ACTIVE GUST LOAD ALLEVIATION ON A FULL-SCALE AIRCRAFT WING USING AN ADAPTIVE FOLDING WINGTIP MECHANISM

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ABSTRACT

This paper develops an integrated aero servo elastic modeling and control framework to quantify and exploit an adaptive folding wingtip as an active gust load alleviation device for future flexible, high aspect ratio transport wings. Motivated by the increased gust sensitivity, elevated wing root bending moments, and ride quality degradation inherent to ultra slender wing concepts, the study treats the folding wingtip as a multifunctional actuator that provides both additional aerodynamic authority and a direct structural load relief mechanism. A full aircraft aero servo elastic plant is constructed on an ATR class baseline by coupling a mid fidelity unsteady aeroelastic solver with gust and actuator dynamics, while representing the dominant structural dynamics in reduced order state space form to enable time domain simulation and controller synthesis. Gust load alleviation is formulated as a constrained multi objective optimal control problem and implemented using nonlinear model predictive control, explicitly enforcing actuator limits and structural load constraints while coordinating folding wingtip commands with conventional flight controls through control allocation. A hybrid sensing and estimation layer fuses inertial measurements with strain based wing root bending moment feedback to regulate both structural and ride quality metrics with robustness to uncertainty and noise. Preliminary simulations for discrete and 1-cosine gust encounters indicate approximately 20 to 40 percent reduction in peak wing root bending moment with concurrent attenuation of flexible mode vibrations, achieved with acceptable control activity and without excessive actuation demand.

INTRODUCTION

Future commercial aircraft concepts envisioned under the European Flightpath 2050 and Airbus Horizon 2050 roadmaps rely heavily on ultra-high aspect ratio, lightweight and flexible wings to minimize drag and fuel consumption [1, 2]. However, the increased structural flexibility of such configurations amplifies sensitivity to atmospheric gusts, leading to higher wing-root bending moments, reduced fatigue life, and degraded ride quality [3, 4]. Passive load alleviation alone is insufficient to meet these competing requirements, motivating the development of actively controlled morphing devices that can respond in real time to unsteady aerodynamic disturbances [5, 6, 7].

Within this context, this paper investigates an actively actuated Folding Wingtip (FWT) as a multifunctional control surface for gust load alleviation and aero-servo-elastic performance enhancement. The folding wingtip concept provides additional aerodynamic authority beyond conventional control surfaces, while simultaneously offering a structural load-relief mechanism that directly targets the dominant bending and torsional responses of slender wings. The present paper focuses on the numerical framework and control architecture developed to assess and optimize this concept on a full-scale transport aircraft wing.

