National Aeronautics and Space Administration

**NASA Engineering and Safety Center Technical Bulletin No. 14-01**

# Designing for Flight Through Periods of Instability

For completeness, it is imperative that Flight Control System (FCS) designers use both complementary time and frequency domain techniques to address periods of instability. Use of standard frequency domain synthesis techniques alone may not always yield an FCS design with sufficient gain and phase stability robustness margins while simultaneously satisfying performance requirements.

## Instability Cause and Consequence

Analysis and evaluation must be performed of any potential source of instability (e.g., propellant slosh, flexible structure, or aerodynamics), while flying through periods of rapidly changing dynamics. A large body of experience has been accumulated regarding successfully flying through not only degraded margins, but also relatively brief periods of linearized model instability. These instabilities occur as the flight environment and vehicle dynamics undergo rapid changes. When linearized stability robustness margin requirements cannot be satisfied, alternative methods are then needed to ensure that deficient stability margins do not present a high risk of losing control during the mission.

The Orion launch abort system successfully flew through brief periods of instability. Known instabilities and risks were evaluated prior to flight using best practices.

## Best Practices for Flight Control System Design

FCS designers should consider employing non-linear system requirements that capture both stability and performance aspects. Occasionally, it may be necessary to set aside the traditional frequency domain gain and phase stability robustness margins in favor of another technique. The tried-and-true guideline that stability always comes before performance in the design process remains the same. However, since real flight systems behave in a non-linear manner, "stability" should be understood as control of the vehicle never being lost while simultaneously achieving attitude control performance requirements.

**Consider four complementary recommendations for certifying FCS designs with deficient stability margins:**

**1) Accept some Relaxed or even Negative Stability Margins:** additional analysis may not be required if a stability margin fails the requirement for only a brief time. Seek out prior experience with similar configurations and conditions.

**2) Evaluation of Uncertainties:** reassess whether the uncertainties input into the analysis are realistic. In certain cases, the effects of correlated variables can be taken into account to reduce the level of uncertainties used in the analysis.

**3) Checking the Time to Double Amplitude:** determine if the vehicle will fly through the region of concern before the oscillations reach unacceptable amplitudes, in which case a relaxed or even negative margin may be acceptable.

**4) Use of Non-Linear Time-Domain Simulations:** exploit the complete non-linear time-domain models to prove that the vehicle exhibits acceptable behavior, even with programmed test inputs to excite oscillations. Additionally, the loop gains and/or time lags can be adjusted in the simulation to evaluate the gain and phase stability margins remaining from a non-linear perspective.

Historically, some launch vehicles have been successfully flown with the known threat of slosh instabilities. The Atlas-II was successfully flown with linearly unstable (as viewed from a purely linear frequency-domain perspective) slosh modes.

An FCS designer should question the application of linear stability requirements and not rely exclusively on the frequency domain approaches to verify stable flight. The use and application of the frequency-domain synthesis and analysis tools must be balanced with the non-linear time-domain performance simulation tools and the Time to Double Amplitude criteria.

## References

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3. NASA/SP–2010–3408, Space Shuttle Entry Digital Autopilot, Section 9.0 Lessons Learned, Larry McWhorter and Milt Reed, Feb. 2010

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