

INSTABILITY AND TRANSITION OF SWEPT-WING FLOW

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1) Summary for a general public

Modern aircraft burn enormous quantities of fuel overcoming the friction between the air and the wing surfaces. This friction depends critically on the state of the thin layer of air flowing over the wing: when it is smooth and orderly (a state known as laminar flow) friction is low; when it becomes turbulent, friction rises significantly. Keeping the flow laminar over a larger portion of the wing could cut a typical airliner's fuel burn by 4% to 7%; on a single Frankfurt–Los Angeles flight this amounts to several tonnes of fuel.

Real wings, however, are not perfectly smooth: they carry small steps and gaps in the junction between manufacturing panels. For nearly a century, such surface imperfections have been typically regarded as detrimental to laminar flow, since they are known to trigger turbulence prematurely; thus forcing manufacturers toward smoother wings at sharply increasing manufacturing cost and complexity.

This thesis challenges that belief: using computer simulations and new theory it demonstrates that, under suitable conditions, a surface step does the opposite of what was assumed: rather than promoting turbulence, it can keep the flow laminar for longer. The work identifies the physical mechanism responsible (a previously unrecognised stabilising effect) and shows how it can be leveraged: future wings might incorporate a tailored micro-surface relief, opening a new route to lower fuel consumption through passive laminar flow control.

2) Scientific summary

2a) Objectives and scientific context

In subsonic swept-wing flow, laminar–turbulent transition is typically driven by the spatial amplification of the stationary crossflow instability (CFI). Surface steps, such as those at the junctions of manufactured wing panels, are widely regarded as detrimental and a substantial body of work reports that they advance transition. Yet large discrepancies exist in the literature regarding the mechanisms governing the interaction between a step and a pre-existing CFI. A central obstacle has been the limited reliability of classic stability methods near sharp surface features, where *short-term* effects such as flow recirculation are expected to play a significant role.

The overarching objective of this thesis is to ascertain, through Direct Numerical Simulations (DNS), how a forward-facing step modifies the transition of a laminar incompressible swept-wing boundary layer carrying a pre-existing stationary CFI. Beyond the underlying physics, the work establishes a more provocative question, prompted by unexpected findings during the project itself: whether a localised surface feature, typically treated as a defect to be minimised, might instead be exploited for passive laminar flow control.

2b) Research methodology

The investigation is built on high-fidelity DNS of the incompressible Navier–Stokes equations. Steps spanning 30% to 50% of the boundary-layer thickness were examined, and cross-validated against linear and non-linear Parabolised Stability Equations (PSE), two-dimensional BiGlobal stability analysis, and independent wind-tunnel measurements within the same group at TU Delft.

Two theoretical frameworks were developed to assess main perturbation mechanisms. The first decomposes the perturbation field relative to the *local flow orientation* rather than to the wall (the convention of classic stability theory), separating a streamwise-aligned component (velocity excess and deficit) from a cross-stream component (momentum-redistributing vortical structures); this preserves structural coherence and distinguishes modal from non-modal growth (Casacuberta *et al.*, 2022). The second, an extended Reynolds–Orr energy framework, isolates the linear and non-linear mechanisms of energy exchange between the laminar (base) flow and each spanwise perturbation mode (Casacuberta *et al.*, 2026). Together they yield a decomposition of the production term that uncovers a central result of the thesis: the lift-up effect (a main driver of non-modal growth) can be reversed, acting to stabilise the boundary layer (Casacuberta *et al.*, 2024, 2025).

