

Assessment of Artemis-1 Pogo Flight Instrumentation System

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As the space industry continues to strive for more efficient launch vehicles, it must rely on increasingly accurate predictive models. Verification of models typically requires physical testing. Flight data measurements offer the most real and therefore the most accurate data for model correlation. As NASA prepares for the inaugural launch of Space Launch System (SLS), Artemis-1, they must rely heavily on predictive system models to ensure flight safety. NASA has implemented a Development Flight Instrumentation (DFI) system in hopes of recovering useful flight data to aid in model correlation. Historically, some of the most important flight measurements are those that monitor the potentially destructive dynamic interaction of the structural and propellant modes – a phenomenon known as pogo. Pogo is a dynamic instability that can occur on a launch vehicle during any phase of ascent. During this investigation an end-to-end assessment of the Artemis-I Pogo-related DFI was performed to identify any obstacles inherent in the current instrumentation system which may prevent successful measurement of the data necessary to validate the current predictive models of the Main Propulsion System (MPS). Input drive signals were approximated and applied to a system-level SLS state-space model to derive predicted pressure and acceleration responses. These predicted responses were then fed through a simulation of the data acquisition process in order to recover predicted measurements. Finally, a mock Flight Data Analysis (FDA) was performed to assess the ability of these measurements to meet the Flight Test Objectives (FTO).

I. Nomenclature

H_s	=	Structural Dynamics Transfer Function
H_f	=	Propellant Dynamics Transfer Function
H_t	=	Turbo-machinery Transfer Function
ΔP	=	Fluctuating Pressure

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A	=	Continuous Time State Matrix
X	=	Continuous Time State Vector
A_m	=	Continuous Time State Matrix Partition (modal degrees of freedom)
X_m	=	Continuous Time State Vector Partition (modal degrees of freedom)
X_{accel}	=	Continuous Time State Vector Partition (physical accelerations)
ϕ	=	Structural mode shape matrix

II. Introduction

Pogo is a self-excited instability due to dynamic coupling of propellant hydro-dynamics and structural dynamics. It was first identified as a threat during the Gemini program and continued to significantly affect NASA launch vehicles until the Space Shuttle Program incorporated an integral pogo suppression system into its first stage (Ref. [1]).

Launch vehicle axial structural dynamics can be represented by a closed loop dynamics model primarily driven by thrust from liquid engine combustion. As shown in Fig. 1, structural perturbations excite propellant resulting in thrust fluctuations in the main combustion chamber (MCC) which in-turn feedback to excite the structure. Ideally, this feedback loop is stable. However, when the frequency and phase of a structural resonance and a propellant fluid resonance combine in a particular manner, this feedback path can become unstable and result in potentially destructive structural vibration. During a pogo stability analysis, this instability presents as a pole of the closed-loop system with negative damping.

