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Lateral flight control design for a highly flexible aircraft using a nonsmooth method

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Abstract—This paper describes a nonsmooth optimization technique for designing a lateral flight control law for a highly flexible aircraft. Flexible modes and high-dimensional models pose a major challenge to modern control design tools. We show that the nonsmooth approach offers potent and flexible alternatives in this difficult context. More specifically, the proposed technique is used to achieve a mix of frequency domain as well as time domain requirements. For a set of different flight conditions.

I. INTRODUCTION

The synthesis of flight control laws for modern aeronautics and space applications remains a challenging task whenever aeroservoelastic phenomena significantly affect the control bandwidth. Such phenomena are especially critical when demanding specification including performance and robustness constraints of different natures must be achieved. Performance specifications for instance, are normally related to control objectives like tracking and decoupling and are naturally expressed in terms of time-domain constraints such as limited overshoot, short settling- or rise-times, small steady-state error and amplitude limitation. Flexible modes, on the other hand, are frequently dealt with via frequency-domain criteria or modal specification (prescribed damping ratios). A further complication is related to structural constraints imposed to the controller. Simpler controllers are generally sought to facilitate on-board implementation and management.

The classical approach in which a control law is designed for the rigid dynamics and a low-pass filter is inserted a posteriori to avoid or reduce spillover effects is no longer a valid scheme for such applications. The reason is that in order to meet appropriate level of performance, the controller bandwidth should overlap with the frequency range of flexible modes which represents a core issue of such problems.

Traditional $H_2$ or $H_\infty$ syntheses as described in the standard textbook [19] do not provide suitable answers to these difficulties First of all, time-domain specification should be addressed indirectly via nontrivial tuning of weighting filters Secondly, these methods produce full-order controllers and therefore rely on model reduction techniques to derive simple controllers which is always prone to failure.

Design methods based on the Youla parametrization [8] offer some flexibility to handle both time- and frequency-domain specifications. The resulting controllers however suffer from substantial size inflation and are hardly amenable to numerical implementation.

Different approaches have been reported in the literature trying to exploit eigenstructure assignment methods to design problems involving lightly-damped flexible modes [11], [12], [15]. Eigenstructure assignment methods are interesting because they allow to capture time-domain specification through modal shaping. Unfortunately, as noted in [11], determining appropriate eigenspaces associated with flexible modes remains an inherent difficulty.

Nonsmooth optimization techniques have been used recently to solve a number of difficult structured controller design problems involving time- or frequency-domain specifications see [2], [3], [7], [10], [16] and references therein. The nonsmooth design method considered here bears the following appealing features. First, time-domain specifications are addressed directly, thus dispensing with the use of auxiliary tuning parameters such as weighting filters Moreover, frequency-domain constraints such as those related to flexible modes are easily incorporated within the same framework. Secondly, such techniques remain operational even for large size plants, and thus allow to short-circuit risky model reduction phases. Finally, they encompass arbitrary controller structures which make them methods of choice when implementation constraints are important.

The central aim of the present work is to illustrate the efficiency and the flexibility of nonsmooth design methods in solving difficult structured control design problems like large size flexible transport aircraft.

The paper is organized as follows. Section II discusses the multi-objective control design problem and outlines key ingredients of the proposed nonsmooth optimization technique. The difficult design problem of lateral flight control for a highly flexible aircraft subject to turbulence and multiple load conditions is addressed in Section III.

Notation

We use $\mathbb{R}^{n \times m}$ to denote the space of $n \times m$ real matrices. The symbol $\alpha(M)$ stands for the spectral abscissa of a matrix $M \in \mathbb{R}^{n \times n}$ and is defined as $\alpha(M) := \max \{ \Re \lambda : \lambda \text{ eigenvalue of } M \}$. The max operator applied to a vector $v \in \mathbb{R}^n$ is defined as $\max v = \max_{i=1,\ldots,n} v_i$. The notation $[.]_+$ applied to a scalar $\alpha$ denotes the threshold
function \( [\alpha]_+ = \max\{0, \alpha\} \). Its generalization to a vector \( v \in \mathbb{R}^n \) is defined as \( [v]_+ = \max\{0, \max_{i=1, \ldots, n} [v_i]_+ \} \).

