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Integrated Control/Structure Design of a Large Space Structure using Structured $\mathcal{H}_\infty$ Control

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Abstract This study presents the integrated control/structure design of a large flexible structure, the Extra Long Mast Observatory (ELMO). The integrated design is performed using structured $\mathcal{H}_\infty$ control tools, developing the Two-Input Two-Output Port (TITOP) model of the flexible multi-body structure and imposing integrated design specifications as H_∞ constraints. The integrated control/structure design for ELMO consists of optimizing simultaneously its payload mass and control system for low-frequency perturbation rejection respecting bandwidth requirements.

Keywords: Integrated Design, structured $\mathcal{H}_\infty$ control, Large Flexible Spacecraft, TITOP model

1. INTRODUCTION

Currently Large Space Structures (LSS) are a challenging problem in control system design because they involve large complex kinematic chains composed of rigid and flexible bodies, mostly large-sized, maximally lightened, low-damped and with closed-spaced low natural frequencies. In this case structural modes interfere with the controlled bandwidth, provoking a critical Control-Structure Interaction (CSI). Therefore, LSS design is increasingly becoming subject to a close coordination among the different spacecraft sub-systems, demanding methods which tie together spacecraft structural dynamics, control laws and propulsion design. These methods are often called as *Integrated Control/Structure Design* (ICSD), *Plant-Controller Optimization* (PCO) or simply *co-design* (CD).

ICSD methods began being studied in the 80s as an opposite technique to the current method of separated iterative sequences within the structural and control disciplines. The first integrated design methodologies were those in Onoda and Haftka (1987) and Messac and Malek (1992). These methods were based on iterative methodologies with optimization algorithms. Lately, other methods have been proposed such as those solved by LMI algorithms or with LQG methods like in Hiramoto et al. (2009). However, these approaches give conservative results and their applicability is restricted by problem dimension. Recently, robust techniques allow a more general and easy approach (Alazard et al., 2013; Watt et al., 2013). Structured robust techniques are based on structured $\mathcal{H}_\infty$ synthesis algorithms developed in Gahinet and Apkarian (2011) or Burke et al. (2006), granting structured controllers and tunable parameters optimization. This synthesis, merged with a correct plant modeling, can reveal important applications of integrated design methodologies in space industry (Alazard et al., 2013) or aviation (Denieul et al., 2015).

This work aims at showing the progress achieved at the end-way of this PhD study about an integrated design methodology with structured $\mathcal{H}_\infty$ control synthesis. This paper is organized as follows. First, the general framework about the integrated design used in this study is explained. This framework presents the modeling technique and optimization specifications that have been developed in order to be able to apply structured $\mathcal{H}_\infty$ synthesis. Second, ICSD is applied to a real case of a LSS: payload weight maximization and controller optimization for perturbation rejection are performed to a large flexible satellite composed of mast segments (ELMO, see Fig 1), developed by CNES space structures department. Finally, results of the ICSD study are discussed and conclussions are presented.

2. INTEGRATED DESIGN METHOD

The ICSD method of this study lies on the structured robust control synthesis. A thorough explanation of structured $\mathcal{H}_\infty$ controller synthesis is given in Gahinet and Apkarian (2011) and Burke et al. (2006), where it is shown how is possible to impose the order, the structure and stability of the controller thanks to the structured $\mathcal{H}_\infty$ synthesis. In the following sections a descriptive view of the ICSD method is presented.

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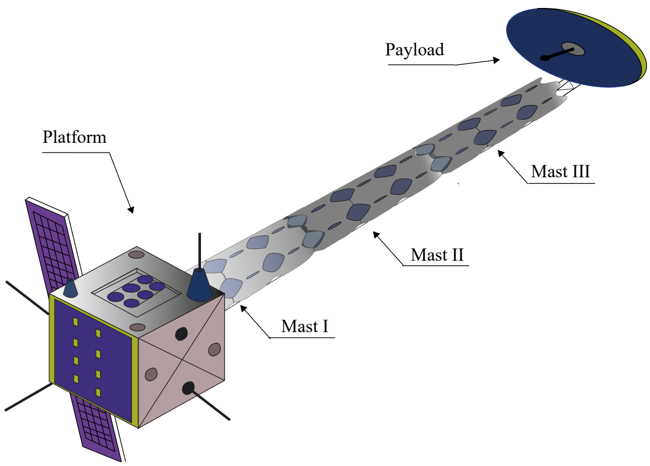

Figure 1. Illustration of the Extra Long Mast Observatory (ELMO) subject integrated control/structure design study

