

Aeroelastic stability calculations of a laminar wing using viscous-inviscid interaction

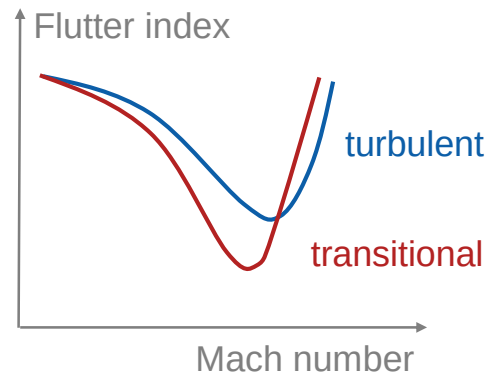
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Laminar wings and flutter



A340 BLADE – H. Goussé & S. Ramadier – Airbus



Flow laminarity will affect aeroelastic stability of wings!

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Laminar wings have been studied for a long time:

- first studies around 1930s;
- recent (flight) demonstrator BLADE by Airbus, in 2017.

However, technology is not used yet in actual aircraft design because of several challenges, e.g. keeping the flow laminar across the flight envelope.

In this work, we focus on the effect of transition from laminar to turbulent flows on the flutter in the transonic regime.

Transitional flows will affect aeroelastic stability of aircraft, and can cause the transonic flutter dip to deepen and shift.

Preliminary aircraft design

Conceptual

Preliminary

Detail



▶ **How to quickly predict flutter for transonic transitional flows?**

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Conceptual design: configuration - mission & cost (about 1% of man-hours)

Preliminary design: simple numerical model – multi-disciplinary optimisation (about 9% of man-hours)

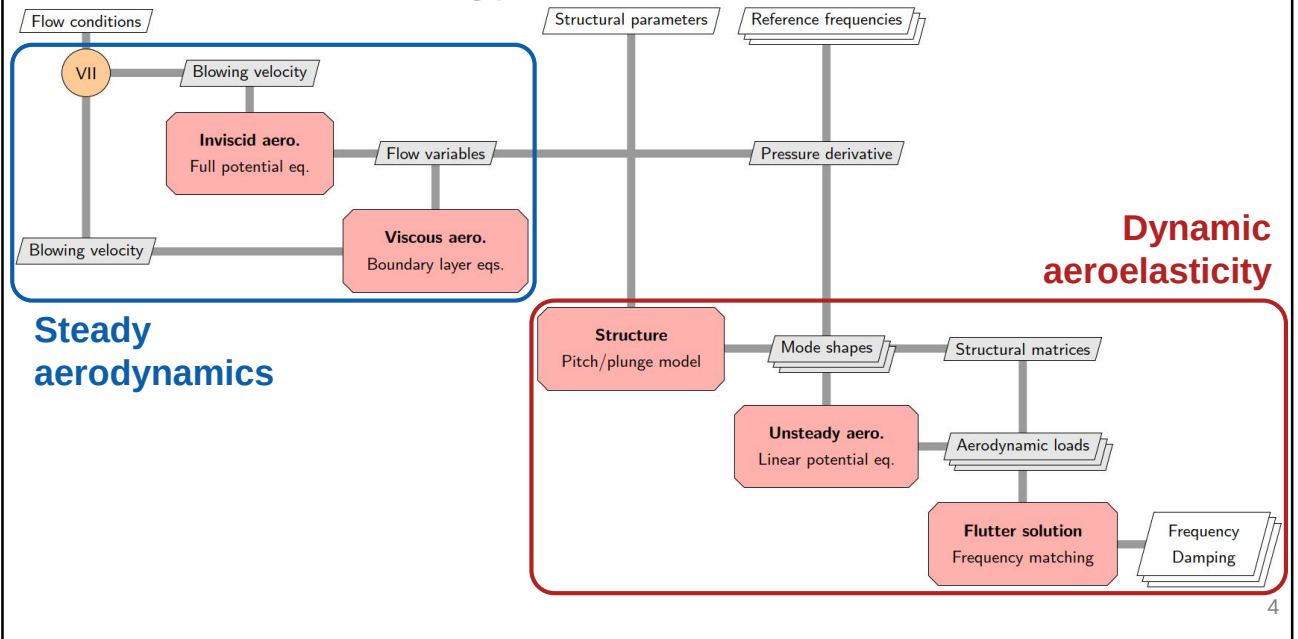
Detail design: detailed numerical model or actual product - manufacturing, certification (about 90% of man-hours)

Preliminary stage:

- global and multi-disciplinary design optimisation
- many design variables
- limited time

=> Important to choose the adequate level of fidelity!