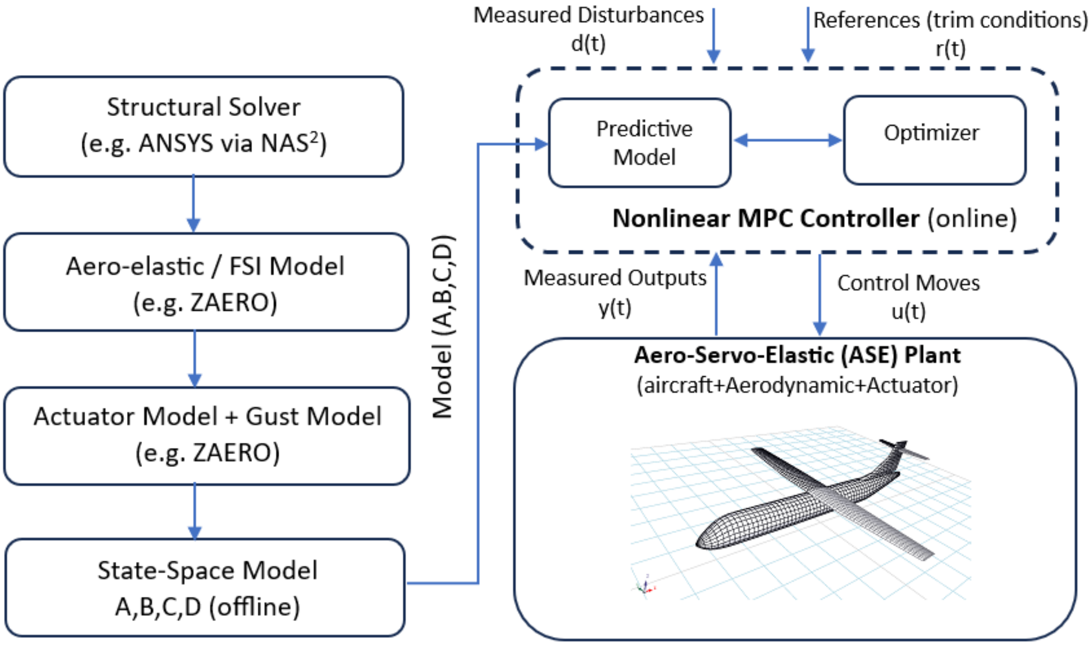

Figure 1: System level overview of the proposed folding wingtip gust load alleviation concept and its integration into the aircraft control loop

The baseline configuration is derived from an ATR-class aircraft model, chosen for its high aspect ratio wing and pronounced aeroelastic behavior. A unified aero-servo-elastic (ASE) modeling environment is constructed by coupling a mid-fidelity aeroelastic solver with an actuator and gust disturbance model. The structural dynamics are described in a reduced-order state-space form, obtained from high-fidelity structural and aerodynamic models, enabling efficient time-domain simulation and controller synthesis. The resulting ASE plant captures the essential interaction between aircraft rigid-body dynamics, flexible wing deformation, aerodynamic unsteadiness, and folding wingtip actuation.

METHODOLOGY

The overall methodology follows a control co-design philosophy in which structural dynamics, actuation limits, sensing architecture, and control laws are treated in a tightly coupled manner. A nonlinear Model Predictive Control (MPC) framework is adopted, as illustrated in Fig. 1, combining a predictive plant model with an online optimizer that explicitly accounts for actuator constraints, structural load limits, and performance objectives. Measured gust disturbances and reference trim conditions are incorporated into the predictive model, allowing the controller to anticipate upcoming load excursions and generate optimal control actions in real time.

The control architecture is further embedded within a complete flight-control system, as shown in Fig. 2. The flight computer integrates the predictive model, optimizer, and control allocation modules, distributing commands between conventional control surfaces (aileron, elevator, rudder) and the folding wingtip actuator. A hybrid sensing strategy is employed, combining inertial measurements (angular rates and accelerations) with structural measurements, particularly the wing-root bending moment obtained from strain gauges. This sensor fusion approach enables the controller to directly regulate both ride quality metrics and structural load indicators, providing a physically meaningful and safety-oriented feedback