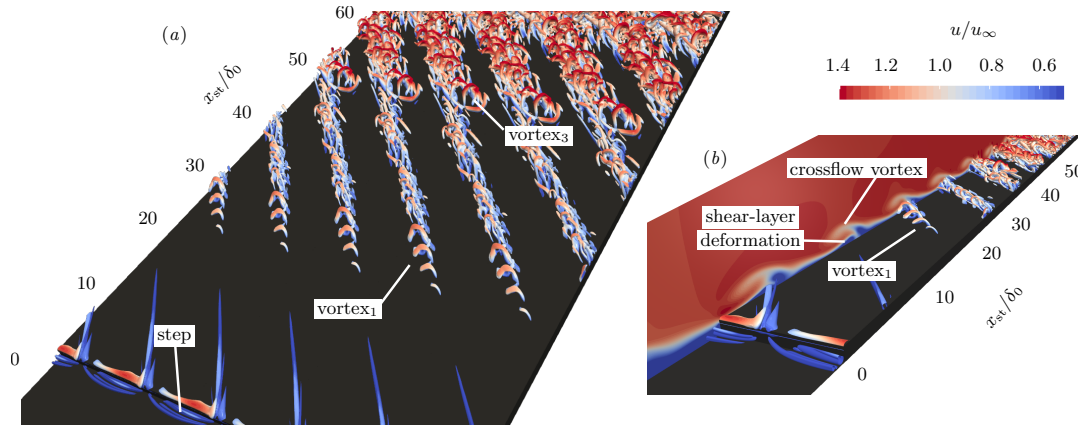


Figure 1: Instantaneous flow organisation at the step (Q -criterion isosurface coloured by chordwise velocity (a)), with a zoom showing the chordwise velocity in an x - y plane (b). The flow moves from bottom to top.

2c) Main results

Transition advancement is driven by a new instability induced at the step. A forward-facing step is widely reported to shift the laminar–turbulent transition front upstream, and the thesis identifies the mechanism responsible. This transition is *not* driven by the classic secondary crossflow instabilities that govern breakdown in the absence of a step. Instead, the deformation of the near-wall shear layer close downstream of the step supports the exponential amplification of a distinct family of high-frequency eigenmodes originating from the shear layers surrounding the step (Casacuberta *et al.*, 2026). First observed in DNS, these step-induced modes have also been reproduced by two-dimensional BiGlobal stability analysis and qualitatively match the transitional behaviour in independent wind-tunnel experiments (Rius-Vidales & Kotsonis 2022). Their growth precedes a hairpin vortex-shedding breakdown (Figure 1), bypassing the classic secondary route altogether and reframing step-induced transition not as an intensification of the existing instability, but as the onset of a fundamentally new one.

The lift-up effect can be reversed. The step’s influence is not confined to this destabilising route. Originally formulated by Ellingsen & Palm (1975), the lift-up effect is a fundamental mechanism of fluid mechanics: a cross-stream perturbation redistributes low- and high-momentum fluid across a shear layer, generating streamwise streaks that grow non-modally. The lift-up effect is almost universally regarded as destabilising, known to drive bypass transition under free-stream turbulence. This thesis uncovers a previously unreported counterpart: a *reverse* lift-up effect that stabilises the flow. When a boundary-layer instability pre-exists and carries streamwise-tangent perturbations, a rapid change in surface geometry (such as the step) can locally *reverse* the momentum redistribution: for certain spanwise phase relationships, the same shear-layer interaction that classically amplifies streaks instead *quenches* them, attenuating the instability. Demonstrated on canonical configurations, the reverse lift-up effect is a previously overlooked limiting case of the original model. Its consequence is critical: contrary to the prevailing view, rapid variations in surface geometry do not universally destabilise the swept-wing boundary layer.

Demonstration: a step that delays transition. The two mechanisms above define an engineering possibility, tested as a numerical experiment. Passively *delaying* transition with a step (an outcome not previously thought attainable) proves possible, but requires a combination of step geometry and flow conditions that achieves two things at once: it must limit the local shear-layer modulation, so that the step-induced eigenmodes are not excited, while weakening (or, in the limiting case, reversing) the lift-up effect that amplifies the incoming instability. A dedicated DNS confirms that a suitably configured step delays transition relative to the no-step case (Figure 3 (a)), as independently corroborated by wind-tunnel experiments (Rius-Vidales & Kotsonis 2021).



Figure 2: Coverage of the discovery in *de Volkskrant*, a Dutch national newspaper (2023), featuring the co-inventors (including the author).

