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Adaptive Finite-time Observer for a Nonlinear and Flexible Space Launch Vehicle

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Abstract: In this paper we propose a new finite-time state observer for a nonlinear space launch vehicle with flexible dynamics and uncertain parameters. Indeed, flexible states are required to ensure nonlinear control objectives of both reference path tracking and bending mode damping. Our main contribution is to show that it is enough to observe a sublinear uncertain system to ensure a finite-time convergence of the whole state. For that purpose, a Luenberger observer is mixed with a parameter and initial state estimator, based on algebraic estimation tools. Closed loop simulations show the effectiveness of the observer in combination with a backstepping control design (extended to flexible systems).

Keywords: Hybrid observer, Nonlinear control, Parameter estimation, Flexible mode

NOMENCLATURE

ψ	Attitude angle, rad
β	Gimbal deflection angle, rad
η	Mode shape temporal coordinate
q	Pitch rate, rad/s
h	Flexible displacement, m
r	Flexible rotation, rad
r_{ci}	Inertial unit flexible rotation, rad
r_{gy}	Rategyro flexible rotation, rad
T	Thrust, kg.m/s^2
L	Lift, kg.m/s^2
G_L	Launcher center of mass
C_T	Gimbal joint
F_L	Aerodynamic center
I_L	Launcher body inertia, kg.m^2
L_T	Algebraic distance from G_L to C_T, m
l_{aero}	Algebraic distance from F_L to G_L, m
$\bar{q}$	Dynamic pressure, Pa
S	Reference area of the vehicle, m^2
ω	Natural frequency of the first bending mode, rad/s
ξ	Natural damping of the first bending mode
$\mathcal{R}_n$	Frame (G_L, x_n, y_n) linked to the reference trajectory
$\mathcal{R}_L$	Frame (G_L, x_L, y_L) linked to the launcher

1. INTRODUCTION

The problem of finite-time observation for linear and nonlinear systems has been widely investigated over the past decades. Two classes of observers emerge in the series of methods that achieve finite-time convergence. The first one, based on the use of delays has deserved a lot of attention [Menold (2003)],[Engel (2002)]. Recently in [Karafyllis (2011)], a novel hybrid dead-beat observer which uses delays has been proposed. The history of the output is used in order to estimate the state of the system. Sliding mode observers that contain large study in the literature make the second class. (see [Shtessel (2010b)], [Ahmed-Ali (1999)] for instance). More recently, homogeneous finite-time observers have been developed for a specific class of nonlinear systems [Perruquetti (2008)]. Most of these approaches make the assumption that the system structure and parameters are known.

In this paper we propose to design a finite-time observer for a space launch vehicle which belongs to the class of uncertain nonlinear systems. Due to mass constraints, space vehicles tend to have lightweight and flexible structures with low natural frequencies, distorting sensors measurement and adding stability problems during flight. Researchers have recently investigated this subject in the field of nonlinear control. Several solutions have been proposed. Some of them, on the one hand, addressed the problem of unknown parameters and uncertainties using direct-adaptive [Fiorentini (2009)], or time varying controller [Hervas (2012)]. Nevertheless, only rigid states, (that means measured states), are used in these proposed methods. On the other hand, using sliding mode state observer, the authors of [Shtessel (2010a)] reconstruct the flexible states in order to remove the undesirable dynamics from the measurements. This approach requires unfortunately a strong knowledge of the mathematical model of the system, in particular flexible modes parameters. However, to the best of our knowledge, the design of a finite-time observer has not been achieved on uncertain nonlinear aerospace models.

As far as we are concerned, we recently designed a Lyapunov-based nonlinear controller, which uses the flexible states, to ensure control objectives of both reference path tracking and bending mode damping for a class of nonlinear and flexible system [Duraffourg (2013a)], [Duraffourg (2013b)], [Burlion (2013)]. Assuming that the whole state is available, this control law has been applied to the rotational dynamics of a space launch vehicle. [Duraffourg (2013c)]. Such assumptions do not hold in practical applications since flexible states are generally not measured. Consequently we need to reconstruct the flexible states. Besides, noting that flexible parameters are subject to uncertainties or variation during flight, this paper proposes to extend existing theory by proposing an indirect adaptive hybrid observer that no longer requires system parameter knowledge. The proposed approach consists in estimating flexible parameters (natural frequency and damping), and state initial conditions using algebraic tools [Fliess (2003)]. The first ones improve the accuracy and the robustness of the observer through indirect adaptive feature. The second ones are used to regularly update the estimated state and so guarantee a finite-time convergence.

This paper is organised as follows. Section 2 describes the space launch vehicle and gives the problem statement. Section 3 develops a parameter estimator and a state observer which are then mixed to design a hybrid adaptive finite-time observer. In section 4, estimated state is used in a nonlinear control law and a closed-loop simulation is presented. Finally Section 5 contains our conclusions and future research directions.

