3.91	86
22	60	-1.91	82
23	67	-0.44	99
24	70	0.00	100
25	71	0.00	98
26	73	0.00	89
27	72	-0.12	85
28	74	0.00	100
29	75	0.00	100
30	76	0.00	100
31	79	-0.26	73
32	80	0.00	100
33	82	0.00	96

Fixed to System Comparison

Fig. 4 Comparison table between fixed and system modes (right), with primary target modes highlighted

ANALYSIS STRATEGY

The analysis strategy was similar to the effort put forward in reference [7], except that instead of investigating just the primary vehicle vertical mode, the first 21 fixed base modes were investigated. FRFs were generated using the system-level model at the five locations on the vehicle and various subsets of the 24 interface DOF defined in Fig. 2. The FRF matrix was partially inverted such that the drive point accelerations of the shakers on the base were used as references instead of the forces. The resulting FRFs were then used to extract modal parameters. The resulting fixed base modes from the procedure were compared to the modes from the fixed base model.

This procedure was performed for six different shaker combinations, each representing a different subset of the 24 interface DOF. The combinations at the base were as follows:

- All 24 DOF: 8 vertical, 16 lateral
- 16 DOF: 8 vertical, 8 lateral
- 14 DOF: 8 vertical, 6 lateral
- 12 DOF: 8 vertical, 4 lateral
- 12 DOF: 6 vertical, 6 lateral
- 11 DOF: 8 vertical, 3 lateral
- 9 DOF: 6 vertical, 3 lateral

The specific locations and directions are plotted as arrows in Fig. 5.

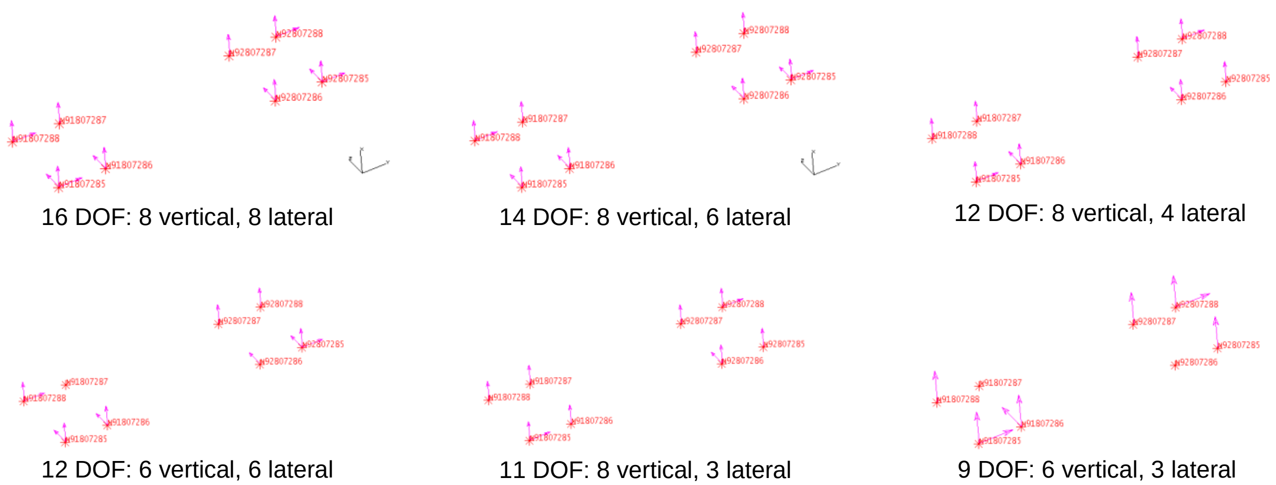


Fig. 5 Base shaker location and directions are shown as arrows

The shaker locations were evenly spread across both interface sets. In the case of three lateral inputs, two inputs in the Y direction were assumed to be able to excite Y-direction motion and in-plane rotation of the interface, and one input in the Z direction to excite in-plane motion in the Z direction.

RESULTS

At the core of the ATA fixed base correction method is the generation of fixed base FRFs that can be used to extract fixed base modes.

The percent frequency difference and cross-orthogonality between the fixed base modes and the corrected fixed base modes for each base shaker configuration are presented in Table 1 and Table 2. The first three columns are associated with the fixed base model. The modes for each shaker case were extracted from the resulting FRFs. The results from the 24-shaker case should exactly match the fixed base results, and any very minor errors in the results are more likely due to the modal extraction algorithm. The modes listed for the system-level model with zero base shakers were copied directly from the comparison table in Fig. 4. The cross-orthogonality values are higher than the extracted modes for this reason.