Important concepts from nonsmooth analysis are covered by Clarke in [9]. For a locally Lipschitz function \( f : \mathbb{R}^n \rightarrow \mathbb{R} \), \( \partial f(x) \) denotes its Clarke subdifferential at \( x \) while \( f'(x; h) \) stand for its directional derivative at \( x \) in the direction \( h \). For functions of two variables \( f(x, y) \), \( \partial f(x, y) \) will denote the Clarke subdifferential with respect to the first variable. For differentiable functions \( f \) of two variables \( x \) and \( y \) the notation \( \nabla_x f(x, y) \) stands for the gradient with respect to the first variable. The symbol \( \mathcal{F}_I(\ldots) \) will refer to the classical lower Linear Fractional Transformation [19, Ch. 10].

II. MULTI-OBJECTIVE CONTROLLER DESIGN VIA NONSMOOTH OPTIMIZATION

To begin with, consider the synthesis interconnection given by the standard form in Figure 1 with \( u \in \mathbb{R}^{m_2} \) and \( y \in \mathbb{R}^{p_2} \) and where the multivalued plant \( P(s) \) takes values in a finite family of linear plants \( \mathcal{P} := \{ P^1, \ldots, P^p \} \) representing, for instance, multiple operating conditions or faulty modes. Each plant \( P \in \mathcal{P} \) is described by a minimal state-space realization of the form

\[
\begin{bmatrix}
\dot{x}(t) \\
\dot{z}(t) \\
y(t)
\end{bmatrix} =
\begin{bmatrix}
A & B_1 & B_2 \\
C_1 & D_{11} & D_{12} \\
C_2 & D_{21} & D_{22}
\end{bmatrix}
\begin{bmatrix}
x(t) \\
w(t) \\
u(t)
\end{bmatrix},
\]

where indexing has been removed for simplicity. In order to address practical controller structures we introduce a state-space parametrization of the form

\[
\kappa \in \mathbb{R}^q \rightarrow \mathcal{K}(\kappa) := \begin{bmatrix} A_K(\kappa) & B_K(\kappa) \\ C_K(\kappa) & D_K(\kappa) \end{bmatrix}
\]

with corresponding frequency-domain representation

\[
K(s, \kappa) = C_K(\kappa)(sI - A_K(\kappa))^{-1}B_K(\kappa) + D_K(\kappa),
\]

where \( A_K \in \mathbb{R}^{k \times k} \). In the above description, \( \kappa \) designates the decision vector of design variables in the controller. Note the case of a static controller \( (k = 0) \) is a particular instance.

The mapping \( K : \mathbb{R}^q \rightarrow \mathbb{R}^{(m_2+k) \times (p_2+k)} \) is assumed to be continuously differentiable but otherwise arbitrary.

Performance specification are given in most cases in terms of time-domain constraints like limited overshoot, short settling- or rise-times, but also amplitude limitation in order to guarantee decoupling properties or to avoid reaching operational limits of the system. Specification on such time-domain characteristics are achieved by direct shaping of closed-loop system responses to fixed test input signals.

More specifically, we assume each plant in the family \( \mathcal{P} \) in feedback loop with the controller \( K(s) \) is subject to one or several input signals \( w \) selected in a finite signal generator set \( \mathcal{W} := \{ w^1, \ldots, w^d \} \). This gives rise to a finite family of closed-loop responses \( z \in \mathcal{Z} \), where \( \mathcal{Z} := \{ z^1, \ldots, z^r \} \). Each instance in \( \mathcal{Z} \) is called a scenario. Practically speaking, the signal generator set is made of typical deterministic test inputs such as steps, ramps, sinuosids, etc.

The above description is flexible enough to reflect situations in which a single plant is submitted to various test signals as in the case when decoupling properties must be examined, or when the response to a given test signal is to be considered for multiple operating conditions or faulty modes. The proposed set-up also accepts more complicate formulations where each plant in the family \( \mathcal{P} \) is tested against several inputs.

The goal is to compute \( \kappa \in \mathbb{R}^q \) such that the closed-loop time responses \( z \in \mathcal{Z} \) obtained with controller \( \mathcal{K}(\kappa) \) meet envelope constraints of the form

\[
l_z(t) \leq z(t) \leq u_z(t), \quad \forall t \geq 0, \quad \forall z \in \mathcal{Z},
\]

where \( l_z \) and \( u_z \) are lower and upper bounds for \( z \) and are assumed piecewise constant in the sequel. These bounds are illustrated as dashed lines in Figure 2 for a step following specification.

