EXPLOITING CONTROL REVERSAL FOR SIMULTANEOUS ACTIVE AND PASSIVE MANOEUVRE LOAD ALLEVIATION

Evangelos Filippou*, Jurij Sodja and Roeland De Breuker
*Faculty of Aerospace Engineering
Delft University of Technology
Kluywerg 1, 2629 HS, Delft, The Netherlands

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ABSTRACT

High-aspect-ratio wings improve aerodynamic efficiency by reducing induced drag, but at the cost of increased spanwise bending moments which leads to increased structural mass. With increasing aspect ratio, manoeuvre loads become more severe, making load alleviation central to lightweight wing design. Existing approaches, however, impose a fundamental trade-off. On one hand, active manoeuvre load alleviation relies on control surface deflections but requires high torsional stiffness to preserve control effectiveness, often increasing structural mass (Binder et al., 2021). On the other hand, passive aeroelastic tailoring exploits bend–twist coupling to redistribute loads inboard through washout deformation, but typically reduces control effectiveness (Werter, 2017). This work introduces a unified alternative that deliberately exploits control surface reversal to enable simultaneous active and passive load alleviation without sacrificing controllability.

Control surface reversal, where structural deformation of the main wing causes the sign of control effectiveness to invert, is traditionally viewed as a hard design limit to be avoided. While reversal has been documented theoretically and experimentally, it is typically interpreted as a local, two-dimensional phenomenon associated with loss of roll authority (Wright and Cooper, 2008). In contrast, this study reframes control reversal as a deliberately exploitable operating regime, enabled by structural tailoring and control-surface scheduling to provide global wing-level load redistribution in flexible, swept composite wings.

In conventional control-surface operation, active and passive manoeuvre load alleviation act in opposition, leading to a fundamental design trade-off between control effectiveness and torsional compliance. This work hypothesises that post-reversal operation of outboard control surfaces resolves this conflict by making control-surface deflections and composite tailoring complementary mechanisms for inboard load redistribution. In this framework, reversal becomes a means of deliberately scheduling control-surface deflections such that active load alleviation and passive aeroelastic tailoring act cooperatively to redistribute manoeuvre loads inboard.

To investigate this concept, a monolithically coupled aeroelastic optimisation framework is developed and implemented in the in-house tool Proteus (Werter and De Breuker, 2016). Aerodynamics are modelled using a compressibility-corrected Unsteady Vortex Lattice Method, while the structure is represented by a geometrically nonlinear Timoshenko beam co-rotational formulation. Control surface deflections are incorporated efficiently by rotating the normals of the pertinent aerodynamic panels about the hinge line, this way the AICs do not have to be recalculated for every CS deflection. In addition, analytical direct sensitivities with respect to control surface deflections are derived for the aerodynamic system and consistently propagated through the aeroelastic and cross-sectional formulations to obtain exact gradients of strain and panel buckling constraints. These sensitivities are validated to machine precision using the complex-step method, ensuring numerical robustness for gradient-based optimisation.

The framework is applied to the SE^{2}A mid-range transport wing, representative of a single-aisle aircraft with increased aspect ratio and moderate sweep. Three control surfaces per semi-span are included. Design variables comprise laminate stiffness parameters, thicknesses, jig twist, and per-load-case control surface deflections. Structural sizing is performed under static manoeuvre load cases with positive and negative load factors at maximum take-off and zero-fuel mass, while cruise-shape

constraints are imposed to preserve baseline aerodynamic performance.

Two optimisation cases are compared. In the first (Case A), conventional control effectiveness is enforced, requiring positive roll authority from the outboard control surface. In the second (Case B), the constraint is inverted, explicitly requiring sufficient negative roll effectiveness and thus operation within the post-reversal regime. In both cases, minimum roll effectiveness targets consistent with acceptable handling quality requirements are imposed, and a failure scenario with a disabled control surface is evaluated to assess robustness. The cruise lift distribution for both cases is identical, ensuring matching cruise drag, which is essential for aerodynamic performance