As expected, the accuracy of estimating the fixed base modes increases as the number of base shakers increases. The first case using nine shakers significantly shifts the frequencies of the modes to levels that may be acceptable for the IMT, and adding more than twelve shakers minimally improves the frequency and cross-orthogonality results.

Table 1 Percent frequency error of modal extractions using ATA fixed base correction method for various numbers of proposed shaker configurations

No. Shakers	24	16	14	12	12	11	9	0
Vertical Shakers	8	8	8	8	6	8	6	Full
Lateral Shakers	16	8	6	4	6	3	3	System
Mode Number	**% Frequency Difference From Fixed Base**							
1	0.0	-1.1	-1.5	-1.5	-2.6	-1.6	-2.9	-12.4
2	0.0	-2.4	-2.7	-4.5	-3.4	-4.8	-5.0	-9.4
3	0.0	-0.4	-0.5	-0.8	-0.8	-1.6	-2.2	-8.7
4	0.0	-1.5	-1.5	-2.1	-2.6	-2.5	-3.6	-6.8
5	0.0	-0.2	-0.3	-0.3	-0.6	-0.5	-0.7	-2.1
6	0.0	-1.3	-1.4	-2.8	-2.0	-3.0	-3.8	-3.4
7	0.0	-1.0	-1.0	-2.1	-1.7	-4.9	-4.1	1.4
8	0.0	-1.6	-2.7	-3.0	-3.7	-3.5	-3.8	-1.6
9	0.0	-1.3	-1.4	-3.9	-1.7	2.0	-8.5	-2.2
10	0.0	-0.1	-0.2	-0.3	-0.2	-0.3	-0.4	0.6
11	0.0	-0.2	-0.4	-0.4	-0.6	-0.6	-0.8	-2.1
12	0.0	-0.8	-1.2	-1.0	-2.2	-1.5	-2.1	-2.2
13	0.0	-1.9	-2.7	-3.1	-2.8	-3.4	-3.2	-6.3
14	0.0	-1.2	0.8	0.7	0.7	0.7	0.7	-1.6
15	0.0	-3.9	-4.4	-4.4	-4.5	-5.1	-4.6	-6.5
16	0.0	-0.3	-0.4	-3.3	-2.9	-4.2	-5.9	-35.2
17	0.0	-0.1	-0.1	-0.3	-0.3	-0.4	-0.8	-0.1
18	0.0	-2.1	-2.1	-2.6	-3.9	-2.7	-4.0	-9.5
19	0.0	-0.4	-0.4	-0.5	-1.0	-0.9	-1.5	-1.5
20	0.0	-3.1	-3.1	-3.7	-3.6	-3.8	-4.6	-6.9
21	0.0	-1.0	-1.2	-2.2	-1.5	-2.4	-2.5	3.9

Table 2 Cross-orthogonality of modal extractions using ATA fixed base correction method for various numbers of proposed shaker configurations

No. Shakers	24	16	14	12	12	11	9	0
Vertical Shakers	8	8	8	8	6	8	6	Full
Lateral Shakers	16	8	6	4	6	3	3	System
Mode Number	**Cross-Orthogonality w/Fixed Base**							
1	100	100	100	100	100	100	100	100
2	100	100	100	100	100	100	100	100
3	100	100	100	100	99	100	91	94
4	100	100	100	100	99	100	90	99
5	100	100	100	100	100	100	100	97
6	99	99	99	100	99	100	94	100
7	100	100	100	99	98	99	97	98
8	100	100	100	100	97	100	93	97
9	100	100	100	96	99	96	77	99
10	100	100	100	100	100	100	90	90
11	100	100	100	100	100	100	100	99
12	100	99	99	99	99	99	99	99
13	100	99	96	92	99	92	86	99
14	100	94	86	85	85	85	86	85
15	100	31	92	90	91	90	87	89
16	100	100	100	99	99	99	98	88
17	100	100	100	98	93	98	82	90
18	100	92	92	93	61	93	55	81
19	100	89	89	91	82	91	76	93
20	100	80	79	91	80	91	93	98
21	100	89	86	94	88	94	58	86

Although 21 modes that correspond to the 21 fixed base modes were extracted, there were also other modes observable in the corrected fixed base FRFs. The number of additional modes increased as the number of base shakers decreased. Fig. 6 presents

FRFs synthesized from the 21 extracted modes presented in Table 1**Error! Reference source not found.** and Table 2 overlaid with the corresponding simulated test data. Spurious modes are shown for the 9-DOF case, and one low-responding mode is observable in the 12-DOF case. These spurious modes are identified by red arrows. Note that there are no spurious modes for the 24-DOF case. Thus, spurious dynamics (additional modes) from the ML are removed as more shakers are added to the base.