On the other hand, design specifications like robustness against exogenous bounded-energy disturbances or structured uncertainties are known to be better addressed by frequency-domain criteria like bounds on the maximum singular value norm of suitable closed-loop transfers. Therefore, in addition to the constraints in (3), the designed controller \( \mathcal{K}(\kappa) \) is required to achieve prescribed bounds for a finite set of closed-loop transfers

\[
\| \mathcal{F}_I( P(s), K(s, \kappa) ) \|_{I_P} \leq \gamma_P, \quad \gamma_P > 0, \quad \forall P \in \mathcal{P}^\infty, \quad \mathcal{P}^\infty \subset \mathcal{P},
\]

where \( \| . \|_{I_P} \) denotes the peak value of the transfer function maximum singular value norm on a prescribed frequency interval \( I_P \):

\[
\| \mathcal{F}_I( P(s), K(s, \kappa) ) \|_{I_P} := \sup_{\omega \in I_P} \sigma( \mathcal{F}_I( P(j\omega), K(j\omega, \kappa) ) ) .
\]

The frequency band \( I_P \) is typically a closed interval \( I_P = [\omega_P^1, \omega_P^2] \), or more generally, a finite union of intervals \( I_P = \)}
where right interval tips may take infinite values. Alternatively, a static dynamic weight can be specified in (4) if necessary
\[ \| W_P(s) F_I (P(s), K(s, \kappa)) \|_{l_p} \leq 1, \forall P \in \mathcal{P}^\infty, \mathcal{P}^\infty \subset \mathcal{P}, \]  
(5)
to stress the relative importance of each channel.

Finally, the most fundamental specification for a closed-loop system is internal stability. Thus, the sought controller \( K(\kappa) \) must also guarantee negative upper bounds on the closed-loop spectral abscissas
\[ \alpha(A_P(\kappa)) \leq \alpha_P, \alpha_P < 0, \forall P \in \mathcal{P}, \]  
(6)
where \( A_P(\kappa) \) is the state matrix of the closed-loop system \( F_I (P(s), K(s, \kappa)) \).

In summary, the considered multi-objective controller design problem may be stated as: fin controller variables \( \kappa \in \mathbb{R}^q \) such that constraints (3)-(6) are satisfied In what follows it is discussed how to solve this problem. Notice, initially, that the time-domain constraints in (3) are automatically met if function
\[ f_t(\kappa) := \max_{z \in \mathbb{Z}, t \geq 0} \{ |z(\kappa, t) - u_z(t)|_+, |l_z(t) - z(\kappa, t)|_+ \} \]  
(7)
is non-positive. Similarly, the frequency-domain constraints in (4) and the spectral constraints in (6) are satisfied if functions
\[ f_{\infty}(\kappa) := \max_{P \in \mathcal{P}^\infty} \| F_I (P(s), K(s, \kappa)) \|_{l_p} - 1 \]  
and
\[ g_\alpha(\kappa) := \max_{P \in \mathcal{P}} (\alpha(A_P(\kappa)) - \alpha_P), \]  
(8)
are also non-positive, respectively.

The nonsmooth design method is thus based on solving the max-type optimization problem
\[ \begin{array}{ll}
\text{minimize} & f(\kappa) := \max_{\kappa \in \mathbb{R}^q} \{ f_t(\kappa), f_{\infty}(\kappa) \} \\
\text{subject to} & g_\alpha(\kappa) \leq 0,
\end{array} \]  
(9)
where \( f(\kappa) \) represents the current iterate and \( \kappa^+ \) the next iterate or a candidate to become the next iterate. The key fact about the progress function (11) is that critical points \( \bar{\kappa} \) of \( F(\cdot, \kappa) \) will also be critical points of the original program (10) [3], [14].

The following iterative procedure is used in order to determine a point \( \bar{\kappa} \) giving 0 \( \in \partial_1 F(\bar{\kappa}, \kappa) \). Suppose the current iterate \( \kappa \) is such that 0 \( \notin \partial_1 F(\kappa, \kappa) \), which implies that it is possible to reduce the function \( F(\cdot, \kappa) \) in a neighborhood of \( \kappa \), that is, to find \( \kappa^+ \) such that \( F(\kappa^+, \kappa) < F(\kappa, \kappa) \). Replacing \( \kappa \) by \( \kappa^+ \), the procedure is repeated. Unless 0 \( \in \partial_1 F(\kappa^+, \kappa^+) \), in which case a critical point has been attained, it is possible again to find \( \kappa^{++} \) such that \( F(\kappa^{++}, \kappa^+) < F(\kappa^+, \kappa^+) \), etc. The sequence \( \kappa, \kappa^+, \kappa^{++}, \ldots \) so generated is expected to converge to the sought local minimum \( \bar{\kappa} \) of (10).