Overall methodology



Dynamic aeroelasticity:

- pitch/plunge analytic structural model, yields mass and stiffness matrices and mode shapes;
- unsteady aerodynamic panel method, yields generalized aerodynamic forces;
- frequency matching flutter solution, yields frequency and damping ratios and flutter speed.

Unsteady panel method is corrected by steady VII (pure aerodynamics) via pressure derivative:

- inviscid full potential finite element method, yields flow variables at edge of boundary layer;
- viscous boundary layer equations, yields transpiration velocity.

Outline

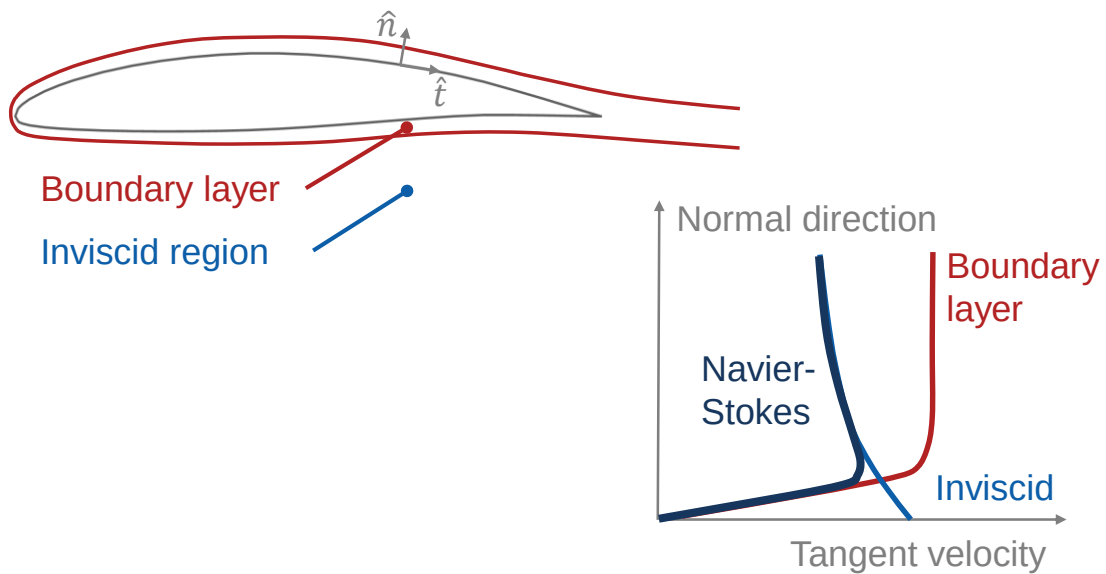
Methodology

- Steady solution – Viscous-inviscid interaction
- Unsteady solution – panel method
- Flutter solution – non-iterative p-k method

Results

- CAST 10-2 aerofoil
- Steady loads
- Flutter

Viscous-inviscid interaction – principles



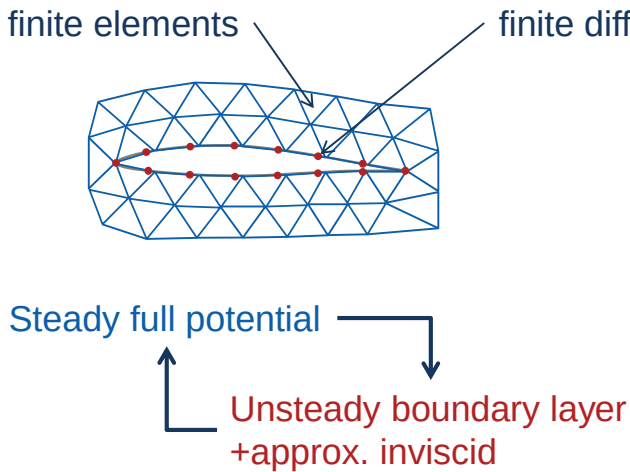
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Physically and mathematically, flow can be considered as inviscid outside the BL and viscous inside. VII is based on the idea to use different equations in these two regions and couple them.