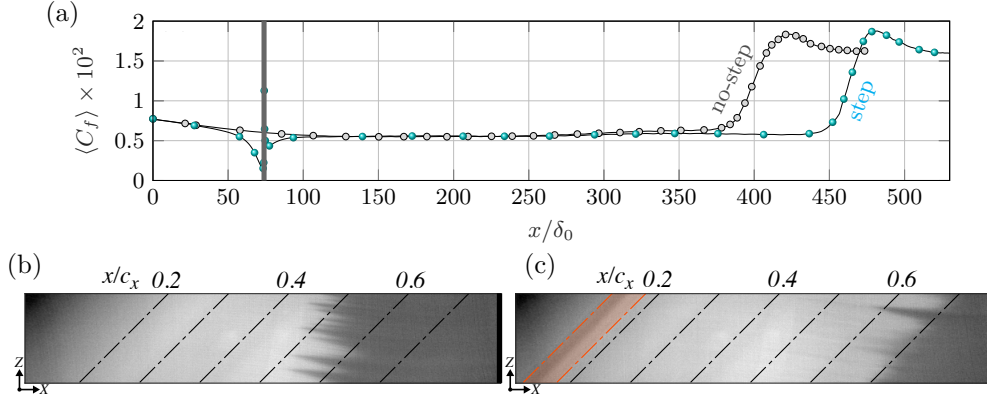


Figure 3: Evolution of the skin-friction coefficient along the wing chord for a stabilising step (cyan spheres), compared to the reference no-step case (black circles); obtained by DNS, it evidences transition delay. Vertical line indicates the step (a). Infrared maps for a reference wing (b) and for the same wing fitted with the “Delft Laminar Hump” (orange region) (c), demonstrating transition delay by the hump (Rius-Vidales *et al.*, 2025).

2d) Achievements and impact

The scope of this thesis concerns the forward-facing step. A central result, the numerical and theoretical demonstration that a surface feature can passively *delay* laminar–turbulent transition, together with the identification of an underlying mechanism, laid foundations for a collaborative research line within the same laboratory at TU Delft. This line, to which the author contributed as co-author, translated the principle into a smoother, aerodynamically more favourable surface feature, the “Delft Laminar Hump”. Several of the achievements below stem from this collaborative follow-on work, to which this thesis contributed mathematical frameworks and physical understanding.

- **A novel passive flow control method.** Using high-fidelity DNS and new theory, the thesis established that a forward-facing step can delay transition via the proposed modification of the production mechanism, as also demonstrated empirically through independent wind-tunnel experiments (Rius-Vidales & Kotsonis 2021), thereby overturning the prevailing view that surface features are universally detrimental to laminar swept-wing flow.
- **Patent and industrial valorization (collaborative).** The underlying principle (transition delay of wing flow via surface features, see Figure 3) has been protected by an international patent (WO 2024/151166 A1).
- **Experimental validation at NASA (collaborative).** The “Delft Laminar Hump” technology is scheduled for experimental testing at NASA Langley Research Center.
- **Public recognition (collaborative).** The discovery received national press coverage in the Dutch newspaper *de Volkskrant* (November 2023); see Figure 2.
- **Award.** The author was recognised with the Best Speaker Award at the Burgers Symposium (2022).

3) Selected publications and research output

1. J. Casacuberta, K. J. Groot, S. Hickel & M. Kotsonis (2026). Transition of swept-wing boundary-layer flow induced by a forward-facing step. *J. Fluid Mech.* **1041**, A19.
2. J. Casacuberta, S. Hickel, S. Westerbeek & M. Kotsonis (2022). Direct numerical simulation of interaction between a stationary crossflow instability and forward-facing steps. *J. Fluid Mech.* **943**, A46.
3. J. Casacuberta, S. Hickel & M. Kotsonis (2024). Passive stabilization of crossflow instabilities by a reverse lift-up effect. *Phys. Rev. Fluids* **9**, 043903.
4. J. Casacuberta, S. Westerbeek, J. A. Franco, K. J. Groot, S. Hickel, S. Hein & M. Kotsonis (2025). Streaky perturbations in swept-wing flow over forward-facing step. *Phys. Rev. Fluids* **10**, 023902.
5. S. Westerbeek, J. Casacuberta & M. Kotsonis (2026). Linear and nonlinear interactions between stationary crossflow instabilities and a smooth surface hump. *J. Fluid Mech.* **1026**, A43.

Total research output: 8 journal articles (4 as first author), 1 international patent, 5 conference articles/proceedings, 6 conference presentations, 1 best-speaker award, 1 invited talk.