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Precise margins to operational limits of the RACS taking into account the PWM implementation

Keysmer Damo
Faculty of Civil and Industrial Engineering
La Sapienza - University of Rome
damo.1217647@studenti.uniroma1.it

Giovanni Cuciniello
Italian Aerospace Research Center – CIRA
g.cuciniello@cira.it

For the VEGA launcher, the **R**oll control during the propelled phases and **A**ttitude control during the ballistic phases is performed by a digital **C**ontrol **S**ystem known by the acronym "**RACS**". Although based on a globally stable control law, experience says that the PWM implementation is such that the RACS is not globally stable. Before this work, the only known way of obtaining precise stability margins of the RACS was to perform iterative simulations. The extraction of a single stability margin for a single flight phase takes approximately 20 min or less, depending on the solicited precision. There is a set of combinations of parameters as inertia moments and tuning gains such that the system is not stable, but as these parameters are varied, other undesired behaviors as persistent relatively high-frequency chaotic oscillations are verified. The presented work is the result of a heuristic time-domain approach carried out ad hoc to device a practical method that simplified the task of finding margins to these operational situations. It does not approximate or neglect any of the characteristics of the RACS and uses the elementary aspects of its behavior to instantly calculate precise margins, potentially constituting a sensible efficiency increase in the overall missionization activities and/or, more importantly, providing flexibility in the general management of the RACS during the missionization campaign.

A detailed study of the behavior of the RACS algorithms, aimed at understanding the conditions for which divergence occurred and the mechanism of this divergence, was carried out. As soon as the mechanism of divergence was identified, the presented approach for the stability analysis was available as an obvious derivation from it.

The RACS is based on the Quaternion Feedback Regulation (QFR) control law (RACS QFR Algorithm for VEGA FPSA program, 2012). QFR consist basically of a feedback proportional action on the error quaternion complemented by a feedback proportional action on the error angular velocity and a compensation for gyroscopic coupling. This has been proven (Wie, et al., 1989) to be globally stable practically for any tuning possibility. However, experience demonstrates that the RACS is not globally stable and that necessarily-introduced hard nonlinearities in the control loop play a fundamental role in the behavior of the system around the limit of stability. This stability problem is typically not treated in spacecraft control textbooks as (Mangiacasale, 2008) or (Wie, 2008), where only the situations for which the pulse characteristic times are short with respect to the attitude motion of the spacecraft are considered. The practical implementation described in (Wie, et al., 1985) also neglects the PWPF implementation in the stability analysis. Even if it was possible to calculate stability margins, what is really needed is margins to persistent high-frequency oscillations, i.e., frequencies that lead to an overly high propellant consumption.

While the QFR is a linear control law, the six actuators of the RACS, the Reaction Control Thrusters (RCT), are rigidly fixed to the launcher's body, work in an ON/OFF basis, and are constrained to a minimum ON command time length (minON) after OFF operation and a minimum OFF command time length (minOFF) after ON operation. Furthermore, avionics constraints oblige the length of ON/OFF commands to be a multiple of a time length called minor cycle (MinC). Hence, intermediate algorithms are dedicated to: a) the distribution of the commanded moment vector among the RCTs; b) the transformation of the amplitude-modulated commands generated by the QFR law into a series of duration-modulated pulses, each one starting at discrete time instants evenly spaced in time (Pulse-Width Modulation implementation, PWM); and c) the saturation of the commands so that the constraints associated to the minON, min OFF and MinC are respected. The functions b) and c) of these intermediate algorithms introduce hard nonlinearities in the closed loop that are unnoticed if the system operates at low frequency errors and intermediate amplitude commands.

The key observation that leads to the presented approach is that the saturation applied to the commands, introduced by function c), entails a saturation effect on the modal behavior of the system. In other words, given that, because of saturation, the command can only take a finite set of values (ON time lengths), also the modes of the system, intended as a series of periodic commands, conform a finite set. It appears that there is not any formal equivalent to this observation in bibliography, at least bibliography about stability of PWM systems or well-known bibliography on hybrid systems (van der Schaft, et al., 2000). The calculation of any margin (e.g. the stability margin) consists simply of the calculation of the margin to the saturation limit that corresponds to the mode that is to be avoided. This calculation is algebraic after the shape of the modes is obtained numerically.

Margins can be calculated axis per axis as if they constituted a SISO system first; and then, the unstabilizing effect of couplings are taken into account. For low amplitude control errors, inter-axis coupling because of the quaternion are negligible. Inertial couplings are also negligible for low angular velocities. In such conditions, couplings, unknown before this work, are still present because of functions a) and c).

Literature on stability of PWM systems is largely focused on DC-DC converters commonly used in power electronics (Stability analysis of a class of PWM systems using sampled-data modeling, 2003). Much of the reported analyses on PWM systems is based on the averaging approach which requires sufficiently high switching frequency, as (Teel, et al., 2004). Many others have applied the direct method of Lyapunov in different ways (Stability analysis of a class of PWM systems using sampled-data modeling, 2003), (Hou, et al., 2001). These theoretical approaches require considerable attention and expertise to be extended and applied in the short term to an immediate industrial problem as the stability analysis of the RACS.

Any industrial implementation of the approach presented herein, in the form of a software tool for example, encounters as a main task the creation of a reliable and fully automatic algorithm for the obtainment of the shapes of the modes. A brief description of a possible solution is provided.

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