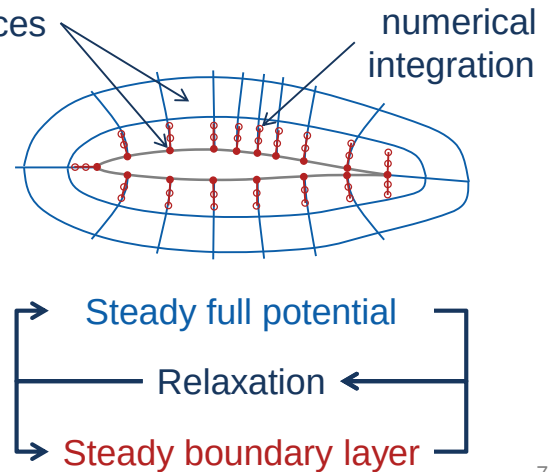
Various coupling algorithms for the VII and formulations/discretisations for the viscous equations exist.

Viscous-inviscid interaction – codes

DART + BLASTER



VIS07



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Two VII methods/codes are used in this work:

- DART/BLASTER (ULiège);
- VIS07 (ONERA legacy).

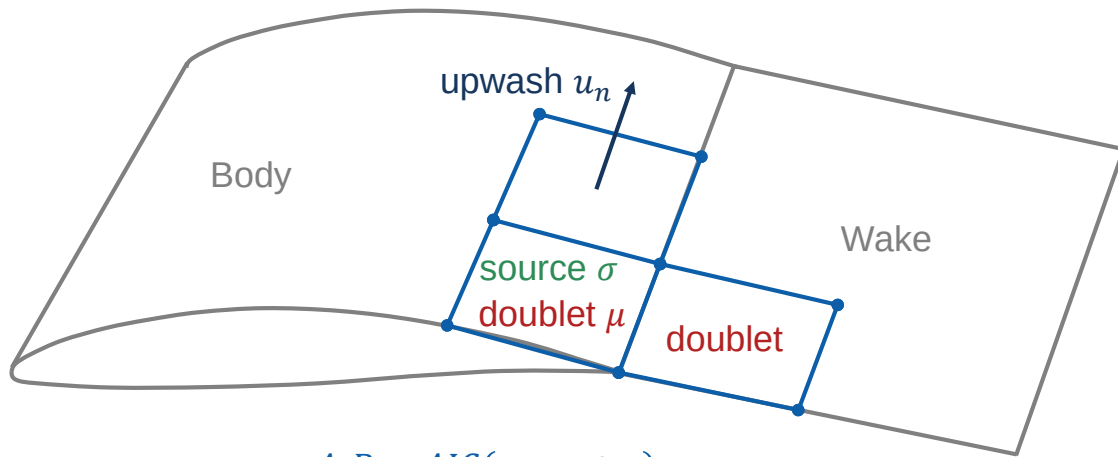
DART/BLASTER:

- inviscid (DART): steady full potential equation discretised using finite elements;
- viscous (BLASTER): pseudo-unsteady integral boundary layer equations discretised using finite differences (space marching).
- coupling (BLASTER): quasi-simultaneous coupling with transpiration boundary condition.

VIS07:

- inviscid: steady full potential equation discretised using finite differences;
- viscous: steady integral boundary layer equations discretised using finite differences (space marching), with analytical velocity profiles integrated numerically along the BL height.
- coupling (BLASTER): semi-inverse coupling with transpiration boundary condition;
- inviscid grid refined for compressibility and viscous grid adapted to follow the streamlines automatically.

Unsteady panel method – SDPM



$$A, B = AIC(\text{geometry})$$

$$\sigma = u_n \rightarrow A\mu = B\sigma \rightarrow c_p = c_p(\sigma, \nabla\mu)$$

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The source and doublet panel method solves the linearised potential equation integrated over the surface of a body. The body surface is discretized into panels containing source and doublets. The normal component of the motion-induced velocity is then imposed at the panel center and determines the source strength. The integral equation then reduces to the solution of a linear set of equations:

$$A\mu = B\sigma,$$

where A and B are the AIC matrices, μ are the doublets and σ are the sources. The pressure coefficient can finally be computed by differentiating the potential, itself obtained from the sources and the doublets.

The method is restricted to linear flows (no shock or boundary layer). However, corrections for flow nonlinearities do exist.