The initial \( \kappa \) being strictly feasible, all consecutive iterates will remain inside the feasibility region and, consequently, inside the stability region. To realize that, notice that for \( F(\kappa, \kappa) = 0 \), so the left hand branch in (11) is active at \( \kappa \).

Since the new \( \kappa^+ \) is such that \( F(\kappa^+, \kappa) < F(\kappa, \kappa) < 0 \), one necessarily has \( g(\kappa^+) \leq F(\kappa^+, \kappa) < 0 \), which means that \( \kappa^+ \) is also strictly feasible. Moreover, this also means that the objective is minimized, since \( f(\kappa^+) - f(\kappa) \leq F(\kappa^+, \kappa) < 0 \). By forcing iterates to remain in the stability region, one
guarantees that the algorithm will progress in a region where function $f_{\infty}$ in (8) is well defined.

Finding the descent step $\kappa^+$ away from the current $\kappa$ is based on solving the tangent program at $\kappa$

$$\min_{\delta \in \mathbb{R}^d} \tilde{F}(\kappa + \delta, \kappa) + \frac{\delta}{2} \| \delta \| ^2, \quad \delta > 0, \quad (12)$$

whose name is derived from the fact that a first-order approximation $\tilde{F}(\cdot, \cdot)$ of $F(\cdot, \cdot)$ is built. Solving the tangent program provides a descent direction $d\kappa$ at $\kappa$, that is, $d_1 F(\kappa, \kappa; d\kappa) < 0$, where $d_1 F$ denotes the directional derivative of $F(\cdot, \kappa)$ at $\kappa$ in direction $d\kappa$. The next iterate is then $\kappa^+ = \kappa + d\kappa$, or possibly $\kappa^+ = \kappa + ad\kappa$ for a suitable stepsize $\alpha \in (0, 1)$ found by a backtracking line search. The quadratic term in (12) can be used to capture second-order information, or it may be interpreted as a trust region radius management parameter. Program (12) can be equivalently formulated as a standard convex quadratic program (CQP), which can be efficiently solved using currently available state-of-the-art codes.

In order to build the first-order approximation $\tilde{F}(\cdot, \cdot)$ of $F(\cdot, \cdot)$ used in (12), one need initially to gather first-order information on the various specification represented by $f_f$, $f_\infty$ and $g_s$. For the spectral abscissa specification in $g_s$, the subdifferential of the function $\partial(\alpha \circ A_P)(\kappa)$ has been given in [6]. Subgradients computation involves only basic linear algebra operations and therefore can be performed very efficiently. The subdifferential of the maximum singular value norm appearing in $f_\infty$ shares a similar structure [2], [16]. Finally, subgradients computation for $f_f$ relies on closed-loop simulations which can be performed very efficiently for LTI systems, the reader is referred to [7] for details.

III. APPLICATION TO LATERAL FLIGHT CONTROL DESIGN OF A HIGHLY FLEXIBLE AIRCRAFT

The nonsmooth method is used in this section to design a fligh controller for the lateral motion of a large carrier aircraft in which fl xiblity has been intentionally degraded to a highly critical level in order to build a difficul control problem and to test the efficiency of various modern techniques. It is a difficul and realistic problem which has been initially presented in [1]. Six linearized models of the lateral motion of the aircraft around equilibrium points are considered here, corresponding to six distributions of the mass inside the plane under the same fligh condition.

Each model is described by a 68th-order state-space representation whose state vector contains 4 rigid states (yaw angle $\beta$, roll rate $p$, yaw rate $r$ and roll angle $\phi$), 36 states corresponding to 18 fl xible modes, 20 secondary states representing the dynamics of servocontrol surfaces and aerodynamic lags, and 8 states modeling turbulence as exogenous disturbance. There are two control inputs, given by aileron deflection $\delta_1$ and rudder deflection $\delta_2$, and one exogenous disturbance input $v$ representing gusts. For the sake of comparison, the same six measurements used in [1] are also used here, which are the roll rate $p_0$ and angle $\phi_0$ measured at the center of the plane, the yaw rates $r_1$ and $r_11$ at the front and the rear of the aircraft, respectively, and the lateral accelerations $\nu_7$ and $\nu_8$ measured at two different points of the fuselage. This set of measurements was selected according to observability properties of the rigid model and first fl xible modes (in an increasing order of pulsation) with respect to sensors location along the fuselage.