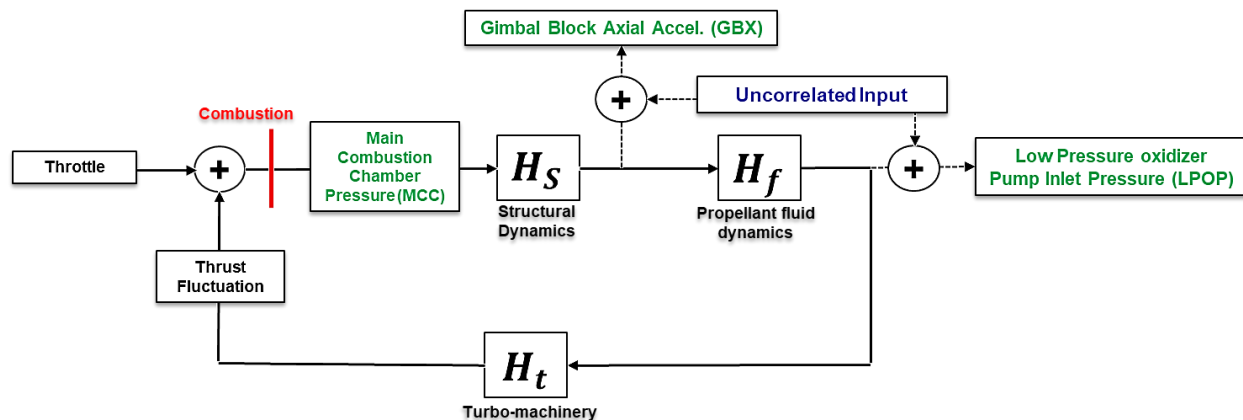


Fig. 1 Pogo closed loop dynamics representation

Typically, predictive models used for pogo assume direct correlation between MCC pressure and vehicle dynamic accelerations. However, on SLS, MCC pressure is not the only forcing function influencing the integrated launch vehicle vibrations during ascent. During the Artemis I flight, loading due to the SRBs is expected to impart a significant amount of in-band excitation, which will be uncorrelated to the Main Propulsion System (MPS) dynamics. Data from Space Shuttle flights before and after SRB separation demonstrated that gimbal axial acceleration is significantly affected by SRB combustion (Ref. [2]). Acceleration will not be the only measurement affected by uncorrelated noise. Pressure measurements will also be affected by uncorrelated sources. The primary expected noise source in feedline pressure measurements is flow turbulence. Flow turbulence appears as broad-spectrum pressure fluctuations caused by flow separation and the formation of eddies within the propellant feedlines.

There are a number of known challenges to identifying self-excited pogo dynamics in the presence of high levels of in-band uncorrelated noise. Pogo measurements must be made in a relatively short duration due to constantly changing flight parameters during ascent (i.e. launch vehicle mass). This limits the amount of data available to determine accurate frequency response relationships in low signal-to-noise (SNR) environments. These challenges are typically present during nominal, stable flight. Structural-propellant transfer functions become increasingly observable as the self-excited dynamics approaches instability. During an anomalous pogo instability, the self-excited dynamics become the dominant signal (Ref. [2]), and correlation is easily observable.

An end-to-end assessment of the Artemis-I Pogo-related DFI was performed to identify any obstacles inherent in the SLS instrumentation system which may prevent successful system identification of the SLS pogo closed-loop

dynamics. Artemis-I closed-loop dynamic responses were approximated using heritage data as well as a SLS state-space model. These predicted responses were then fed through a simulation of the Artemis-1 data acquisition system in order to recover predicted flight measurements. Finally, a mock Flight Data Analysis (FDA) was performed to assess the ability of the measurements to meet the Flight Test Objectives (FTO).

III. Signal Synthesis

For this analysis, representative time domain signals were generated for the engine Gimbal Axial acceleration (GBX) channels as well as Low-Pressure Oxidizer Pump (LPOP) inlet fluctuating pressure channels. These signals were informed by analytical predictions as well as Space Shuttle flight data. With the help of NASA/MSFC, target power spectral densities (PSD) were derived for each channel using corresponding measurements recovered from STS flight data. As discussed in section II, it was assumed that the magnitude of the PSDs included response driven by the MPS (signal of interest) as well as response driven by various other sources uncorrelated to the MPS (uncorrelated noise). In order to capture this combination, the signal generation process was performed in two steps (illustrated in Fig. 2):