Transonic correction for SDPM

Linearized steady pressure coefficient derivative

$$c_p(0) \simeq \frac{2}{\beta} \left(\partial_x^S \mu(0) + n_x \sigma(0) \right)$$

$$\partial_\alpha c_p(0) \simeq \frac{2}{\beta} (\partial N_x^S A^{-1} B n_z + n_x n_z)$$

$$\partial_\alpha c_p^{\text{ref}}(0) \simeq \frac{2}{\beta} (\partial N_x^S D^{\text{corr}} A^{-1} B n_z + n_x n_z)$$

Procedure

1. Compute pressure derivative $\partial_\alpha c_p^{\text{ref}}(0)$ from steady CFD
2. Solve for diagonal correction matrix D^{corr}
3. Compute doublets: $\mu(\omega) = A^{-1} B \sigma(\omega, u_{m_{x,y}}) + D^{\text{corr}} A^{-1} B \sigma(\omega, u_{m_z})$

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This transonic correction method has been developed by Dimitriadis and is based on the linearised steady pressure coefficient derivative.

It is expressed as a function of the AICs and all the nonlinearity is assumed to be contained in a correction factor matrix, which terms can be obtained by using reference data.

Symbols:

- $\mathbf{x} = (x, y, z)$: coordinates
- $\beta = \sqrt{1 - M_\infty^2}$: compressibility factor
- c_p : pressure coefficient
- ω : frequency
- σ : source strength
- μ : doublet strength
- α : angle of attack
- $\partial_x^S, \partial N_x^S$: surface gradient operator (x-direction)
- A, B : AICs
- D^{corr} : diagonal correction matrix
- $\mathbf{u}_m$: motion-induced velocity
- $\mathbf{n}$: unit normal vector

Non-iterative p-k method – PyPK

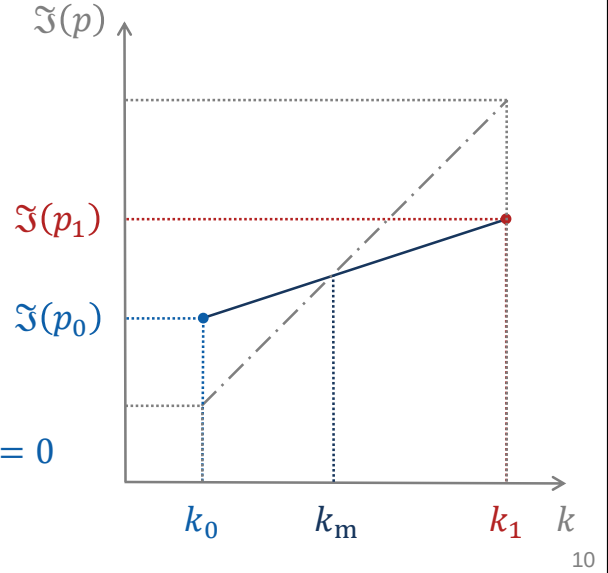
Flutter equation

$$\left(\frac{u_\infty^2}{l_{\text{ref}}^2} p^2 M + K - \frac{1}{2} \rho_\infty u_\infty^2 Q(k) \right) q = 0$$

$$p = gk + ik$$

Procedure

1. Compute $Q_i(k_i)$ for a set of k_i
2. Solve eigenvalue problem for p_i
3. Interpolate k_m such that $\Im(p_m) - k_m = 0$



The non-iterative p-k method is a frequency matching flutter solution technique, stemming from the well-known p-k method. The latter is iterative, because the flutter equation depends on the reduced frequency, which is unknown.

Instead of interpolating the aerodynamic forces for each reduced frequency iteratively (standard p-k), the non-iterative p-k method interpolates the reduced frequency after having solved the flutter equation for each reference reduced frequency.