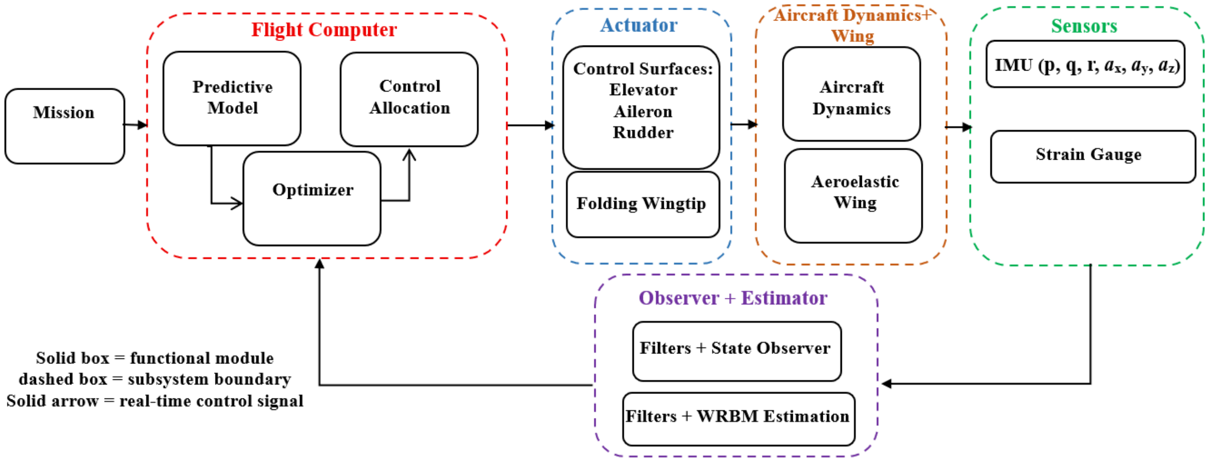

Figure 2: Flight control system block diagram integrating folding wingtip actuation and load aware feedback

structure.

State estimation is performed using dedicated observer and filtering modules that reconstruct both rigid-body states and dominant flexible modes, as well as estimating the wing-root bending moment in real time. This estimation layer is essential to ensure robustness against sensor noise, model uncertainties, and unmeasured disturbances, and it provides the controller with reliable information on the instantaneous aeroelastic state of the aircraft. The proposed framework formulates gust load alleviation as a multi-objective optimal control problem. The primary objectives include:

1. Minimization of peak wing-root bending moment during discrete and continuous gust encounters.
2. Reduction of structural vibration levels and acceleration-based ride-quality metrics.
3. Limitation of folding wingtip deflections, rates, and actuation power consumption.
4. Preservation of closed-loop stability and sufficient robustness margins.

The novelty of the present work lies in the explicit and simultaneous treatment of structural design, folding wingtip kinematics, and feedback control within a unified ASE framework. Rather than treating the folding wingtip as an add-on control surface, it is modeled as an integral part of the load-carrying structure and included directly in the system dynamics and control optimization. This enables the derivation of quantitative design rules that balance aerodynamic effectiveness, structural benefits, actuation mass and power penalties, and closed-loop stability constraints.

Preliminary numerical results demonstrate that the adaptive folding wingtip provides a significant additional degree of freedom for gust load alleviation compared to conventional control surfaces alone. For representative discrete and 1-cosine gust profiles, reductions of approximately 20–40 % in peak wing-root bending moment are observed, together with measurable attenuation of flexible-mode vibrations. These reductions are achieved without excessive actuation demands and while maintaining acceptable control activity levels on the primary flight control surfaces.

The developed toolchain constitutes a complete ASE–control environment, capable of supporting both control law development and morphing device design. Beyond the specific folding wingtip application, it provides a general framework for assessing future morphing concepts on highly flexible wings.

Model Predictive Control Design - Control Objectives and Architecture

The objective of the proposed control framework is the simultaneous regulation of aircraft longitudinal rigid-body motion and structural load alleviation under atmospheric gust disturbances [8]. Specifically, the controller aims to regulate the angle of attack α, pitch rate q, and pitch angle θ, while minimizing vertical acceleration at the aircraft center of mass a_z and the wing-root bending moment M_{rbm}.

To achieve this, a constrained nonlinear Model Predictive Control (MPC) strategy is adopted, using a reduced-order aero-servo-elastic (ASE) prediction model derived from the coupled rigid-body, aerodynamic, and structural dynamics of the aircraft. The MPC framework enables explicit treatment of nonlinearities, gust disturbances, and actuator saturation while optimizing multiple competing objectives in a unified optimal control formulation.

The controller commands both conventional longitudinal control surfaces (elevator) and the folding wingtip actuator, with the latter acting as a multifunctional device providing both aerodynamic authority and direct structural load alleviation capability.