1. Generate the signal of interest
2. Pollute the signal of interest with in-band, random noise

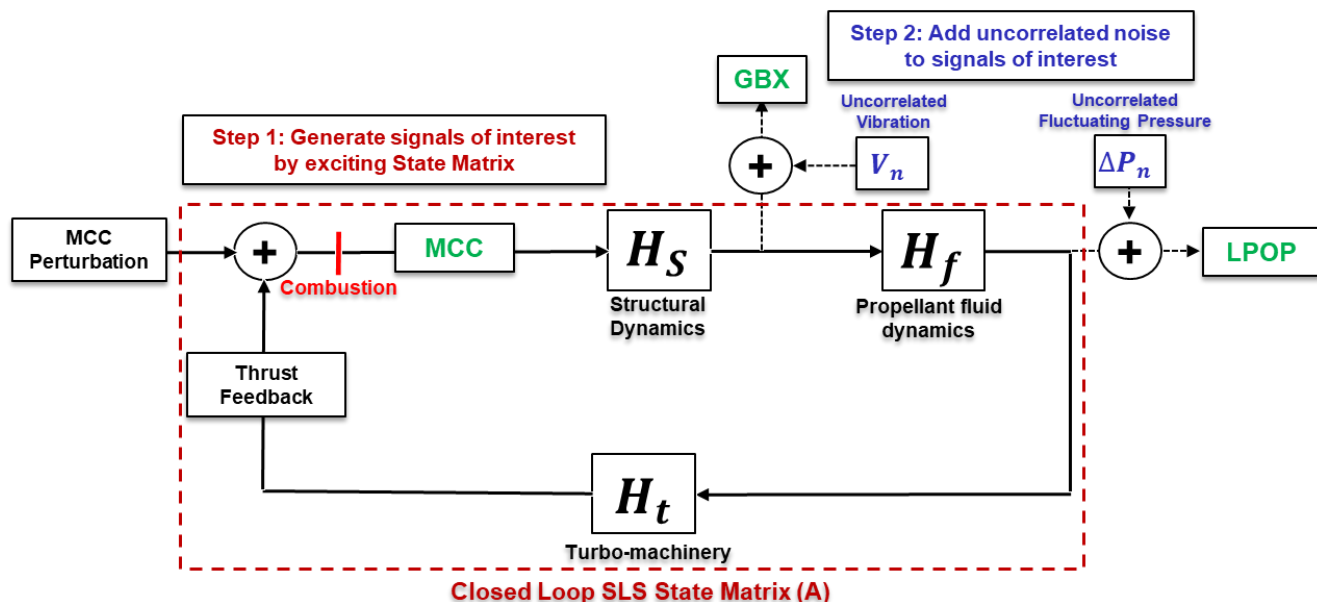


Fig. 2: Nominal signal generation process

The signal of interest was generated by exciting an SLS state matrix (A) that represented the full, closed-loop Artemis I flight configuration just before Main Engine Cutoff (MECO)⁵. This model was excited using four, random pressure time histories applied at each MCC as a representation of main engine thrust pressure fluctuations. The random pressure time histories were informed by discrete PSDs from various Space Shuttle flights (Ref. [2, 3]). It was assumed that all four MCC excitations were uncorrelated to each other at all frequencies. The excitation was incorporated as a perturbation to the state vector derivative at rows corresponding to MCC pressure as shown in Eq. (1). The state vector was then integrated in time using MATLAB's ode23tb function, which uses an implicit Runge-Kutta and trapezoidal integration with backward differentiation. As shown in Eq. (2), resulting modal velocities were converted to physical accelerations by differentiating using a partition of the state matrix (A_m) and transforming to physical coordinates using an SLS structural mode shape matrix (ϕ).

⁵ This particular model was analyzed because of its availability at the time this analysis was performed. Future iterations of this analysis should consider multiple flight models representing multiple phases of flight

$$\frac{dX}{dt}(t) = AX(t) + \begin{bmatrix} \cdot \\ \cdot \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \\ \frac{d\Delta P_{MCC_1}(t)}{dt} \\ \frac{d\Delta P_{MCC_2}(t)}{dt} \\ \frac{d\Delta P_{MCC_3}(t)}{dt} \\ \frac{d\Delta P_{MCC_4}(t)}{dt} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \\ \cdot \\ \cdot \\ \cdot \end{bmatrix} \quad (1)$$

$$\mathbf{X}_{accel}(t) = (\mathbf{A}_m \mathbf{X}_m(t))^T \boldsymbol{\phi} \quad (2)$$

(where m indicates all rows of state matrix corresponding to modal velocities)

After generating the signal of interest, the resulting GBX and LPOP response magnitudes were compared to STS flight measurements. In a PSD comparison, it was found that the simulated SLS responses were lower than the target STS responses. The PSD peak magnitudes were similar, however significant discrepancies occurred at frequencies between PSD peaks. This result was expected, as the STS measured spectra included a significant amount of response that is not related to the MPS closed-loop dynamics (discussed in the section II of this report). This additional response was represented as uncorrelated noise and was added as in-band random noise at various levels ranging from 0% to 100%. 100% corresponded to the case in which the RMS magnitude levels of SLS vs STS signals were equal. Fig. 3 shows simulated SLS response PSDs compared to STS flight PSDs with varying levels of uncorrelated noise added to the SLS channels. Based on the prominence of PSD peaks, the 50% uncorrelated noise case was selected to represent the most appropriate signal to noise ratio (SNR) for a nominal, stable flight.

