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A Flexible Appendage Model for Use in Integrated Control/Structure Spacecraft Design

J. Alvaro PEREZ * **Christelle PITTET** **
Daniel ALAZARD *** **Thomas LOQUEN** *
Christelle CUMER *

* *ONERA System Control and Flight Mechanics Department, Toulouse, 31000 France (e-mail: Jose-Alvaro.Perez_Gonzalez@onera.fr; thomas.loquen@onera.fr; christelle.cumer@onera.fr).*
** *Centre National d'Etudes Spatiales (CNES), Toulouse, 31000 France (e-mail: christelle.pittet@cnes.fr)*
*** *Institute Superieur de l'Aeronautique et de l'Espace, Toulouse, France, (e-mail: daniel.alazard@isae.fr)*

Abstract The study presents and validates a flexible appendage model to be used in an integrated control/structure spacecraft design. The integrated design methodology needs an accurate LFT representation of spacecraft flexible appendages so that parametric variations can be included. This requirement can be met using the Interconnected Flexible Appendage model studied in Perez et al. (2015). The model suitability is validated through the modeling of a real deployable boom, obtaining the same frequency modes and dynamical behavior.

Keywords: Integrated Design, Structured H_∞ Synthesis, Flexible Structures, Attitude Control System (ACS), Linear Fractional Representation (LFT).

1. INTRODUCTION

The design of new generation space vehicles is increasingly becoming subject to design integration, that is, close coordination in the design of various systems constitutive of the spacecraft. For example, space structures involving very large complex chains composed by rigid and flexible bodies require integration between the Attitude Control System (ACS) and the structure to avoid elastic instabilities. To address the challenge of integrated spacecraft design (also called co-design), methods which tie together spacecraft structural dynamics, control laws and propulsion design methods are needed.

Integrated design relevance has increased for the last three decades due to two main advantages. The first one, it reduces prototyping time and, as a consequence, decreases development costs. The second one, integrated design approaches allow to optimize simultaneously control laws with other subsystems, using the full design freedom of the plant to improve the closed-loop performance. For instance, structural strength and stiffness requirements could be softened if the controller which reduces the dynamical response is optimized simultaneously to compensate strength reduction, leading to many useful advantages such as mass saving, length augmentation or the minimization of the energy consumed by the located actuators. Many studies of integrated structure/control design have been made since the publication of the first integrated design methodologies such as those in Onoda and Haftka (1987) or Messac and Malek (1992). These methods were based on iterative methodologies with optimization algorithms. Lately, other more generic methods have been proposed such as those solved by LMI algorithms or with LQG methods like in Hiramoto et al. (2009) and Cimellaro et al. (2008) respectively. However, these approaches give conservative results and their applicability is restricted by problem dimension. Recently, a counterpart technique currently under development in ONERA Toulouse Research Center allows a more general approach (Alazard et al., 2013). Actually, this method is based on structured H_∞ synthesis (Gahinet and Apkarian, 2011), granting structured controllers and tuneable parameters optimization. In addition, particular properties can be imposed to the controller as well, as its internal stability or frequency template. This synthesis, merged with a correct plant modeling, can reveal important applications in integrated design methodologies.

As stated before, a correct plant modeling is needed in order to implement integrated design. Particularly for this study, the problem lies on finding a consistent plant modeling for a spacecraft considered as *flexible*. For this kind of methodology, models have to be implemented as Linear Fractional Representations (LFT) so that the tools used for structured H_∞ synthesis can be applied. In the case of this study, flexible spacecraft integrated design, a linear model which includes appendages flexible modes is needed. LTI representation methods for appendages attached to spacecraft hub have been presented with very interesting concepts in Alazard et al. (2008) and Alazard et al. (2015), based on the coordinate transformation given

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by the component modes synthesis (Craig Jr, 2000) to obtain the inputs and torques applied to the main hub by a flexible appendage. However, these studies only considered star structure configuration of flexible appendages, without offering the possibility of interconnecting several substructures in chain-like assembly. Inspired by the Finite Element Transfer Matrix Method (Tan et al., 1990) and the Finite Element Component Synthesis (Young, 1990), Perez et al. (2015) proposed the Interconnected Flexible Appendage (IFA): a flexible appendage model in LFT representation which allows to interconnect several substructures in open-chain assembly, granting its usage for ACS control law synthesis.

This work aims at demonstrating Interconnected Flexible Appendage (IFA) accuracy and suitability for future usage in integrated ACS/Structure design applications which involve large chains of flexible bodies. The model is validated in the real-case application of a deployable boom from the TARANIS [1] microsatellite. To accomplish this task, first an explanation of the integrated design methodology is given. Next, a description of the modeling procedure for the deployable boom is given to demonstrate the need of LFT appendage representation. Then, model dynamics are tested in a real-case scenario of an attitude maneuver. Finally, perspectives are extracted for future works in integrated design.