Augmented aero-servo-elastic aircraft model

The reduced-order nonlinear aero-servo-elastic model used for prediction in the MPC is written in continuous-time state-space form as

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{f}\big(\boldsymbol{x}(t), \boldsymbol{u}(t), \boldsymbol{d}(t)\big), \qquad \boldsymbol{y}(t) = \boldsymbol{h}\big(\boldsymbol{x}(t), \boldsymbol{u}(t)\big), \tag{1}$$

where the state vector is defined as

$$\boldsymbol{x} = \begin{bmatrix} \alpha & q & \theta & \boldsymbol{\eta}^T & \dot{\boldsymbol{\eta}}^T \end{bmatrix}^T, \tag{2}$$

with $\boldsymbol{\eta}$ denoting the dominant structural modal coordinates retained in the reduced flexible wing model. The control input vector is

$$\boldsymbol{u} = \begin{bmatrix} \delta_e & \delta_f \end{bmatrix}^T, \tag{3}$$

where δ_e denotes elevator deflection and δ_f denotes folding wingtip angle. The disturbance vector $\boldsymbol{d}(t)$ represents atmospheric gust inputs.

The measured and controlled outputs are selected as

$$\boldsymbol{y} = \begin{bmatrix} \alpha & q & \theta & a_z & M_{\text{rbm}} \end{bmatrix}^T, \tag{4}$$

where a_z is the vertical acceleration at the aircraft center of mass and M_{rbm} denotes the wing-root bending moment reconstructed from structural states and aerodynamic loads.

For MPC implementation, the dynamics are discretized with sampling time T_s,

$$\boldsymbol{x}_{k+1} = \boldsymbol{f}_d(\boldsymbol{x}_k, \boldsymbol{u}_k, \boldsymbol{d}_k), \qquad \boldsymbol{y}_k = \boldsymbol{h}_d(\boldsymbol{x}_k, \boldsymbol{u}_k), \tag{5}$$

where $\boldsymbol{f}_d(\cdot)$ and $\boldsymbol{h}_d(\cdot)$ denote the discrete-time nonlinear prediction model.

Constrained MPC Problem Formulation

At each sampling instant k, the MPC computes a sequence of control inputs $\{\boldsymbol{u}_{k+i|k}\}_{i=0}^{N_c-1}$ by solving the following constrained finite-horizon optimal control problem [9]:

$$\begin{aligned} \min_{\{\boldsymbol{u}_{k+i|k}\}} \quad & \sum_{i=0}^{N_p-1} \left(\boldsymbol{y}_{k+i|k} - \boldsymbol{y}_{\text{ref}}\right)^T \boldsymbol{Q} \left(\boldsymbol{y}_{k+i|k} - \boldsymbol{y}_{\text{ref}}\right) \\ & + \sum_{i=0}^{N_c-1} \boldsymbol{u}_{k+i|k}^T \boldsymbol{R} \boldsymbol{u}_{k+i|k} + \sum_{i=0}^{N_c-1} \Delta\boldsymbol{u}_{k+i|k}^T \boldsymbol{S} \Delta\boldsymbol{u}_{k+i|k}, \end{aligned} \tag{6}$$

subject to the prediction model

$$\boldsymbol{x}_{k+i+1|k} = \boldsymbol{f}_d(\boldsymbol{x}_{k+i|k}, \boldsymbol{u}_{k+i|k}, \boldsymbol{d}_{k+i|k}), \tag{7}$$

$$\boldsymbol{x}_{k|k} = \hat{\boldsymbol{x}}_k, \tag{8}$$

and the following actuator, rate, and structural constraints:

$$\boldsymbol{u}_{\text{min}} \le \boldsymbol{u}_{k+i|k} \le \boldsymbol{u}_{\text{max}}, \tag{9}$$

$$\Delta\boldsymbol{u}_{\text{min}} \le \Delta\boldsymbol{u}_{k+i|k} \le \Delta\boldsymbol{u}_{\text{max}}, \tag{10}$$

$$\boldsymbol{y}_{\text{min}} \le \boldsymbol{y}_{k+i|k} \le \boldsymbol{y}_{\text{max}}, \tag{11}$$

$$|M_{\text{rbm},k+i|k}| \le M_{\text{rbm}}^{\text{max}}, \tag{12}$$

for all $i = 0, \dots, N_p - 1$. The control increment is defined as

$$\Delta\boldsymbol{u}_{k+i|k} = \boldsymbol{u}_{k+i|k} - \boldsymbol{u}_{k+i-1|k}, \tag{13}$$

with $\boldsymbol{u}_{k-1|k} = \boldsymbol{u}_{k-1}$.