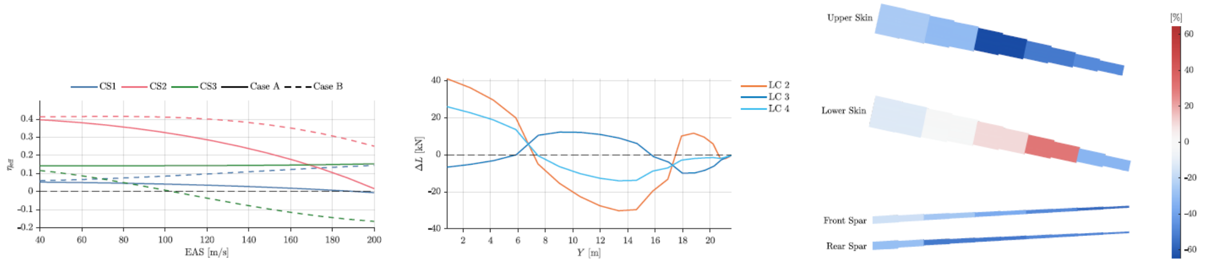
The results demonstrate a clear benefit of the reversal-enabled design, with the underlying mechanisms and resulting structural changes summarized in Figure 1. The post-reversal configuration achieves a 13.3% reduction in structural mass relative to the conventional baseline while satisfying all strength, buckling, aeroelastic stability, and roll-effectiveness constraints. Outboard upper-skin thickness reductions of up to 60% are observed, accompanied by a shift in governing constraints from widespread outboard buckling to more localised inboard normal and shear strain allowables.

Detailed aeroelastic analysis reveals that control surface reversal in swept composite wings is inherently a three-dimensional global phenomenon. Upward deflection of the outboard surface in the post-reversal regime reduces lift not only locally but also across the mid-span through spanwise bending–torsion coupling and induced washout. The effect is driven by misalignment between aerodynamic, elastic, and flexural axes, rather than by a local, two-dimensional aileron reversal mechanism confined to the control-surface section. Load redistribution extends far inboard of the surface itself, enabling effective unloading of structurally critical regions.

Furthermore, the study shows that roll reversal and reversal for manoeuvre load alleviation are not equivalent. Classical reversal is defined by a sign change in rolling-moment derivatives, whereas structural benefit arises from spanwise lift redistribution that governs local panel-level constraints. The control-surface deflection that maximises negative rolling moment does not generally coincide with the deflection that yields the greatest structural benefit. Recognizing this distinction is key to exploiting reversal as a design mechanism rather than avoiding it as a limit.

A minimum-norm control allocation analysis confirms operational viability. The reversal-enabled wing achieves target roll rates across the flight envelope using distributed control strategies that deliberately exploit negative effectiveness of the outboard surface, without increased control activity. Under a representative failure scenario, roll authority is preserved through redistribution to remaining surfaces, demonstrating robustness.

In summary, this work demonstrates that control surface reversal, traditionally viewed as detrimental, can be deliberately exploited to unify active and passive manoeuvre load alleviation. By reframing reversal as a wing-level load-control mode enabled by three-dimensional aeroelastic coupling, the study opens a new design space for lighter, more efficient transport wings. These findings are directly relevant to future high-aspect-ratio aircraft concepts, where structural efficiency and controllability must be achieved simultaneously.



(a) Outboard control effectiveness: conventional vs reversal-enabled.

(b) Spanwise lift: redistribution with post-reversal scheduling.

(c) Thickness/stiffness changes enabling 13.3 % mass reduction.

Figure 1: Key results underpinning the reversal-enabled design: (a) maintained roll authority despite negative outboard effectiveness; (b) three-dimensional spanwise load redistribution that unloads the tip and shifts loads inboard;(c) structural

tailoring that leverages redistributed loads to achieve a 13.3% structural mass reduction while satisfying strength and buckling constraints.

REFERENCES

Binder, S., Wildschek, A., De Breuker, R., 2021. The interaction between active aeroelastic control and structural tailoring in aeroservoelastic wing design. Aerospace Science and Technology 110, 106516. https://doi.org/10.1016/j.ast.2021.106516

Werter, N.P.M., 2017. Aeroelastic Modelling and Design of Aeroelastically Tailored and Morphing Wings. Delft University of Technology. https://doi.org/10.4233/UUID:74925F40-1EFC-469F-88EE-E871C720047E

Werter, N.P.M., De Breuker, R., 2016. A novel dynamic aeroelastic framework for aeroelastic tailoring and structural optimisation. Composite Structures 158, 369–386. https://doi.org/10.1016/j.compstruct.2016.09.044

Wright, J.R., Cooper, J.E., 2008. Introduction to aircraft aeroelasticity and loads. Wiley, Chichester.