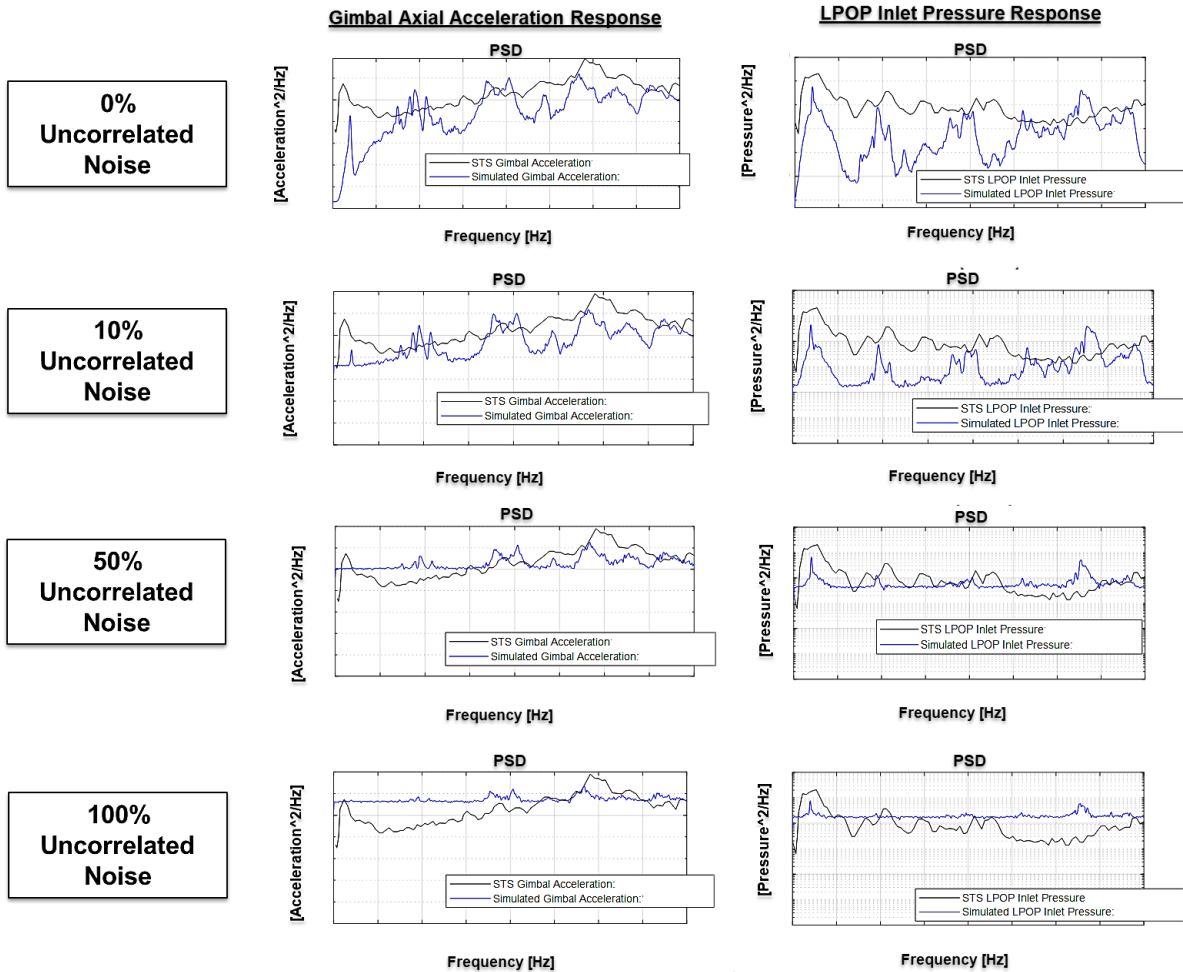


Fig. 3: Comparison of STS flight-measured PSDs to SLS simulated response PSDs with various levels of uncorrelated noise

IV. Other Sources of Operational Noise

Two independent sources of operational noise were recognized for this analysis:

1. Out-of-band High Frequency Random Vibration (HFRV) driven by aeroacoustic loading on the launch vehicle
2. Turbo-pump noise in the propellant feedlines

For the GBX LFA channels, HFRV was accounted for based on SLS maximum expected vibroacoustic environments. Based on Saturn IVB flight data as documented in NASA SP-8050, it was assumed that a -12dB knockdown should be applied to these levels during quiescent phases of flight (Ref. [4]). Though this noise is out-of-band, it could still result in signal clipping which would affect analysis at all frequencies.

In true operation, pressure transducers would respond to noise due to the blade-pass effects of the LOX turbo-pumps. This noise would consist of a superposition of sinusoids related to the low pressure and high pressure oxidizer turbo-pump blade-pass frequencies and their harmonics. No data was available to quantify the magnitude of this noise and very limited data was available to inform the driving frequencies. Fig. 4 shows a high pressure oxidizer turbo-pump (HPOP) radial accelerometer test performed on Space Shuttle Main Engines (SSME) in 1987 operating at a 104% power level (max operating power). This test indicated that the RS-25 HPOP blade-pass frequency was very narrow-band and outside of the frequency range of typical pogo measurements (Ref. [5]). For these reasons, and due to a deficiency of relevant data, the turbo-pump blade-pass frequency was not included as a source of noise in this

analysis. However, relevant data should be gathered and turbo-pump noise should be included in future iterations of this assessment. The primary focus of including this noise would be to assure that channels are ranged properly to avoid clipping from out-of-band noise.

