Applied Time Domain Stability Margin Assessment for Nonlinear Time-Varying Systems

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The baseline stability margins for NASA's Space Launch System (SLS) launch vehicle were generated via the classical approach of linearizing the system equations of motion and determining the gain and phase margins from the resulting frequency domain model. To improve the fidelity of the classical methods, the linear frequency domain approach can be extended by replacing static, memoryless nonlinearities with describing functions. This technique, however, does not address the time varying nature of the dynamics of a launch vehicle in flight. An alternative technique for the evaluation of the stability of the nonlinear launch vehicle dynamics along its trajectory is to incrementally adjust the gain and/or time delay in the time domain simulation until the system exhibits unstable behavior. This technique has the added benefit of providing a direct comparison between the time domain and frequency domain tools in support of simulation validation.

This technique was implemented by using the Stability Aerospace Vehicle Analysis Tool (SAVANT) computer simulation to evaluate the stability of the SLS system with the Adaptive Augmenting Control (AAC) active and inactive along its ascent trajectory. The gains for which the vehicle maintains apparent time-domain stability defines the gain margins, and the time delay similarly defines the phase margin. This method of extracting the control stability margins from the time-domain simulation is relatively straightforward and the resultant margins can be compared to the linearized system results. The sections herein describe the techniques employed to extract the time-domain margins, compare the results between these nonlinear and the linear methods, and provide explanations for observed discrepancies.

The SLS ascent trajectory was simulated with SAVANT and the classical linear stability margins were evaluated at one second intervals. The linear analysis was performed with the AAC algorithm disabled to attain baseline stability margins. At each time point, the system was linearized about the current operating point using Simulink's built-in solver. Each linearized system in time was evaluated for its rigid-body gain margin (high frequency gain margin), rigid-body phase margin, and aero gain margin (low frequency gain margin) for each control axis.

Using the stability margins derived from the baseline linearization approach, the time domain derived stability margins were determined by executing time domain simulations in which axis-specific incremental gain and phase adjustments were made to the nominal system about the expected neutral stability point at specific flight times. The baseline stability margin time histories

were used to shift the system gain to various values around the zero margin point such that a precise amount of expected gain margin was maintained throughout flight. When assessing the gain margins, the gain was applied starting at the time point under consideration, thereafter following the variation in the margin found in the linear analysis. When assessing the rigid-body phase margin, a constant time delay was applied to the system starting at the time point under consideration.

If the baseline stability margins were correctly determined via the linear analysis, the time domain simulation results should contain unstable behavior at certain gain and phase values. Examples will be shown from repeated simulations with variable added gain and phase lag. Faithfulness of margins calculated from the linear analysis to the nonlinear system will be demonstrated.