2. MODELS FOR INTEGRATED DESIGN BASED ON STRUCTURED H_∞ SYNTHESIS

A thorough explanation of structured H_∞ controller synthesis is given in Gahinet and Apkarian (2011). This study shows how it is possible to impose controller order, structure and stability thanks to the structured H_∞ synthesis. Figure 1 shows standard problem is composed of two elements: a Linear Fractional Representation (LFT) of the controlled system, $P(s)$, and a structured controller with tunable parameters $C(s) = diag(K_1(s), \ldots, K_N(s))$.

Given $\gamma_{obj} > 0$, structured H_∞ synthesis consists on tuning the free parameters of $C(s)$ to enforce closed-loop internal stability such that:

$$||\mathcal{F}_l(P(s), C(s))||_\infty < \gamma_{obj} \tag{1}$$

and satisfy a set of design requirements in the form of M normalized H_∞ constraints, $H_1(s), H_2(s), \ldots H_M(s)$, such that $||H_j(s)||_\infty < 1$ (Gahinet and Apkarian, 2011). Observing that each H_∞ requirement has the form $H_j(s) = \mathcal{F}_l(P_j(s), C(s))$, the problem can be reformulated with the controller $C(s)$ repeated multiple times in the Standard Form $P(s)$, which is a rearrangement of the input/output channels of $diag(P_1(s), \ldots P_M(s))$. This is what is called the *Multi-Model H_∞ synthesis*, and it allows to impose the controller different properties besides its structure, such as its internal stability (Alazard et al., 2013), frequency template (Loquen et al., 2012) or maximum gain values.

The *multi-model* methodology can be enlarged to include integrated design between certain tunable parameters of the controlled system $P(s)$ and the stabilizing structured controller $C(s)$, as demonstrated in (Alazard et al., 2013).

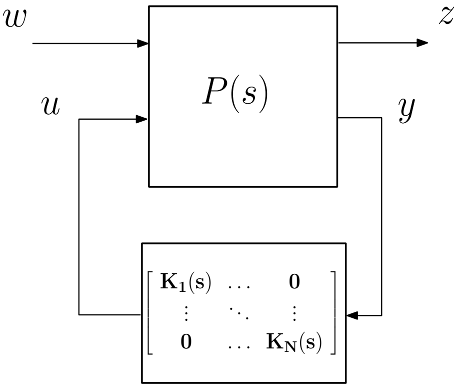

Figure 1. Standard form for structured H_∞ synthesis.

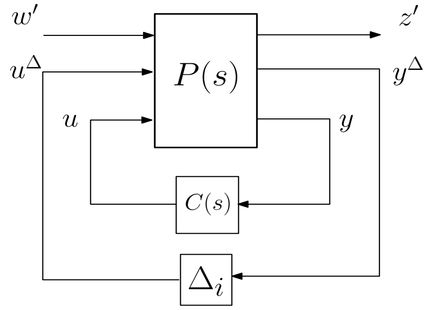

Figure 2. Integrated Design H_∞ standard form.

This obliges to establish how the dynamical behaviour of $P(s)$ is affected by changes in those parameters. This can be included considering a LFT $P(s) - \Delta_i$, where Δ_i is the uncertainty matrix commonly used in μ-analysis. However, for integrated design case, Δ_i matrix is no longer considered as plant uncertain dynamics but as a matrix which includes how parameter variations of $P(s)$ affect its dynamical behaviour. The goal is to optimize such variations simultaneously with the controller in order to meet the normalized H_∞ constraints that could include, for example, dynamical requirements in $P(s)$ and controller requirements of $C(s)$.

In other words, the **Structured H_∞ Integrated Design Synthesis** tunes the free parameters contained in the augmented controller $K(s) = diag(C(s), \Delta_i)$ to ensure closed loop internal stability and meet normalized H_∞ requirements (Figure 2). Obviously, the difficulty lies on how to impose the correct normalized H_∞ requirements so that successful integrated design synthesis is guaranteed.

Thus, when considering integrated structure/control design of a flexible spacecraft, a **LFT representation of the different mechanical subsystems is needed** so that parametric variations can be considered in the plant model. Next sections show how the Interconnected Flexible (IFA) model explained in (Perez et al., 2015) is formed to suit integrated design requirements.

3. FLEXIBLE MULTI-BODY MODELLING

As stated before, integrated structure/control design of a flexible spacecraft needs a LFT representation of the plant. However, a spacecraft is often composed of several rigid and flexible appendages attached to the main hub: solar panels, robotic arms, antennae, propellant tanks,

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[1] Tool for the Analysis of RAdiation from lightNing and Sprites