Stability Assessment and Tuning of an Adaptively Augmented Classical Controller for Launch Vehicle Flight Control

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ABSTRACT

Recently, a robust and practical adaptive control scheme for launch vehicles [[1] has been introduced. It augments a classical controller with a real-time loop-gain adaptation, and it is therefore called Adaptive Augmentation Control (AAC). The loop-gain will be increased from the nominal design when the tracking error between the (filtered) output and the (filtered) command trajectory is large; whereas it will be decreased when excitation of flex or sloshing modes are detected. There is a need to determine the range and rate of the loop-gain adaptation in order to retain (exponential) stability, which is critical in vehicle operation, and to develop some theoretically based heuristic tuning methods for the adaptive law gain parameters.

The classical launch vehicle flight controller design technics are based on gain-scheduling, whereby the launch vehicle dynamics model is linearized at selected operating points along the nominal tracking command trajectory, and Linear Time-Invariant (LTI) controller design techniques are employed to ensure asymptotic stability of the tracking error dynamics, typically by meeting some prescribed Gain Margin (GM) and Phase Margin (PM) specifications. The controller gains at the design points are then scheduled, tuned and sometimes interpolated to achieve good performance and stability robustness under external disturbances (e.g. winds) and structural perturbations (e.g. vehicle modeling errors).

While the GM does give a bound for loop-gain variation without losing stability, it is for constant dispersions of the loop-gain because the GM is based on frequency-domain analysis, which is applicable only for LTI systems. The real-time adaptive loop-gain variation of the AAC effectively renders the closed-loop system a time-varying system, for which it is well-known that the LTI system stability criterion is neither necessary nor sufficient when applying to a Linear Time-Varying (LTV) system in a frozen-time fashion. Therefore, a generalized stability metric for time-varying loop=gain perturbations is needed for the AAC.

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Two approaches can be employed for the determination of the margins for the adaptive gain variation: (i) the well-known Circle Criterion (CC) for absolute stability, and (ii) a regular perturbation approach. For (i), the AAC can be formulated as a Lure's absolute stability problem, which provides uniform asymptotic stability for memoriless, nonlinear, time-varying loop-gain perturbations within a sector bounds, which amounts to an upper and lower margin of loop-gain perturbation, and will subsequently called Absolute Gain Margins (AGM). It is noted that, strictly speaking, the loop-gain adaptation is a dynamic process, so a justification has to be made in order to utilize the AGM. Also, the CC is established for Uniform Asymptotic Stability (UAS) only, but we require Exponential Stability (ES) for the closed-loop system in order to have the necessary robustness. However, for LTI and LTV systems, UAS is equivalent to ES, and the ES of a linearized (TI or TV) system is equivalent to that of the underlying Non-Linear (NL) system at the equilibrium point where it is linearized.

Approach (ii) is based on a recently introduce Generalized Gain Margin (GGM) concept for regularly perturbed NL systems [2-[11]. In nonlinear system analysis, system perturbations (modeling errors) are generally categorized as regular perturbations and singular perturbations [3]. The former are perturbations from the nominal system that do not change the order of the nominal system, such as the neglected nonlinearity in linearization of a NL system, frozen-time treatment of a TV system as TI system, and parametric variations and uncertainties; whereas the latter changes the order of the system, such as neglected high frequency flex and sloshing modes, fast dynamics of actuators and sensors, and other parasitic dynamics. Since the adaptive loop-gain variations do not change the order of the nominal system model, it can be considered as a regular perturbation. The margins on the allowable loop-gain perturbation without loss of ES are called the GGM, which can be (conservatively) calculated by Lyapunov second method using a Quadratic Lyapunov Function (QLF). A potential problem with this method is the conservativeness of the QLF in estimating the GGM, particularly for closed-loop nominal systems with a poorly conditioned modal (eigenvector) matrix. This problem was overcome by using the balanced realization for the linearized vehicle model.

In addition to determining the margins for the adaptive loop-gain variations, a simulation/flight-data based adaptive law gain parameter tuning method has been developed, whereby the Absolute Mean (ABSM) based on the one-norm, Root-Mean-Square (RMS) based on the two-norm, and absolute peak value (PEAK) based on the infinity-norm are calculated and plotted in the parameter space as surface and contour plots. These plots allow the designer to visualize the "sweet spots" in the design space, and perform trade-off between the tracking performance and control effector activities, which typically have opposite requirements on the parameters.

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