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A dual loop strategy for the design of a control surface actuation system with nonlinear limitations

Alessandro De Gaspari *, Andrea Mannarino, Paolo Mantegazza

Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa 34, 20156 Milano, Italy

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ABSTRACT

A novel frequency-based optimization algorithm, suitable to tune generic controllers involved in the dual loop architectures, is presented. A control scheme, based on standard industrial regulators, is adopted to incorporate nonlinear constraints reproducing technological limitations, in a control surfaces actuation system installed on a wind tunnel aeroelastic demonstrator. An integrated observer for disturbance rejection helps to meet one of the required constraints when aerodynamic loads are present. Numerical and experimental results are presented with the aim to design the actuation system and validate the methodology, considering both standard input signals and realistic command profiles.

1. Introduction

During the design of control loops, actuators are usually considered linear, whereas their behavior is intrinsically nonlinear. In fact, even during normal operational conditions, they may saturate in position, e.g. the maximum reachable displacement or rotation, in rate, e.g. the maximum speed that an actuator is able to achieve, and in force, e.g. the maximum load that the actuation system is able to produce [1]. In addition, electro-hydraulic actuators may present other internal nonlinearities, such as free-play and friction [2], usually experienced during the motion of the actuation valves [3] and turbulent fluxes across valves and piston orifices [4]. Hysteresis is another phenomenon that can be found on this type of actuators [5]. Actuator failures can also result in significant deviation from the nominal dynamics and may cause departure into highly nonlinear regimes [6]. These kind of saturations are intrinsically embedded by the physical limitations of the actuator components. When some sort of scaled testing is required, i.e. a wind tunnel experiment, actuators working on different physical principles are selected and these limitations are lost most of the time. However, when not accounted for, actuation system nonlinearities can reduce the performance of the control loop, eventually making it unstable.

In this work, actuator nonlinearities are reconstructed by an ad-hoc control law in the design of the control surfaces actuation system of a wind tunnel demonstrator. Such nonlinearities are introduced through the saturation of signals between two nested PID control loops. Because PID controllers are commonly used in practice, this methodology would allow a direct application to problems of industrial interest.

The control law tuning algorithm is one of the original contributions of this work. The proposed approach takes inspiration from the works [7–10]. Such methods, labeled as data-driven, are based on the generation of a fictitious reference signal,

* Corresponding author.
E-mail addresses: alessandro.degaspari@polimi.it (A. De Gaspari), andrea.mannarino@polimi.it (A. Mannarino), paolo.mantegazza@polimi.it (P. Mantegazza).

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Nomenclature

b	local airfoil semi-chord [m]
C	motor damping [Nm·s]
$\mathrm{C}(s;\ \boldsymbol{p})$	transfer function of the controller
C_i	control transfer function of the inner loop
C_o	control transfer function of the outer loop
$C_{/p_k}$	control transfer function derivative w.r.t. the k-th optimization variable
$\mathbf{E}(j\omega)$	fictitious error array
$E_l(j\omega)$	fictitious error of the load loop
$E_m(j\omega)$	fictitious error of the motor loop
$E_{/p_k}$	fictitious error derivative w.r.t. the k-th optimization variable
$\mathbf{J}(j\omega)$	error Jacobian matrix
$\mathcal{J}$	optimization cost function
J_m	motor inertia [kg·m^2]
J_a	aileron inertia [kg·m^2]
K	motor stiffness [N·m]
k	belt stiffness (tensioned side) [N/m]
$\mathrm{k_D}$	derivative gain of the aileron loop
$\mathrm{k_I}$	integral gain of the aileron loop
$\mathrm{k_P}$	proportional gain of the aileron loop
$\mathrm{k_I^m}$	integral gain of the motor loop
$\mathrm{k_P^m}$	proportional gain of the motor loop
$M(s)$	closed-loop transfer function
$M_l(j\omega)$	load closed-loop transfer function
$M_m(j\omega)$	motor closed-loop transfer function
N	filter cut-off frequency of the aileron loop [Hz]
$\mathrm{N_m}$	filter cut-off frequency of the motor loop [Hz]
$\boldsymbol{p}$	array of the control law parameters
$p_1, \ldots, p_8$	optimization variables
$r(s),\ r(t)$	reference signal in the Laplace and time domain
$r_1,\ r_2$	pulley diameters [m]
$R_{l_p}(j\omega)$	fictitious input of the load loop
$R_{m_p}(j\omega)$	fictitious input of the motor loop
s	Laplace variable
$U(j\omega),\ u(t)$	motor input signal in the Laplace and time domain
V_∞	asymptotic aerodynamic speed [m/s]
$Y_l(j\omega)$	output signal of the load loop
$Y_m(j\omega)$	output signal of the motor loop
α	belt pretensioning stiffness factor
θ_1	motor rotation [rad]
θ_2	aileron rotation [rad]
τ	gear ratio between motor and aileron pulley
ω	frequency of oscillation ($\omega = \Im(s)$) [rad/s]
ω_0	desired bandwidth
ω_r	reference motor rate

which is generated recursively from a set of one-shot computational/experimental input-output data. The main difference with respect to model-based methods is that data-driven approaches do not attempt to identify the plant model, using instead the data produced by the plant to find the optimal controller setup. The cited methodologies can be divided in two groups:

- The Virtual Reference Feedback Tuning (VRFT) was first developed in [9] and then formalized in [11]. This approach selects a reference signal on the basis of a target system transfer function. This signal is then used to force the closed loop system to behave like the target through optimization iterations based on the data collected during the experiment.
- The Fictitious Reference Iterative Tuning (FRIT) is an automatic tuning method developed in [10]. Differently from the VRFT, where the reference signal is specified before starting the optimization, a virtual reference signal is computed recursively during the iterations, as the name might suggest.