Part IV

Theoretical limitations and shortcomings of xflr5

Limitations and shortcomings

1. Viscosity
    1. Lack of interaction loop between boundary layer and inviscid flow
    2. Estimation of viscous drag
2. Panel modelling
    1. Flat quad panels
    2. Uniform strength singularities
    3. Incomplete modelling of body-wing interactions
3. Flat wake

1. Viscosity

VLM and panel methods excluding LLT

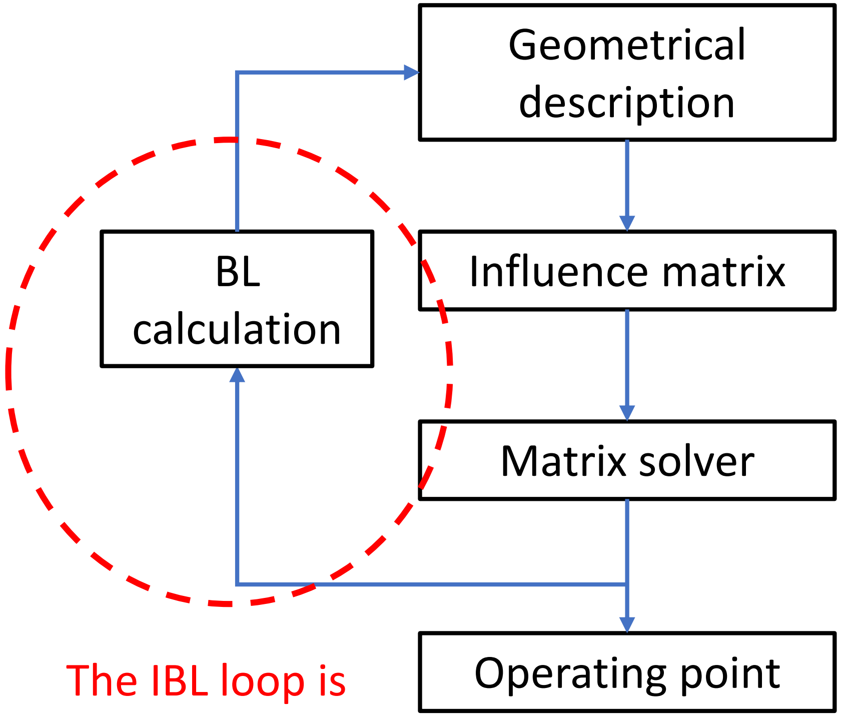
Viscous drag estimation

• Potential methods such as the VLM and the 3d panel methods in xflr5 make the assumption of inviscid flow • The fluid behaves as “dry water”	cf. part I
• In 2d, XFoil implements a full IBL loop	cf. part III
• The non-linear LLT implements a viscous loop using 2d viscous data obtained on airfoils	cf. NASA TN 1269
• The VLM and 3d method merely interpolate 2d viscous drag from local wing lift	Not great…

1.1 Lack of a viscous IBL loop

Lack of a viscous IBL loop

- The Interactive Boundary Layer, or IBL, is a coupling method between potential flow and viscous flow on surfaces – cf. part III
- The effect of the boundary layer is to modify the geometry of surfaces and to disturb the inviscid potential flow
- A loop is therefore needed to reach a solution that satisfies both the viscous model and the potential flow model
- This loop is not implemented in the panel methods available in xflr5