The following design specification are define for this problem:

S1 flyin quality requirements represented by time-domain templates on the step responses with respect to $\beta$ and $\phi$,
S2 large Dutch roll damping ratio,
S3 no degradation, or preferably improvement in damping ratios of fl xible modes,
S4 improved comfort during turbulence. The comfort performance index is measured on the frequency response of transfers between the gust $v$ and lateral accelerations at the front, the middle and the rear of the fuselage,
S5 robustness with respect to the various loading conditions,
S6 to facilitate on-board implementation a reduced-order controller order is desirable.

The adopted control configuratio and the corresponding synthesis interconnection are depicted in Figure 3, where $G(s)$ represents the aircraft transfer matrix for a given load condition, $u = [\delta_1 \delta_2]^T$ are the control inputs, $y = [\nu_7 \nu_8 p_0 r_1 r_11 \phi_0]^T$ are the measured outputs and $r := [\beta \phi]^T$ is the reference vector. Different outputs will be selected so as to form the regulated output vector $z$ according to the various criteria.

Using the fl xibility provided by parametrization (2), the feedback controller $K(s, \kappa)$ is selected a 10th-order state-space system, which means that the reduced controller order specificatio (S6) is ensured. For comparison, it should be noticed that the controller order obtained in [1] using model reduction techniques was 20. Additionally, the feedback controller is forced to be strictly proper ($D_K(s) \equiv 0$ in (2)) in order to improve robustness with respect to high frequency fl xible modes and achieve better noise attenuation. The feedforward controller $F \in \mathbb{R}^{2 \times 2}$ is selected as a static matrix gain again for simplicity.

The firs time-domain specificatio in (S1) which is imposed on the fina closed-loop system is the steady-state constraint

$$\lim_{t \to \infty} \left[ \begin{array}{c} \beta(t) \\ \phi(t) \end{array} \right] = \left[ \begin{array}{c} 1 \\ -1 \end{array} \right] \left[ \begin{array}{c} \beta_r(t) \\ \phi_r(t) \end{array} \right], \quad (13)$$

This constraint can be addressed via appropriate selection of the pre-flite gain $F$. Indeed, notice that (13) will be
automatically met if $F$ is derived through
\[
F = \mathcal{F}_l (G_{\beta \phi}(0), -K(0, \kappa))^{-1} \begin{bmatrix} 1 & 0 \\ -1 & 1 \end{bmatrix},
\]
where $G_{\beta \phi}(s)$ is the open-loop transfer matrix from $[u^T \ k^T]^T$ to $[[\beta \ \phi \ \gamma \ \kappa]^T]^T$ and assuming existence of the inverse matrix. In practice, (14) can be written equivalently as
\[
F = \mathcal{F}_l (M, K(0, \kappa))^{-1} \begin{bmatrix} 1 & 0 \\ -1 & 1 \end{bmatrix},
\]
where matrix $M$ is such that
\[
\mathcal{F}_l (M, K(0, \kappa)) = \mathcal{F}_l (G_{\beta \phi}(0), -K(0, \kappa))^{-1},
\]
Existence of matrix $M$ is guaranteed by the fact that the open-loop transfer matrix from $u$ to $[\beta \ \phi]$ is non-singular [19, p.242]. The feedforward gain $F$ is thus uniquely determined by the design variables vector $\kappa$ via the continuously differentiable parametrization (15), which can be easily incorporated into the nonsmooth method framework. Consequently, both feedback and feedforward controllers will be designed simultaneously throughout the optimization.

As discussed in Section II, the time-domain templates translating flying quality requirements in (S1) are handled directly within the nonsmooth method. Two basic scenarios are initially considered. In the first scenario, a unit step is applied to reference $\beta_r$ while $v$ and $\phi_r$ are considered to be zero, and appropriate envelope constraints are imposed on the relevant outputs. Figure 4 depicts the envelope constraints imposed on rigid $\beta$ and $\phi$ for this scenario, as well as the evolution of the system responses throughout the optimization sequence, starting from the initial stabilizing controller. Notice that constraints such as minimal phase response for $\phi$ can be addressed easily via time-domain templates. The second scenario consists in a unitary step being applied to $\phi_r$ while the other two inputs are kept to zero. The corresponding envelope constraints imposed on rigid $\beta$ and $\phi$ are depicted in Figure 5.