The output weighting matrix in (6) is structured as

$$\boldsymbol{Q} = \text{diag}\{w_\alpha, w_q, w_\theta, w_{a_z}, w_M\}, \tag{14}$$

where high weights w_{a_z} and w_M explicitly enforce ride-quality improvement and gust load alleviation by penalizing vertical acceleration and wing-root bending moment excursions, respectively. The reference output vector is chosen as

$$\boldsymbol{y}_{\text{ref}} = \begin{bmatrix} \alpha_{\text{trim}} & q_{\text{trim}} & \theta_{\text{trim}} & 0 & 0 \end{bmatrix}^T, \tag{15}$$

corresponding to trim regulation with zero structural and acceleration excursions.

Elevator and folding wingtip actuators are constrained explicitly as

$$\delta_e^{\text{min}} \le \delta_e \le \delta_e^{\text{max}}, \qquad \dot{\delta}_e^{\text{min}} \le \dot{\delta}_e \le \dot{\delta}_e^{\text{max}}, \tag{16}$$

$$\delta_f^{\text{min}} \le \delta_f \le \delta_f^{\text{max}}, \qquad \dot{\delta}_f^{\text{min}} \le \dot{\delta}_f \le \dot{\delta}_f^{\text{max}}, \tag{17}$$

while structural safety is ensured through hard bounds on wing-root bending moment and, optionally, flexible modal amplitudes,

$$|M_{\text{rbm}}| \le M_{\text{rbm}}^{\text{lim}}, \qquad |\eta_j| \le \eta_j^{\text{max}}. \tag{18}$$

State Estimation and Closed-Loop Implementation

The MPC requires real-time knowledge of both rigid-body and dominant structural states. However, only a subset of these states is directly measurable. Therefore, a nonlinear observer is employed to reconstruct the full aero-servo-elastic state vector,

$$\hat{\boldsymbol{x}}_{k+1} = \boldsymbol{f}_d(\hat{\boldsymbol{x}}_k, \boldsymbol{u}_k, \boldsymbol{d}_k) + \boldsymbol{L}\left(\boldsymbol{y}_k - \hat{\boldsymbol{y}}_k\right), \tag{19}$$

where $\hat{\boldsymbol{y}}_k = \boldsymbol{h}_d(\hat{\boldsymbol{x}}_k, \boldsymbol{u}_k)$ and $\boldsymbol{L}$ denotes the observer gain matrix. Structural states are reconstructed using a hybrid sensing architecture combining inertial measurements and strain-based wing-root bending moment feedback, enabling direct regulation of structural loads rather than indirect modal damping.

At each sampling instant, the estimated state $\hat{\boldsymbol{x}}_k$ is used as the initial condition in (7)–(12), and the nonlinear constrained optimization problem (6) is solved over the prediction horizon. Only the first optimal control input $\boldsymbol{u}^\star_{k|k}$ is applied to the plant,

$$\boldsymbol{u}_k = \boldsymbol{u}^\star_{k|k}, \tag{20}$$

and the horizon is shifted forward at the next sampling instant in a receding-horizon fashion. The inclusion of control increment penalties, hard actuator bounds, and structural load constraints guarantees smooth actuator behavior, feasibility under saturation, and strict compliance with certified load envelopes. Stability and robustness of the closed-loop system are further enhanced by selecting prediction horizons and weighting matrices consistent with local linear-quadratic regulator designs around trim and by enforcing constraint satisfaction at all prediction steps.

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