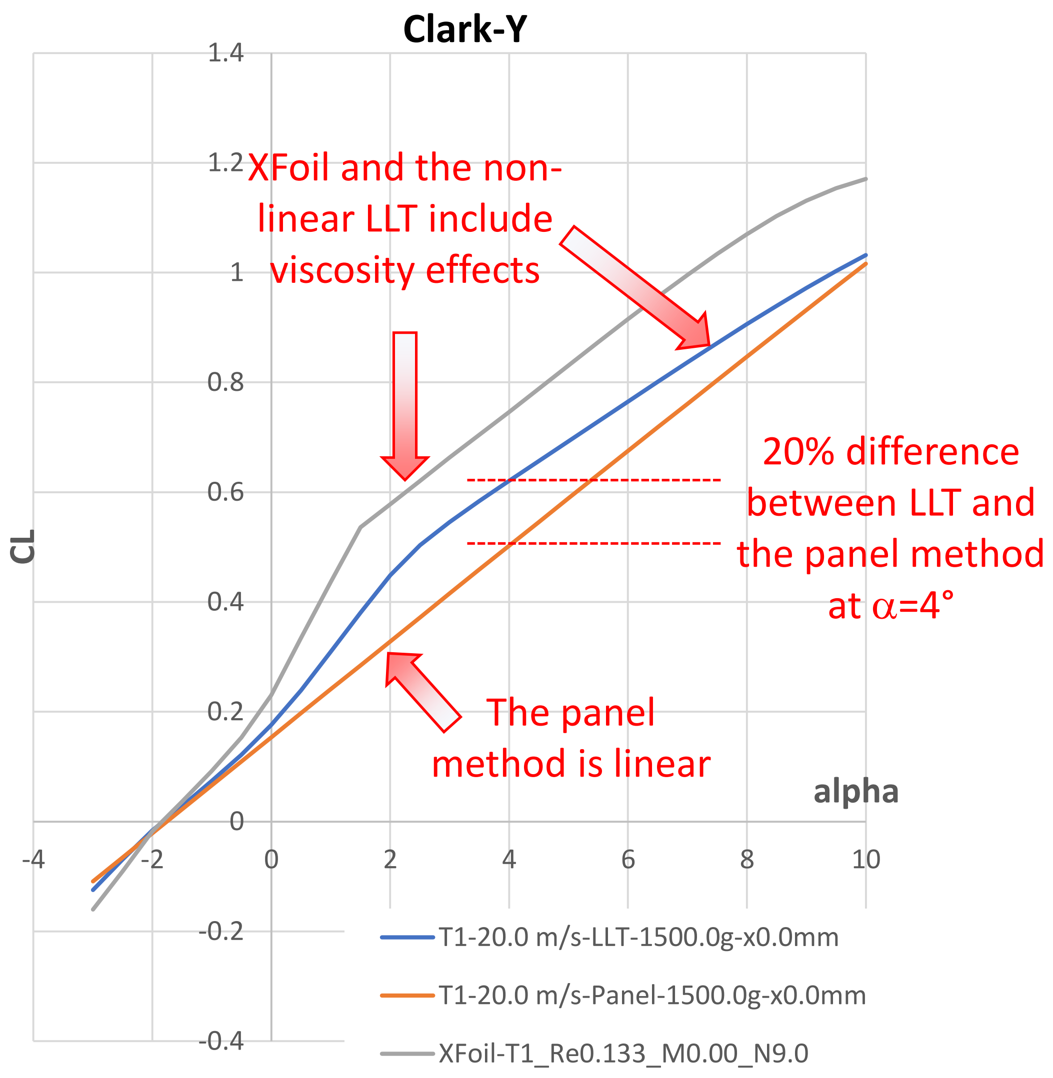


The IBL loop is not implemented

Lack of a viscous IBL loop

- Consequences / drawbacks
  - The lift is a linear function of the a.o.a., unlike with XFoil or with the non-linear LLT
  - Significant differences in the lift coefficient predictions at low Reynolds numbers

→ The potential flow model is only valid in conditions of limited flow separation