2.1 Theory

Figure 2 shows the standard multi-channel $\mathcal{H}_\infty$ synthesis problem. Given a Linear Fractional Representation (LFR) of the controlled system, $G(s)$, in which the corresponding parametric variations have been extracted as a tunable block Δ_i, and added to an augmented structured controller with tunable parameters $K(s) = diag(C(s), \ldots, \Delta_i)$, structured $\mathcal{H}_\infty$ synthesis computes the optimal tuning of the free parameters of $C(s)$ and Δ_i to enforce closed-loop internal stability such that:

$$\begin{aligned} &\min_{C(s),\Delta_i} \{\max\{||W_\Delta(s)\Delta_i||_\infty, ||W_C(s)C(s)||_\infty\}\} \\ &\quad under : ||W_z(s)T_{w\to z}(s)||_\infty < \gamma_{perf} \end{aligned} \quad (1)$$

i.e., it minimizes the $\mathcal{H}_\infty$ norm between the transfer of the perturbation input w and the performance output z, $T_{w\to z}(s)$, such that it is constrained to be below $\gamma_{perf} > 0$ to meet performances. The problem is in the form of *Multi-Channel $\mathcal{H}_\infty$ Synthesis*, and it allows imposing to the augmented controller different properties such as its internal stability (Alazard et al., 2013), frequency template (Loquen et al., 2012) or maximum gain values. In substance, the **Structured $\mathcal{H}_\infty$ Integrated Design Synthesis** tunes the free parameters contained in the augmented controller $K(s) = diag(C(s), \Delta_i)$, $C(s)$ being a structured controller and Δ_i the set of structural parameters to be optimized, to ensure closed loop internal stability and meet normalized $\mathcal{H}_\infty$ requirements through W_z, W_C and W_Δ. The difficulty lies on how to impose the correct normalized $\mathcal{H}_\infty$ requirements so that successful integrated design synthesis is guaranteed.

2.2 Modeling Technique

As noted in Section 2.1, ICSD method with $\mathcal{H}_\infty$ control of a LSS needs a LFR representation of the different mechanical subsystems, so that parametric variations can be considered in the final plant model $G(s)$. A correct and straightforward modeling technique of a multi-body flexible spacecraft is the Two-Input Two-Output Port

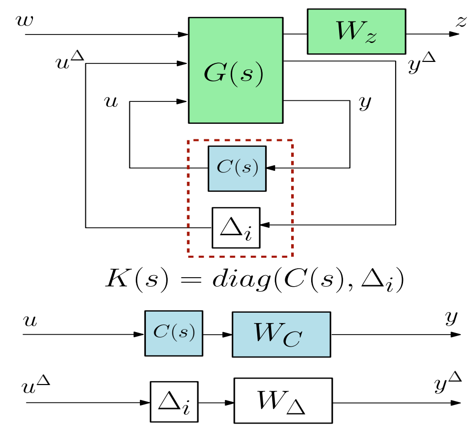

Figure 2. Block Diagram of Integrated Design Optimization

(TITOP) modeling technique (Perez et al., 2015; Murali et al., 2015), which allows casting different structural data (Finite Element Models, geometry, flexible modes) in the state-space domain, with the added possibility of including tunable variables. In substance, the different TITOP models of the different substructures can be easily assembled through load-acceleration transmission at the connection points in order to reproduce the fully assembled LSS. There are two different types of TITOP models so far: actuated and non-actuated models.

- The *non-actuated TITOP model* (see Fig. 3b) of a substructure $\mathcal{A}$ represents a single mechanical subsystem between two mechanical subsystems, $\mathcal{P}$ and $\mathcal{Q}$, in which accelerations, $\ddot{u}$, are transmitted downstream (from the hub to the tip), and loads, F, are transmitted upstream (from the tip to the hub). Two connection points, P and Q, are considered as the interfaces of the mechanical substructure with other substructures. The reader might consult Perez et al. (2015) if more information about this modeling technique is desired.
- The *actuated TITOP model* (see Fig. 3c) has the same mechanical considerations as the *non-actuated TITOP model*; i.e., has the same set of mechanical inputs/outputs. In addition, the model takes into account the electro-mechanical behavior of the substructure when piezoelectric elements are included inside the structure, adding additional inputs, the set of applied voltages v, and additional outputs, the set of measured electric charges g_c, which are suitable for accurate control action modeling. The reader might consult Perez et al. (2016) if more information about this extension of the TITOP modeling technique is desired.

Moreover, TITOP models can be enriched including parameter variations which can be used to create the final LFR model, $G(s)$ from which the set of tunable parameters Δ_i is extracted to be optimized.

2.3 Integrated Design Specifications

The basic LSS design objectives for the control systems are (i) to obtain sufficiently high bandwidth and satisfactory closed-loop damping ratios for rigid-body structural modes; and (ii) to obtain satisfactory pointing errors. The