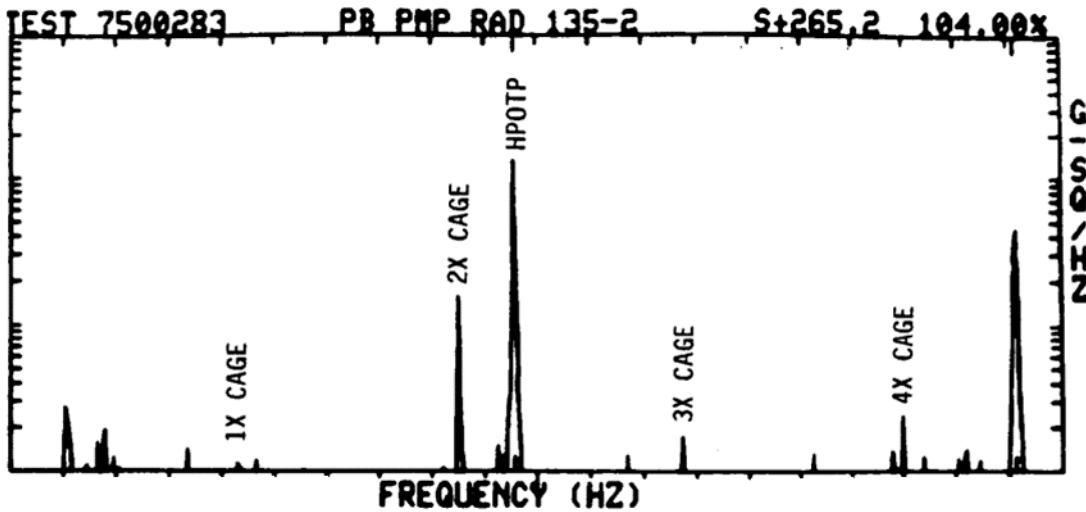


Fig. 4: HPOP radial accelerometer test on SSME (1987) [Tischer]

V. Signal Quality Assessment

In order to assess the Artemis-I data acquisition unit (DAU) settings, an in-depth data acquisition simulation was performed on the channels corresponding to GBX acceleration and LPOP inlet pressure. This data acquisition simulation is outlined in Fig. 5 and included anti-aliasing filters, analog to digital conversion, down-sampling to the final telemetry sample rates, and more. To represent the majority of flight, MPE-12dB operational noise levels were applied to the LFA channel (see section IV). The synthesized signals showed no wide-spread signal degradation introduced by the DAQ settings. Fig. 5 shows an example time history comparison at each phase of data acquisition. For this particular example, some low-frequency distortion was observed due to an AC coupling filter. The signal deviates from the original sensor reading after the AC coupling filter step. This distortion is not detrimental to any of the pogo FDAs, but should be accounted for in post-processing of actual Artemis I flight data.

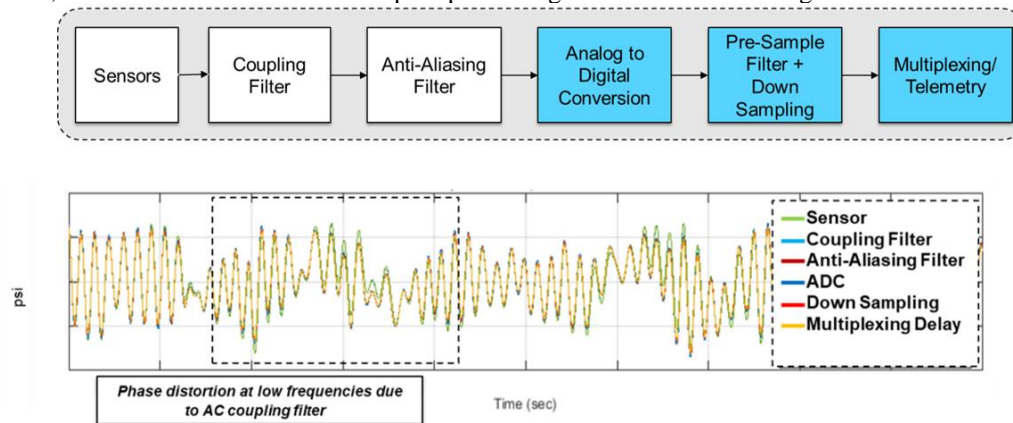


Fig. 5: Example data acquisition simulation

VI. FDA Processing

The primary pogo FDA for SLS supports the objective of validating the MPS model as well as extracting discrete frequency response relationships between pogo pressure and LFA channels. Two mock flight data analyses were performed to identify any issues driven by the sensors or data acquisition system.