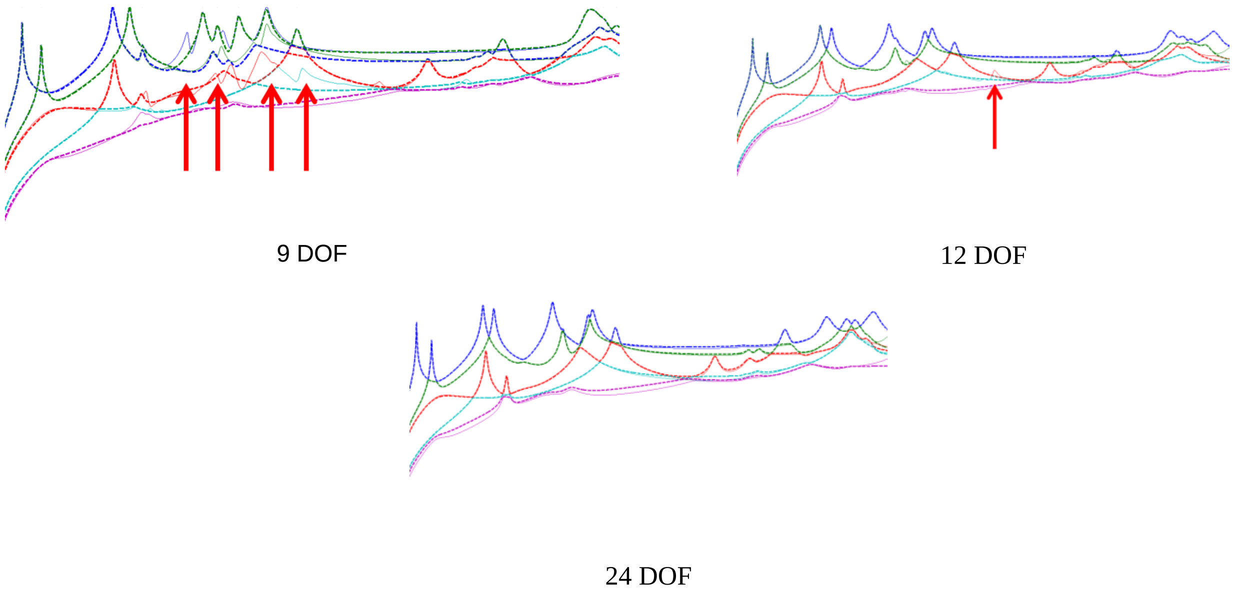


Fig. 6 Comparison of CMIFs from synthesized FRFs from the 21 extracted modes to the FRFs from the fixed base correction method

The issue of spurious modes can be accounted for by using spatial filtering to deemphasize nontarget modes and simultaneously emphasize target modes. Spatial filtering can also help emphasize modes that may not be observable from the complex mode indicator function (CMIF) plot.

TECHNOLOGY READINESS LEVEL

This method has been used on funded projects, including the European Structural Test Article (E-STA) modal survey in 2016. Data processing scripts have been developed but have not yet been packaged into a commercially available format.

SUMMARY

This paper presents the results using the ATA fixed base correction method to help generate fixed base FRFs of the Artemis-1 flight vehicle while it is mounted on the dynamically active ML. The method is better able to generate fixed base modes as the number of base shakers increases. Ultimately, however, the number of shakers needed for the base will depend on how closely the corrected fixed base modes will match the actual fixed base modes in frequency.

Although there may be spurious modes in the frequency range of interest, methods such as spatial filtering of the test-measured data can be used to help identify the target modes.

For this study, the minimum number of base shakers was determined to be nine, and the maximum effective number of shakers is likely to be twelve, with six vertical and six lateral shakers mounted near the interface. The frequencies are predicted to be approximately within 2.5%–3.5% of the fixed base modes for major target modes with high effective mass and closer in frequency for modes with lower effective mass.

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