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Discussion on: "Adaptive Variable Structure Maneuvering Control and Vibration Reduction of Three–axis Stabilized Flexible Spacecraft"

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This work presents some variable structure controllers for linear systems of the form

$$\begin{aligned} \dot{x} &= (A + \Delta A)x + (B + \Delta B)\Phi(u) + f \\ y &= Cx \end{aligned} \tag{1}$$

with ΔA, ΔB uncertainty matrices, A, B, C the nominal matrices, $\Phi(u)$ a nonlinear continuous function, x, u, y the state, input and output of the system, and $f \in R^n$ a disturbance. The design is based on the adaption of the bounds on the uncertainty matrices and the disturbance, through the application of Barbalat lemma, as common in adaptive control. The theoretical results are then applied to the attitude control of flexible spacecraft subject to external disturbances.

The subject of the paper is of interest in attitude control of flexible structures. Many contributions can be found in the literature. In fact, in the last decades the research effort has been focused on the nonlinear nature of the spacecraft model, and various works are available either in for rigid [10, 17, 24, 2] or flexible spacecraft [18, 20, 21, 22, 1, 12, 14], also in the digital setting [19, 9]. The robustness of these nonlinear controllers has been one of the main issues addressed [23, 11, 13].

In this perspective, the present paper raises some perplexities, both for the theoretical and the application contributions. In the remaining of this discussion some observations, which can be considered as issues for further research activities, are illustrated.

The authors assume that the uncertainties ΔA, ΔB and the disturbance f are matched by the input

$$\Delta A = BH, \quad \Delta B = BE, \quad f = Bd$$

with H, E, d bounded in norm. This simplifies terribly the control problem, since (1) become

$$\begin{aligned} \dot{x} &= Ax + B\Phi(u) + B\Big(Hx + E\Phi(u) + d\Big) \\ y &= Cx. \end{aligned}$$

Indeed, on this subject various works can be found in the literature, even for more general structures, see for instance [4] and references therein. Also the nonlinear nature of the term $\Phi(u)$ does not pose particular difficulties, since it is assumed locally Lipschitz. The stability analysis hence becomes trivial, since this term behaves like a linear one. This is crucial in the proof of the theorems.

The study on the input saturation, as claimed in the introduction of the paper, and that justifies the analysis of nonlinear functions $\Phi(u)$, is not convincing, since analyzed only by simulations and not theoretically. Nevertheless, some works on input saturation can be found in the literature, see for instance [15, 16].

A further assumption which weakens the interest in the proposed controllers is that the state and the input are bounded, as assumed in the proofs, so allowing a simple determination of the gains of the controller. Further hypotheses on the bound of f will be discussed later on.

The application of the theoretical results to the attitude control of flexible spacecraft is weak for various reasons. To begin with, it should be observed that the authors consider some simplifying assumptions under which the model of a flexible spacecraft can be approximated by equations (1). These simplifications are only valid for small rotation angles and small angular velocities, and transform the nonlinear kinematics and the spacecraft dynamics given in equation (44) of the paper to the form (1). For large slewing maneuvers the proposed controller can not guarantee the asymptotic stability. In fact, in this case the nonlinear contribution to the dynamics, due to the gyroscopic term, can not be ignored. Alternatively, the authors should have studied the error determined by the application of the proposed controllers to the nonlinear spacecraft model. Furthermore, the use of classical PD–like controllers could be a valid alternative to the proposed strategy, and could be compared with the proposed controllers, also in term of computational efforts.

Another aspect that could be explored as further investigation, and linked to these model approximations and with the discontinuous nature of the variable structure controller, are the spill–over effects induced on higher–modes [6, 7].

An aspect claimed in the introduction but not studied in the paper is the active suppression of vibrations of the flexible appendages. In fact, usually the term "active" refers to the presence of actuators (e.g. piezoelectric actuators) which contribute in the damping of the vibrations induced by slewing maneuvers. Many papers deal with this subject, see for instance [5, 14, 3, 8] and references therein.

The application to the spacecraft is weak for another aspect. In the simulation section the disturbance term f is considered as function of the state and the input of the spacecraft. This is a common approach, in which the nonlinearities are considered as disturbances acting on the system. The critical point, again, is given by the assumptions made. In fact, since it is assumed that $f = Bd$ with $\|d\| \leq \beta_3$, the stabilization problem is trivially simplified, since this implies assuming a bound on the state. But this is the aim of the stabilization problem. Assuming bounded the state of part of the system dynamics is a strong hypothesis.

Finally, the control considered in the simulations is given in equation (50) of the paper, and is a slight modification of the designed controller considered in order to attenuate the chattering problem deriving from the applied technique. A theoretical proof of the asymptotic stability property of the system is an interesting point of further investigation.

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