In order to improve performance robustness with respect to load variation, as required by (S5), the above scenarios are considered for two extreme load conditions: the lightest and the heaviest models. In the framework of Section II, this means that the plant family $\mathcal{P}$ will consist of two models which we refer to by light and heavy. Correspondingly, two different test inputs as discussed previously will be applied to both plants. This result in a total of four scenarios which must be adequately controlled. The main idea here is that by guaranteeing similar system responses even under extreme load variations, satisfactory closed-loop system behavior can also be expected for intermediate conditions. If, however, final closed-loop system response proves to be unsatisfactory for a given intermediate load condition, one may alternatively restart the design but this time taking the critical intermediate scenario into account via an enriched plant family $\mathcal{P}$. Analogously, constraints are imposed via (9) on the closed-loop spectral abscissas with both light and heavy models to achieve stability robustness requirements.

The feedforward gain $F$ is not depending on load conditions, so a nominal model has to be defined in (14): the light model has been selected to play this role. Notice, however, that the case of an adaptive gain could also be easily handled: the only change necessary would be to consider in (14) the transfer $G_{\beta \phi}$ accordingly.

Improvement in comfort during turbulence is obtained by minimizing, in the fl xible modes frequency range, the magnitude of the transfer functions from the exogenous disturbance $v$ to the lateral acceleration measured at three distinct points of the fuselage: front ($v_{(1)}$), center ($v_{(6)}$) and rear ($v_{(11)}$). Figure 6 shows the corresponding transfer magnitudes for the uncontrolled plant and the corresponding achieved closed-loop frequency responses. Horizontal dashed lines in Figure 6 materialize bounds which have been prescribed via $\gamma_P$ in (8). These frequency-domain constraints are the same for both light and heavy models in order to improve robustness with respect to load variations.

Finally, norm constraints (5) are imposed on the sensitivity
function $S = (I + G_y K)^{-1}$, $G_y(s)$ being the open-loop transfer from $u$ to $y$, for both light and heavy models. In addition to increasing the stability margin, these constraints allows to increase the damping ratios of the Dutch roll and the flexible modes. The largest singular-value of $S$ is depicted in Figure 7 for both light and heavy loads. The dotted-lines in Figure 7 represent the corresponding desired norm-bounds define via dynamic weights $W_P$ in (5).

It is well-known that pole-zero cancellations is a critical issue when designing controllers with frequency domain techniques. Incorporating various load conditions in the synthesis is a simple device to overcome cancellations of flexible modes. In the same vein, the possibility to work with low-order controllers (order 10 as compared to the plant order of 68) is another favorable feature to prevent pole/zero cancellations. The $H_2$/PRLQG criterion used in [1] to increase the damping ratios of flexible modes is another potential option which requires constructing a linear fractional representation to model parametric uncertainty in flexible modes. We have not followed this route here as LFR models suggest using $\mu$-synthesis as design tool with the difficulties discussed above in terms of controller order and structure.

Figure 8 depicts the position of closed-loop poles in the complex plane as the controller gain is varied from 0 to 100%. As required, the Dutch roll damping ratio has been significantly increased, as well as the damping ratios of the first flexible modes. Additionally, no critical damping ratio...
degradation is observed.

Closed-loop system responses for six different load conditions are depicted in Figure 9, more precisely the rigid yaw angle $\beta$ together with the roll rate $p_6$, the yaw rate $r_6$ and the roll angle $\phi_6$ measured at the center of the airplane. System responses meet the flying quality requirements and robust performance has been obtained. Additionally, the closed-loop system clearly satisfies comfort and damping ratio requirements for load conditions.

IV. CONCLUSION

This paper has focused on the design of a flight controller for the lateral motion of a highly flexible aircraft subject to exogenous disturbances and different load conditions. A reduced-order feedback controller as well as a static feed-forward controller have been designed simultaneously without recourse to risky order reduction schemes. The study case is a challenging application as it involves a 68th-order plant, several operating conditions and stringent time- and...
frequency domain specification in addition to structural constraints on the controller. The proposed nonsmooth optimization technique has been shown to hold promise in solving a set of concurrent constraints and in achieving turbulence attenuation and robustness with respect to flexible aircraft uncertainties.

The proposed approach is local in nature which means optimality certificate are local as opposed to the indisputable global certificate. We think this is a minor weakness widely offset by the flexibility to directly cope with multiple specifications. Specification are indeed handled as stated in practice by designers thus bypassing conservative embedding as is usually the case with more traditional techniques.

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