2. PROBLEM STATEMENT

2.1 Launcher mathematical model

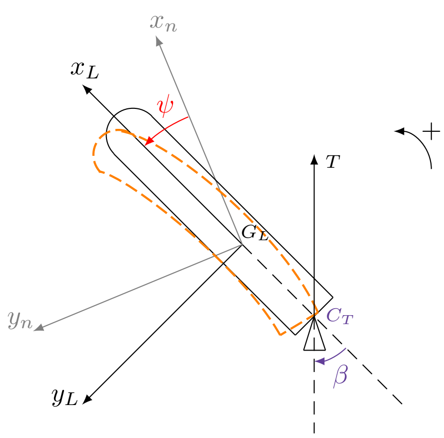

Fig. 1. Schematic model for a flexible launcher

The rotational dynamics of a nonlinear flexible launch vehicle is extracted from [Duraffourg (2013c)], where Lagrange's formalism was developed to get the full-mathematical model. The equations of motion are given by:

$$\begin{cases} \dot{\psi} &= q \\ \dot{q} &= -\dfrac{l_{\text{aero}}}{I_L} L(\psi) + \dfrac{T}{I_L}(L_T r - h)\eta + \dfrac{T L_T}{I_L}\beta \\ \ddot{\eta} &= -(\omega^2 - hrT)\eta - 2\xi\omega\dot{\eta} + hT\beta \end{cases} \tag{1}$$

where ψ and η are real variables and the lift L is a nonlinear function of the attitude, given by:

$$L(\psi) = \bar{q}S\big(C_L^1\psi - C_L^2\psi^2\big)$$

The launch vehicle is equipped with an inertial unit and a rategyro that give attitude and pitch rate informations. As the first bending mode distorts the sensors measurement, the available outputs are:

$$\begin{cases} y_1 &= \psi + r_{\text{ci}}\eta \\ y_2 &= q + r_{\text{gy}}\dot{\eta} \end{cases} \tag{2}$$

Measurement corruption terms make the control law design more difficult.

2.2 Nonlinear control law

A nonlinear control law, denoted Flexible Backstepping, that achieves the control objectives of both reference path tracking and bending mode damping has been developed in [Duraffourg (2013c)]. This controller limits the interaction of the rigid-dynamics on the transient of the flexible dynamics, and so, improves the damping of the bending mode. However, it is based on the deep knowledge of the flexible states and parameters.

Using the notation $y_3 = y_2 + (r_{\text{ci}} - r_{\text{gy}})\dot{\eta}$, system (1) can be reformulated as follow:

$$\begin{cases} \dot{y}_1 &= y_3 \\ \dot{y}_3 &= \bar{g}(y_1, N)y_1 + KN + \dfrac{hT}{C_\beta}\beta + O(\eta^2) \\ \ddot{\eta} &= -\bar{\omega}^2\eta - 2\xi\omega\dot{\eta} + hT\beta \end{cases} \tag{3}$$

where:

$$\bar{\omega}^2 = \omega^2 - hrT \quad C_\beta = \frac{I_L h}{L_T + I_L r_{\text{ci}} h}$$

$$\bar{g}(y_1, N) = -\frac{l_{\text{aero}}\bar{q}S}{I_L}\Big(C_L^1 - C_L^2 y_1 + 2C_L^2 r_{\text{ci}}\eta\Big)$$

$$K = \left(\frac{l_{\text{aero}}\bar{q}SC_L^1 r_{\text{ci}}}{I_L} + \tfrac{T}{I_L}(L_T r - h) - r_{\text{ci}}\bar{\omega}^2 \quad -2\xi\omega r_{\text{ci}}\right)$$

$$N = (\eta\ \dot{\eta})^T$$

Then, the following change of coordinates is applied to the flexible-dynamics:

$$z = N - C_\beta \begin{pmatrix} y_1 \\ y_3 \end{pmatrix} \tag{4}$$

System (3) becomes:

$$\begin{cases} \dot{y}_1 &= y_3 \\ \dot{y}_3 &= \bar{g}(y_1, N)y_1 + KN + \dfrac{hT}{C_\beta}\beta + O(\eta^2) \\ \dot{z} &= A_z z + \bar{F}(y_1, N)y_1 + Gy_3 + O(\eta^2) \end{cases} \tag{5}$$

with:

$$A_z = \begin{pmatrix} 0 & 1 \\ -\bar{\omega}^2 & -2\xi\omega \end{pmatrix} - \begin{pmatrix} 0 \\ C_\beta \end{pmatrix} K$$

$$G = A_z \begin{pmatrix} 0 \\ C_\beta \end{pmatrix} - \begin{pmatrix} C_\beta \\ 0 \end{pmatrix}$$

$$\bar{F}(y_1, N) = A_z \begin{pmatrix} C_\beta \\ 0 \end{pmatrix} - \begin{pmatrix} 0 \\ C_\beta \end{pmatrix} \bar{g}(y_1, N)$$