XFoil and the non-linear LLT include viscosity effects

20% difference between LLT and the panel method at α=4°

The panel method is linear

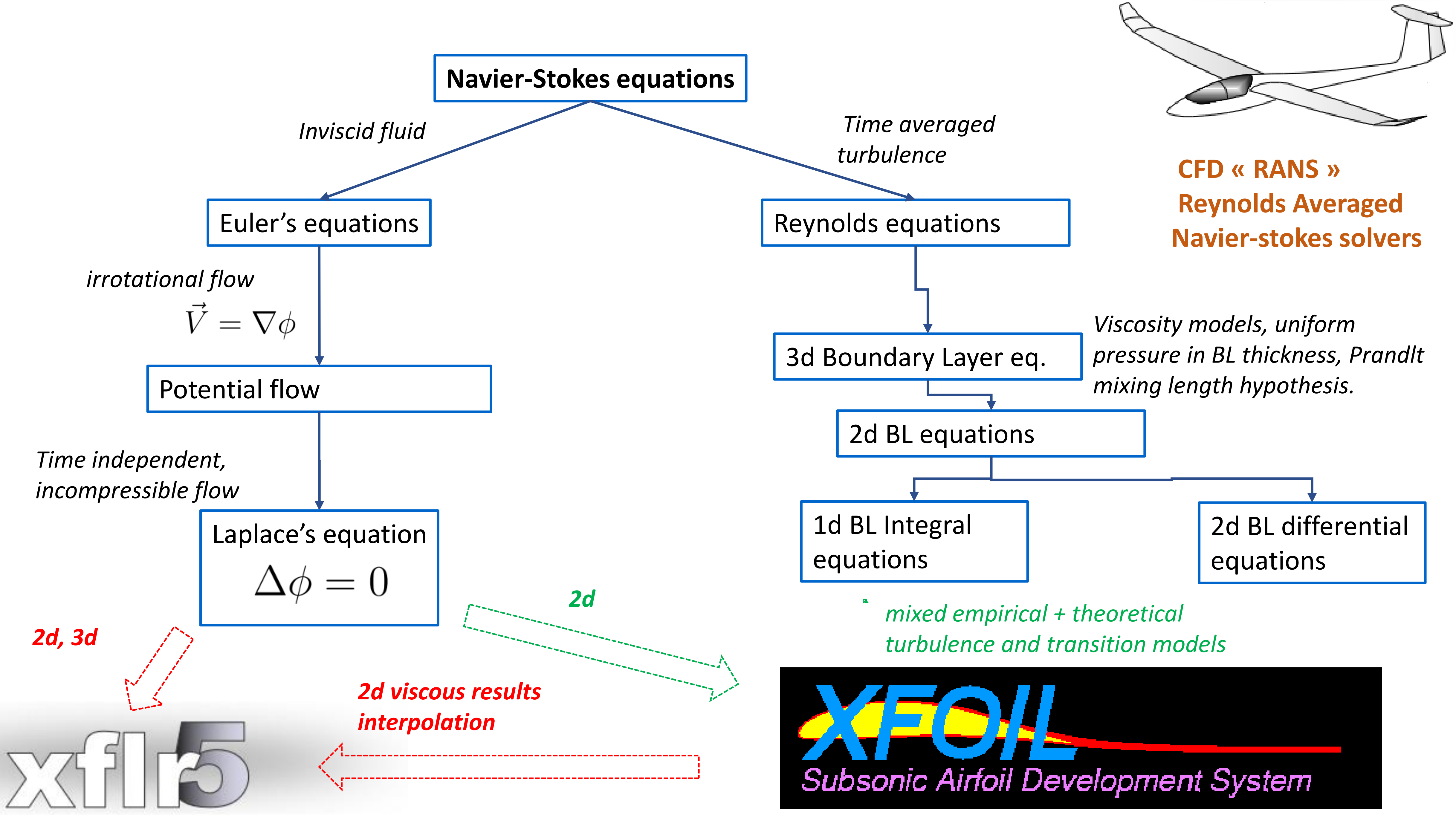
Lack of a viscous IBL loop

- What can be done about it
  - Not much…

→Limit the analysis to conditions of limited flow separation

- High Reynolds numbers
- Low angles of attack
- Low flap deflections

1.2 Viscous drag estimation



Navier-Stokes equations

Inviscid fluid

Euler's equations

irrotational flow

$$\vec{V} = \nabla\phi$$

Potential flow

Time independent, incompressible flow

Laplace's equation

$$\Delta\phi = 0$$

Time averaged turbulence

Reynolds equations

CFD « RANS »
Reynolds Averaged
Navier-stokes solvers

3d Boundary Layer eq.

Viscosity models, uniform pressure in BL thickness, Prandlt mixing length hypothesis.