The first FDA assessed was frequency response function (FRF) extraction. Target FRFs were first computed from the raw response time histories (before adding uncorrelated noise and simulating data acquisition). The target FRFs were computed utilizing the multiple-input-multiple-output (MIMO) functionality of the MATLAB `modalfrf` function with GBX accelerations at each engine as inputs and LPOP inlet pressures at each engine as outputs.

FRFs were then computed from the DAU synthesized data and compared to the target FRFs. Since system dynamics is changing rapidly during flight, the FRF computations from DAQ synthesized data were limited to 10 second time windows resulting in limited spectral averages and coarse frequency resolution. Fig. 6 shows FRF extraction from the nominal signals with varying levels of uncorrelated noise after they are passed through the data acquisition simulation. Even using the 0% uncorrelated noise signals, some error was observed in the FRF recovery at low frequencies. This was caused by the presence of the AC coupling filter on the LPOP channels. The limited 10 second time windows resulted in difficulty approximating the FRF with nearly any amount of uncorrelated noise. However, some success occurred using the 10% uncorrelated noise level. This high SNR case represents anomalous periods of flight when feedback is observed and the correlated signal is loud relative to uncorrelated sources. The FRF was not recovered at all using the 50% and 100% uncorrelated noise cases. These low SNR cases represent nominal, stable flight – when the vehicle’s self-excited dynamics are very quiet compared to uncorrelated vibration and pressure sources. It should be noted that some of the above observed challenges could be eased by employing parametric transfer function estimation techniques and incorporating data from additional channels. However, this study established that phase / gain relationships will be challenging to extract during stable flight when SRBs are active.