Symbols:

- M : mass matrix
- K : stiffness matrix
- Q : generalized aerodynamic forces matrix
- ρ_∞ : freestream density
- u_∞ : freestream velocity
- l_{ref} : reference length
- p : eigenvalue solution
- q : eigenmode solution
- k : reduced frequency
- g : damping

Outline

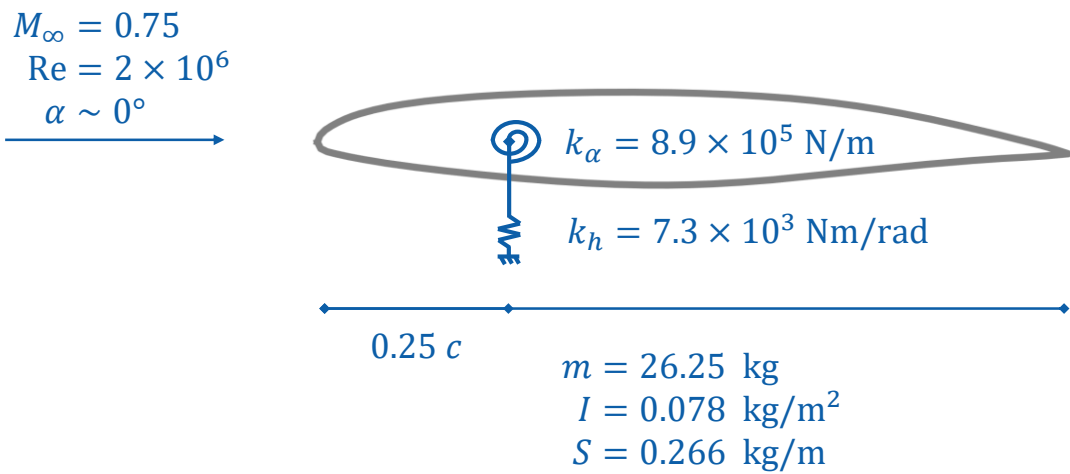
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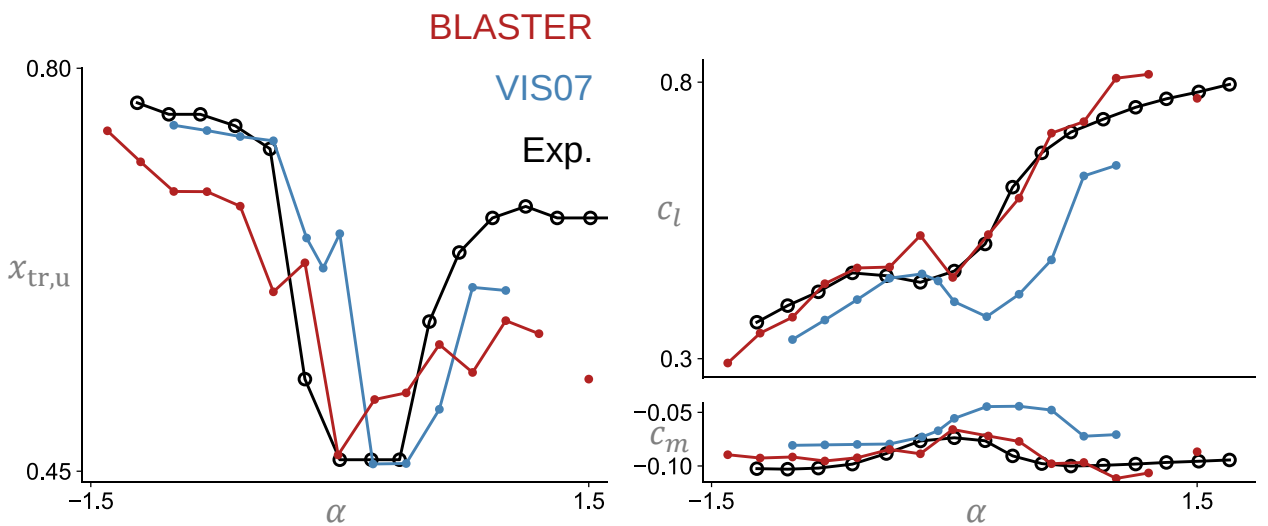
CAST 10-2 aerofoil



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The CAST 10-2 is a transonic and laminar aerofoil designed by Dornier and tested by NASA in the 1980s as part of a DLR/NASA collaboration. It has received a lot of attention in the 2010s from the DLR, through several experimental and numerical test campaigns.