2d BL equations

1d BL Integral equations

2d BL differential equations

2d, 3d

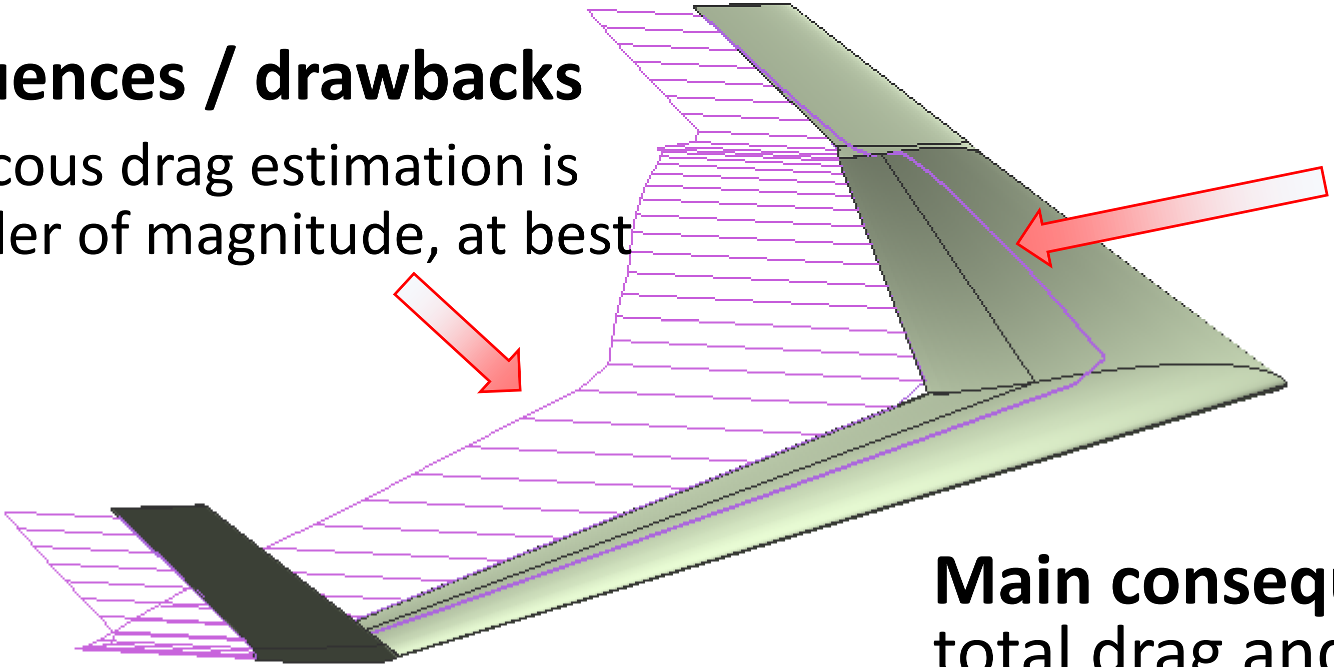
2d

mixed empirical + theoretical turbulence and transition models

2d viscous results interpolation

Viscous drag estimation

The VLM and 3d method merely interpolate 2d viscous drag from local wing lift



Consequences / drawbacks

→ viscous drag estimation is an order of magnitude, at best

→Transition location from laminar to turbulent flow ignores cross-flow effects and is not reliable

Main consequence: Underestimation of total drag and over-estimation of glide ratio and other performance factors

2. Panel modelling

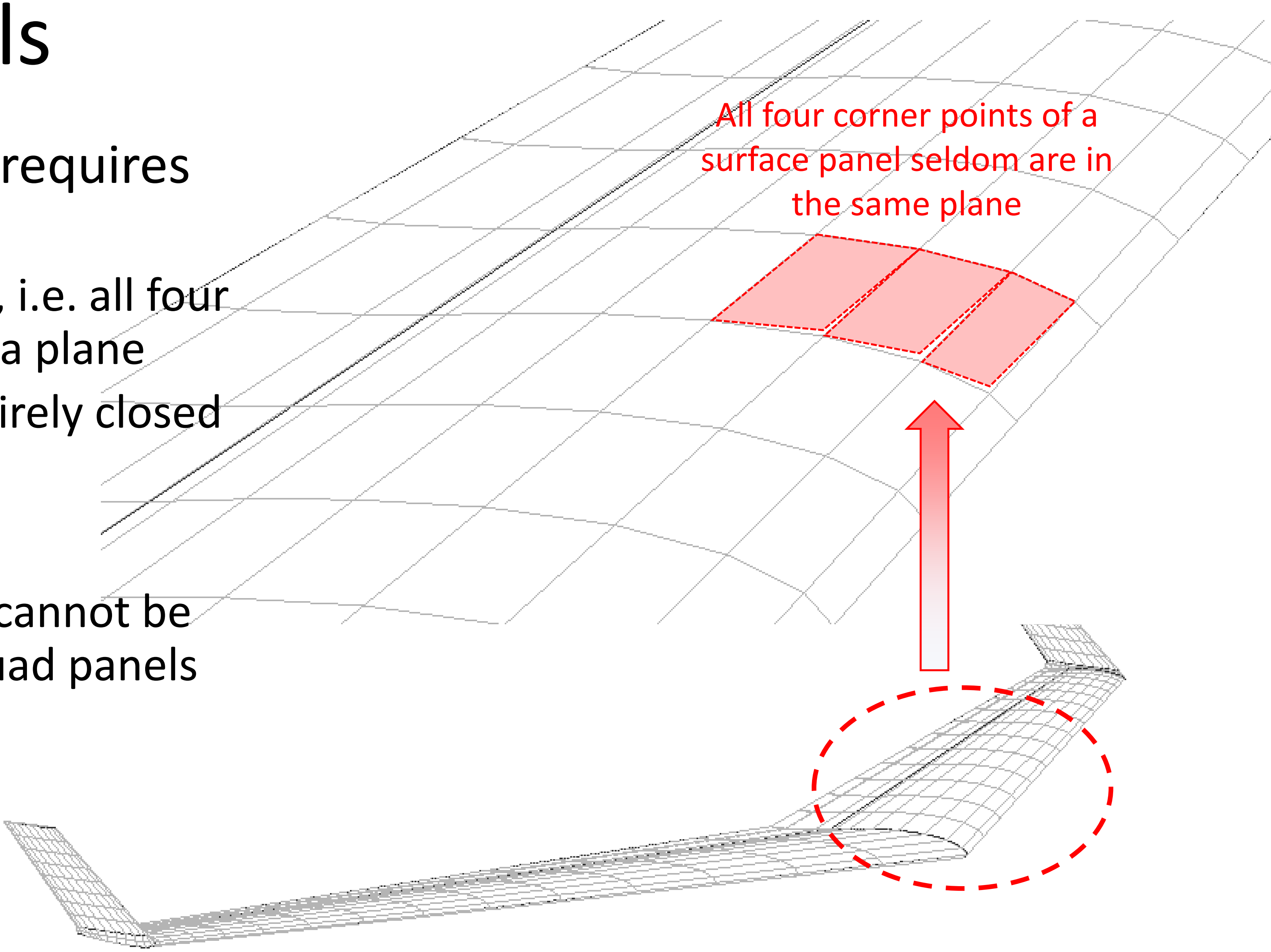
3d-panel method excluding VLM and LLT

2.1 Flat quad panels

VLM and panel methods excluding LLT

Flat quad panels

- The 3d panel method requires that
  1. quad panels are flat, i.e. all four corner points are in a plane
  2. the volumes are entirely closed by surface elements
- However
  - 3d surfaces generally cannot be decomposed in flat quad panels