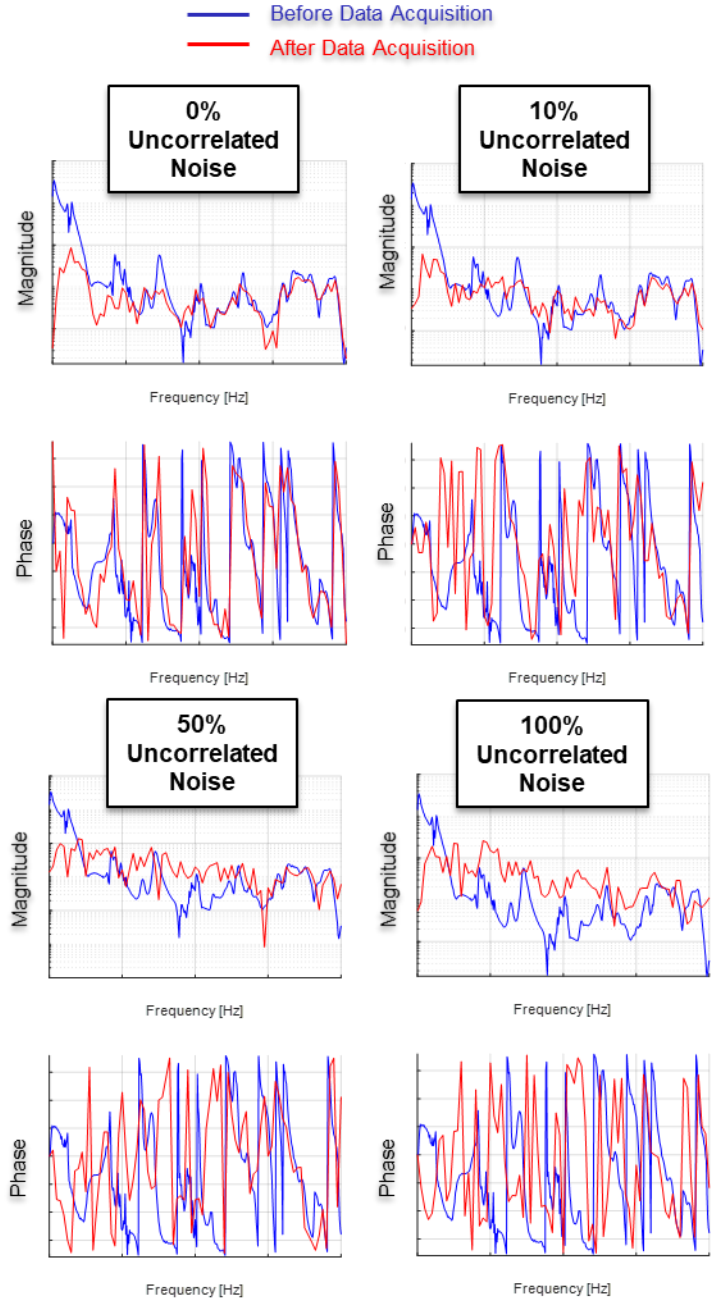


Fig. 6: Mock FDA (LPOP / GBX) DAQ synthesized vs target computed for main engine 1

The second FDA assessed was system identification of closed-loop poles using an Operational Modal Analysis (OMA) technique known as Stochastic Subspace Identification (SSI). An Unweighted Principal Components (UPC) algorithm was used to estimate poles at various mode orders (Ref. [6]). Stable poles were then assessed using a mode stabilization diagram. As in the FRF FDA discussed above, the analysis was performed on GBX and LPOP signals after simulating the Artemis I data acquisition process. It was performed at all levels of uncorrelated noise and analysis time windows were limited to 10 seconds. Due to schedule limitations, no detailed comparison of the extracted poles and the target state matrix eigenvalues was performed. Nevertheless, stable poles were successfully identified for the 0% and 10% uncorrelated noise cases (shown in Fig. 7). However, similar to the FRF extraction discussed above, system identification became increasingly difficult for the 50% and 100% uncorrelated noise cases (shown in Fig. 8).

- + Stable Mode
- Unstable Mode
- Noise Mode

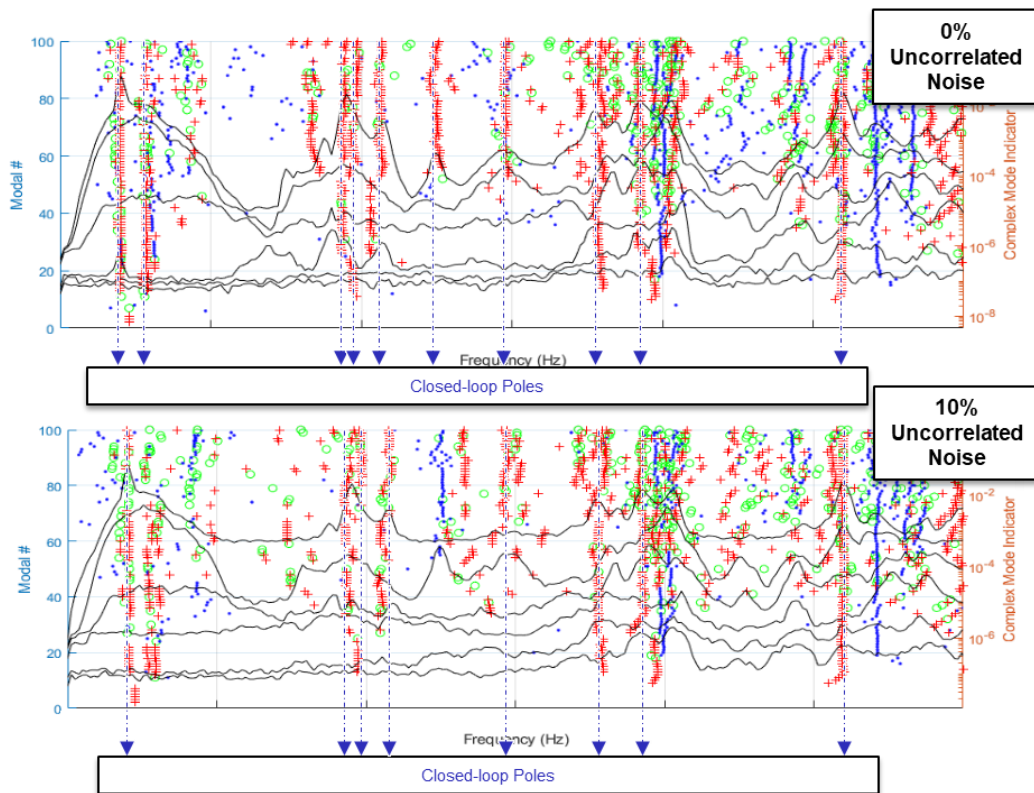


Fig. 7: Pole stabilization of DAQ synthesized signals (0% and 10% uncorrelated noise levels)