Steady loads and transition

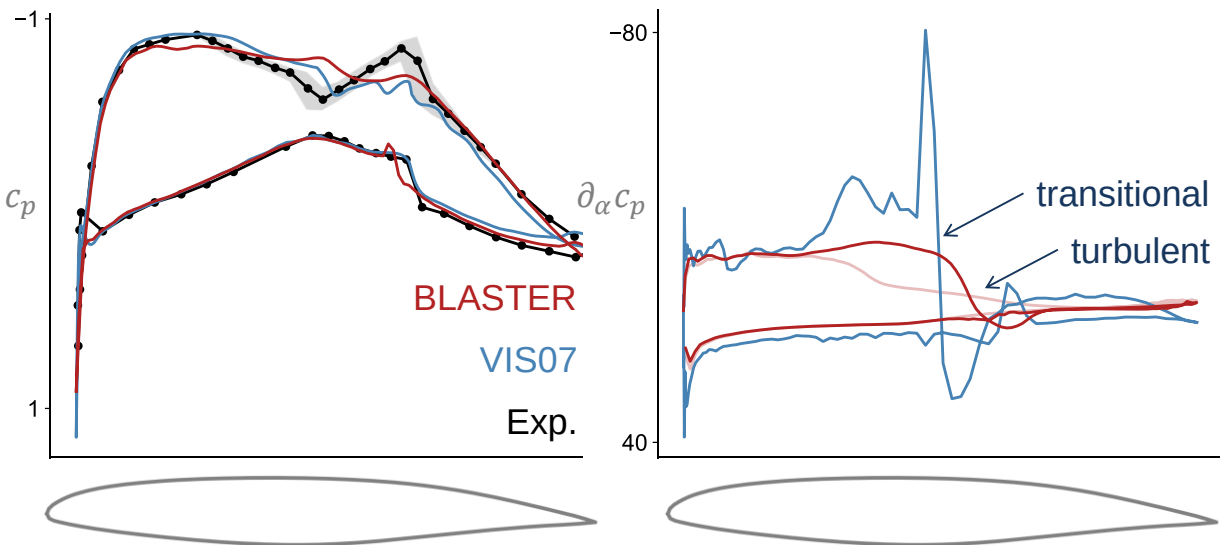


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Both BLASTER and VIS07 capture the change in the location of the transition and in the aerodynamic load coefficient as the angle of attack is varied.

VIS07 results are shifted by about 0.5 degree compared to the experimental data, while BLASTER results are oscillatory. This shows how challenging this case is and denotes a certain lack of robustness of the VII solvers.

Steady pressure coefficient and derivative



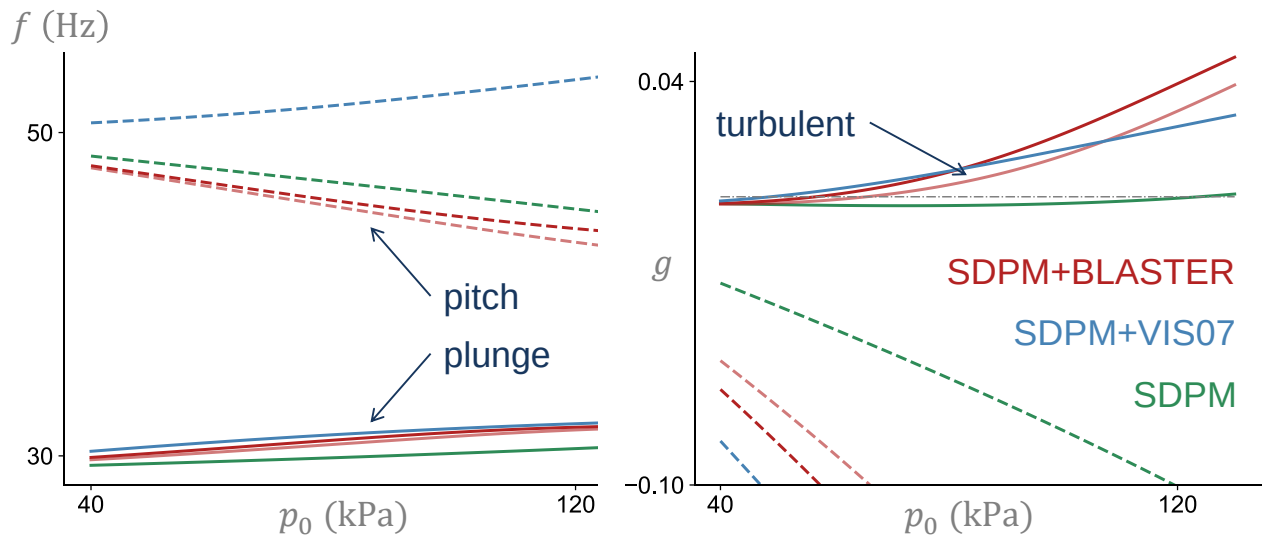
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BLASTER and VIS07 reproduce similar features as the experimental data (Braune, 2018). However, in the experimental data, the first recompression (40% chord) is mostly due to a shock, while it is caused by the transition in VII computations. VII also smears the second shock (65% chord). Note that the first shock was not observed in another set of experiments (Hebler, 2013).