All four corner points of a surface panel seldom are in the same plane

Flat quad panels

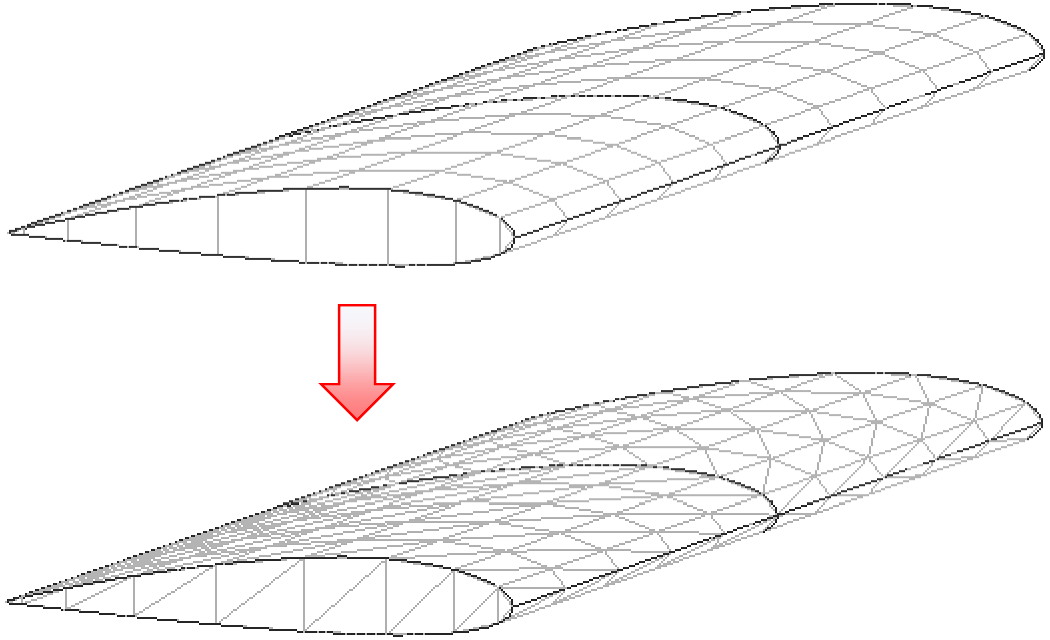
- Consequence / drawbacks
  - xflr5 discretizes the geometry with warped panels, but uses the flat panel model
    - → Numerical errors
    - → Error increases with warping/twisting of the panels
  - The order of magnitude of the error is expected to be low, even though it’s difficult to evaluate

Flat quad panels

- What can be done about it
  - Not much…

→ Limit the analysis to geometries with low level of warping

The long term fix is the implementation of a triangle panel method: any 3d surface can be covered by (flat) triangle



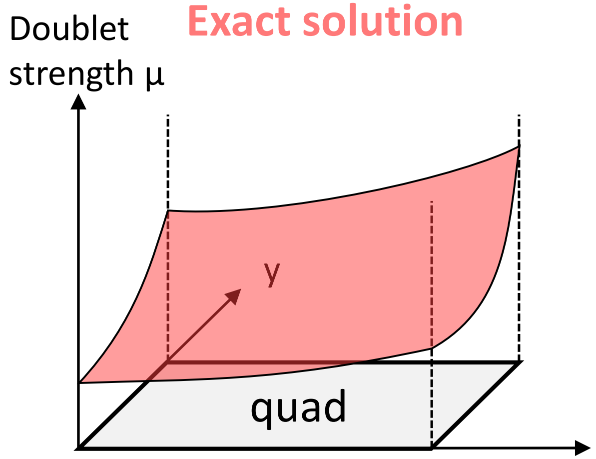
2.2 Uniform strength singularities

3d-panel method excluding LLT

Uniform strength singularities

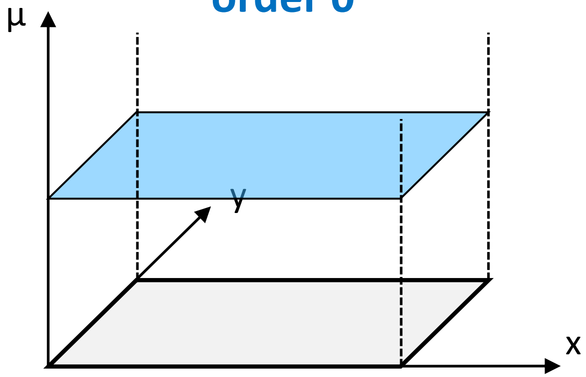
- Panels method in xflr5 are of the uniform type
  - Uniform vortex strength on each panel in the case of the VLM
  - Uniform source and doublet strengths in the case of the panel method
- Methods of higher order are more precise