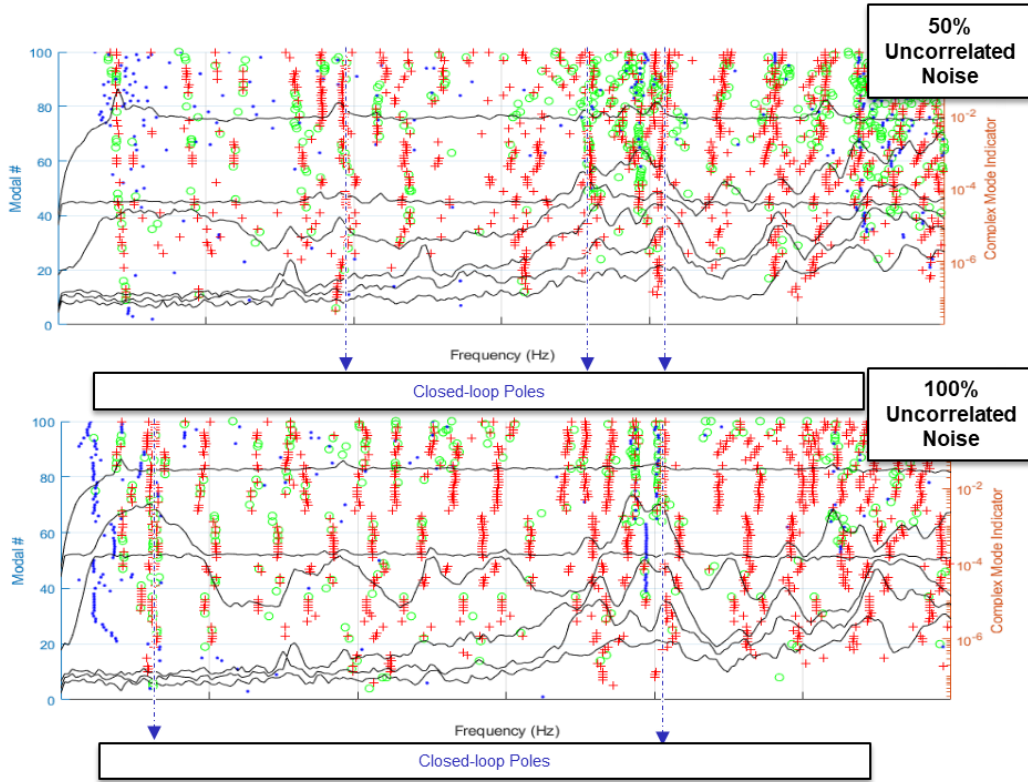


Fig. 8: Pole stabilization of DAQ synthesized signals (50% and 100% uncorrelated noise levels)

VII. Conclusion

An end-to-end assessment of the SLS Artemis I pogo-related DFI was performed to verify adequate measurements for successful fulfillment of the pogo-related FTOs. Signals were generated using an SLS closed-loop state space model in conjunction with heritage Space Shuttle flight data. Data from STS pogo reports indicated that past pogo measurements had high levels of noise that were not correlated with the MPS (i.e. vibration from SRBs, feedline turbulence, etc...). In order to capture flight like conditions, varying levels of uncorrelated noise were added. In addition, out-of-band HFRV was added to the LFA channels as operational noise. Finally, the generated signals were fed through a simulation of the Artemis-I data acquisition system.

Two mock FDAs were performed to identify difficulties that could arise when analyzing flight data acquired through the SLS DAUs. SLS does not have a sensor for measuring MCC fluctuating pressure, therefore only engine gimbal acceleration and LPOP inlet pressure channels were analyzed. Since both of these channels were affected by uncorrelated noise sources, the FDAs were only successful for high SNR cases. These cases represent times of flight when SLS coupled dynamics are very loud in comparison to response from uncorrelated sources (i.e. during an anomalous transient event, or quiescent flight after SRB separation). This finding indicated that gathering useful data for MPS model validation - especially before SRB separation - may pose challenges during a nominal Artemis I flight. However, additional system identification methods – such as covariance driven SSI, ERA, maximum entropy, etc., may offer improved results and should be explored in future iterations of this analysis.

References

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