The pressure derivative predicted by both codes are different, which could be expected (from the pressure coefficient). The oscillations in the VIS07 results are due to incomplete convergence of the VII process (step of 0.02 degree required to perform the finite difference used to calculate the derivative, below the "resolution" of the code). The results are also compared to a fully turbulent BLASTER calculation. Fixing the location of the transition to the leading edge has a significant effect on the pressure derivative and will certainly affect flutter prediction.

NB: BLASTER and exp. data shown at zero degree AoA, while VIS07 solution calculated at 0.4 degree to attain the same lift coefficient.

Flutter solution – frequency and damping



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Taking into account nonlinear effects (compressible, viscous and transition) can change the flutter speed drastically. The flutter mechanism can also be affected. In particular, the differences between BLASTER and VIS07 are probably due to the differences noted in the pressure derivative, especially in the downstream of the second shock. Note that various flutter mechanism were observed experimentally and calculated numerically in the literature. This again illustrates how challenging this case is.

Flutter solution – stagnation pressure

Inviscid linear flow	$p_{0, \text{crit}}$ (kPa)	
SDPM	125	
Fully turbulent flow		compressibility viscosity
SDPM+BLASTER	64	
Experiments	70	
Transitional flow		laminarity
SDPM+BLASTER	56	
SDPM+VIS07	48	
Experiments	[50; 45]	

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Ignoring nonlinear (compressible + viscous) effects has a dramatic effect on the flutter speed.

Assuming the flow to be fully turbulent, rather than transitional, yields a higher flutter speed than that observed experimentally.

VII effectively captures the experimental behaviour, even though there are some discrepancies in the values of the stagnation pressure at flutter. These discrepancies are probably due to inaccuracies in the computation of the pressure and its derivative.

Conclusion

Outcome

- **VII** calculates representative **steady loads** for **transonic** and **transitional flows**.
- **Combined** to a **panel method** and a **flutter solution** technique, **VII** captures the **decrease of critical flutter pressure due to transition**

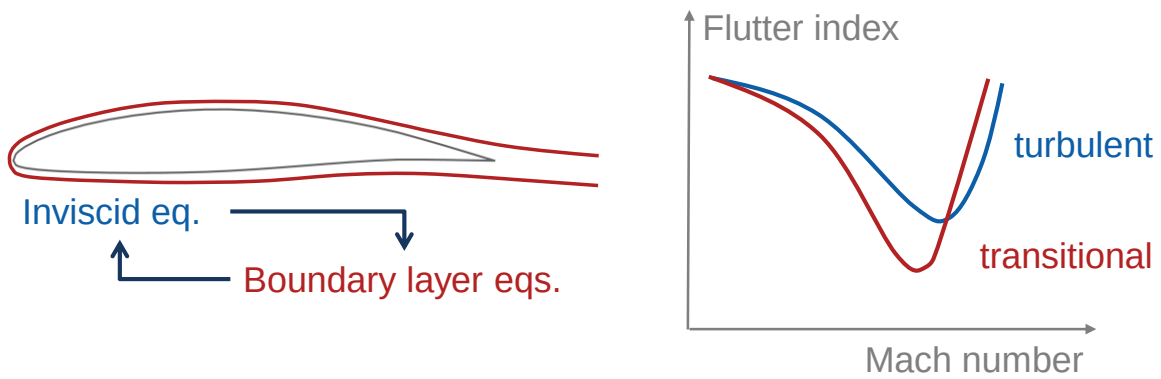
Future work

- Improve **robustness of BLASTER**
- Improve **transonic correction technique in SDPM**
- Extend the study to **all Mach numbers**
- Investigate **flutter mechanism**

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Viscous-inviscid interaction for laminar flutter

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<https://acrovato.github.io>