Exact solution



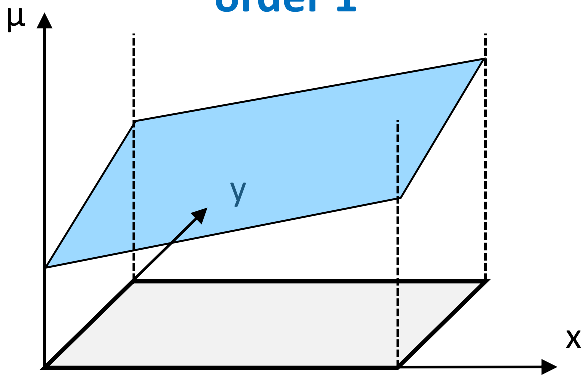
$\mu = \mu(x,y)$

Uniform model order 0



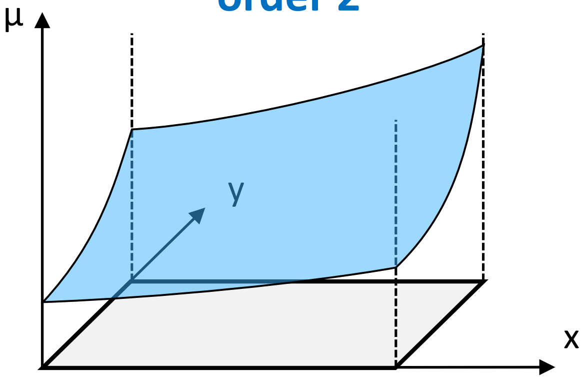
$\mu = \mu_c$

Linear model order 1



$\mu = \mu_0 + \mu_x x + \mu_y y$

Quadratic model order 2

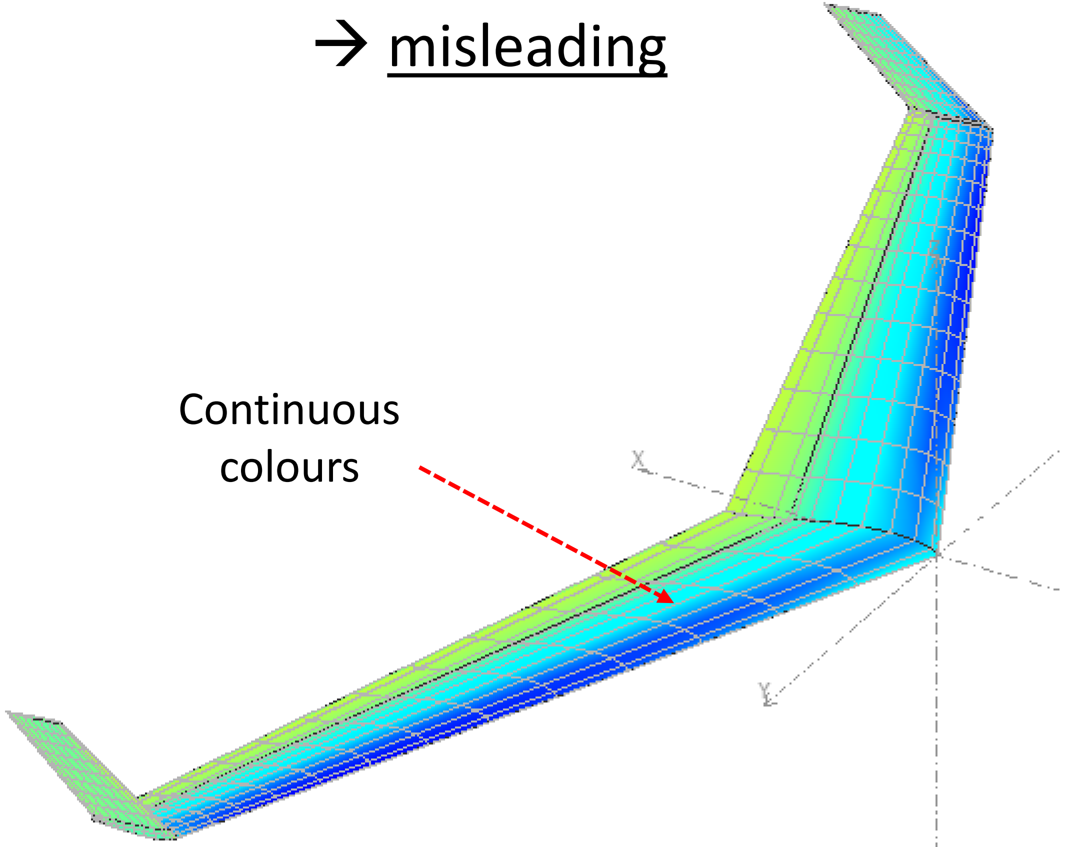


$\mu = \mu_0 + \mu_x x + \mu_y y + \mu_{xy} xy + \mu_{x2} x^2 + \mu_{y2} y^2$

Uniform strength singularities

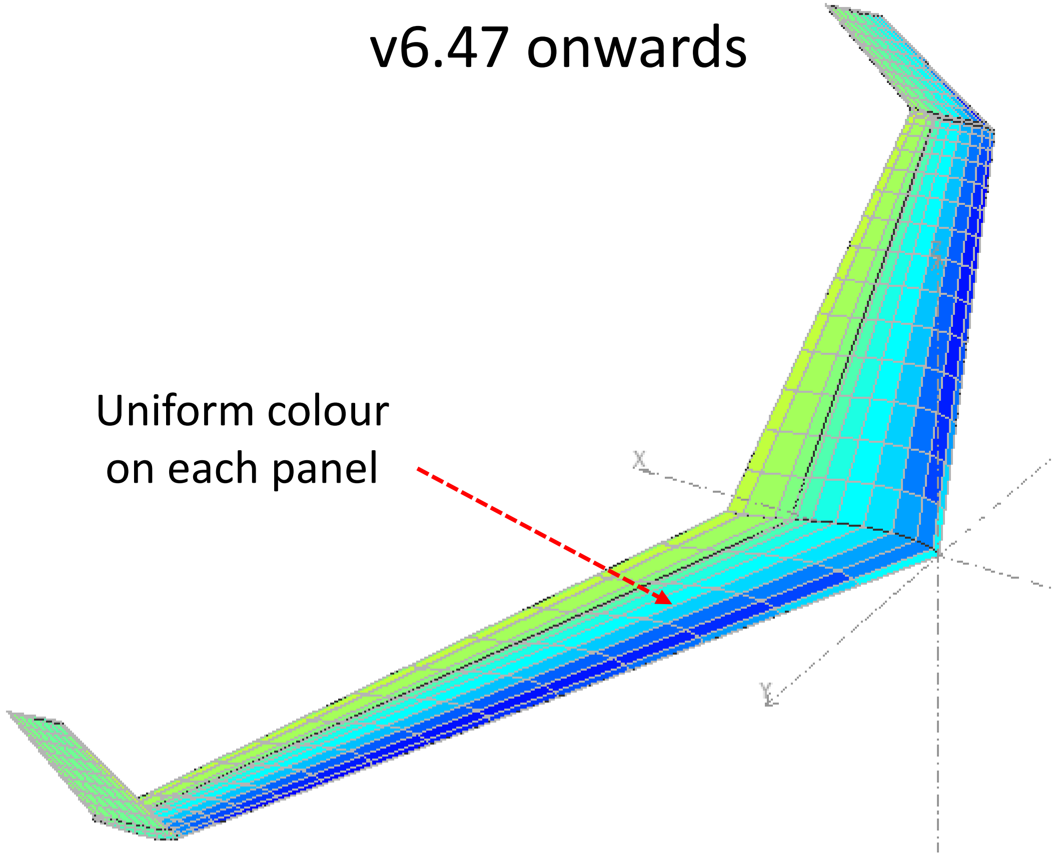
To emphasize the uniformity of singularity strengths, the display of pressures is modified in xflr5 v6.47

What it looks like in xflr5 up to v6.46
→ <u>misleading</u>



Continuous colours

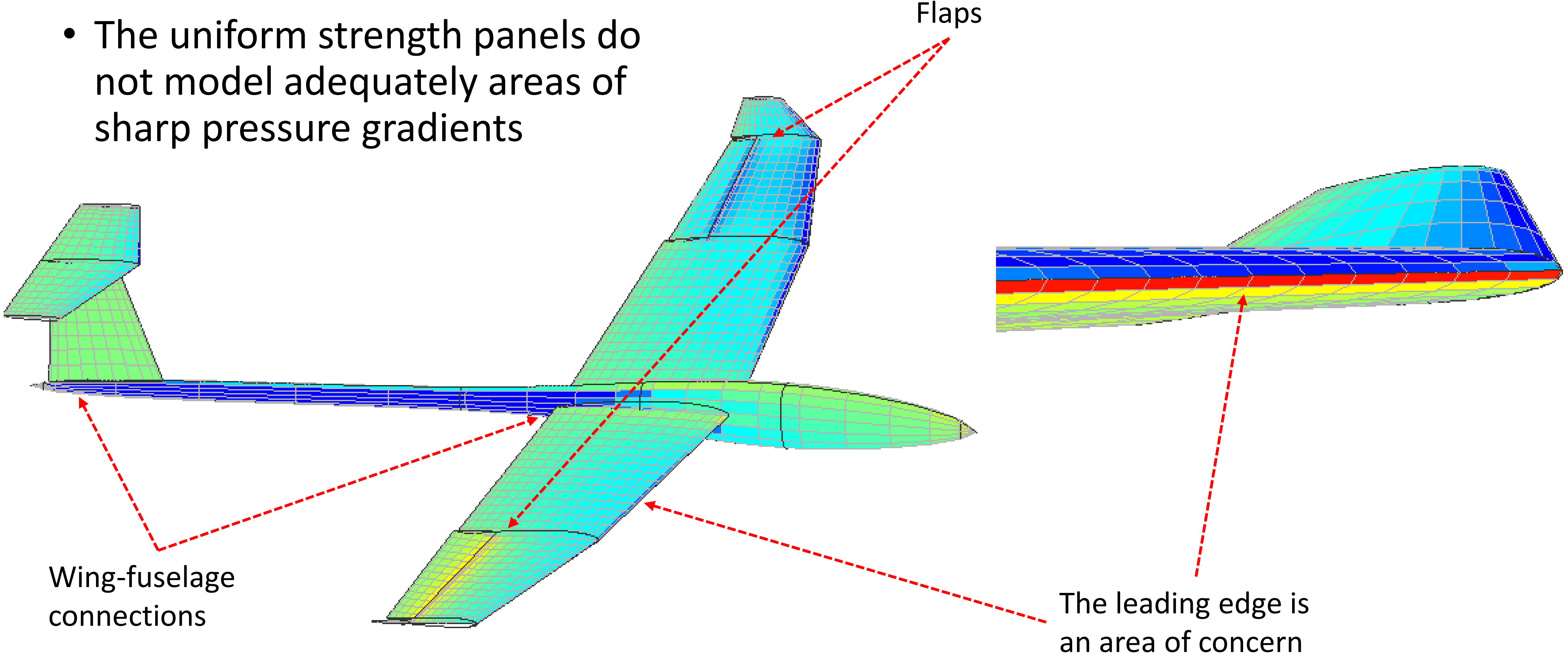
What it should and will look like from v6.47 onwards



Uniform colour on each panel

Uniform strength singularities

- Consequence / drawbacks
  - The uniform strength panels do not model adequately areas of sharp pressure gradients



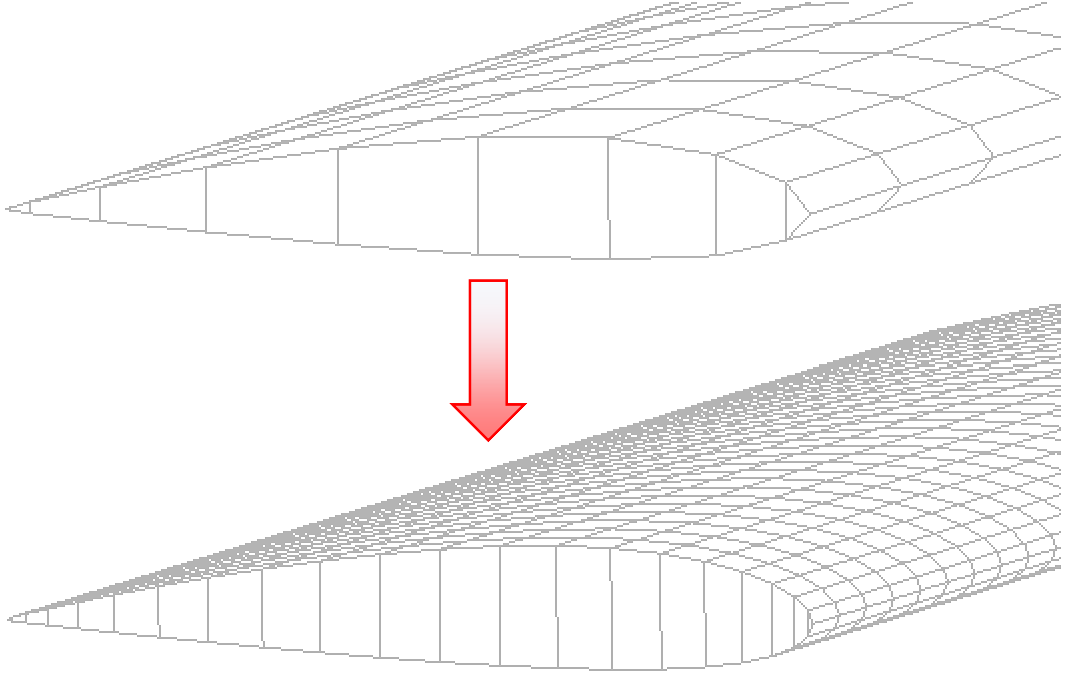
Flaps

Wing-fuselage connections

The leading edge is an area of concern

Uniform strength singularities

- What can be done about it
  - The panel density should be increased as much as possible within the limits allowed by memory usage and computation times



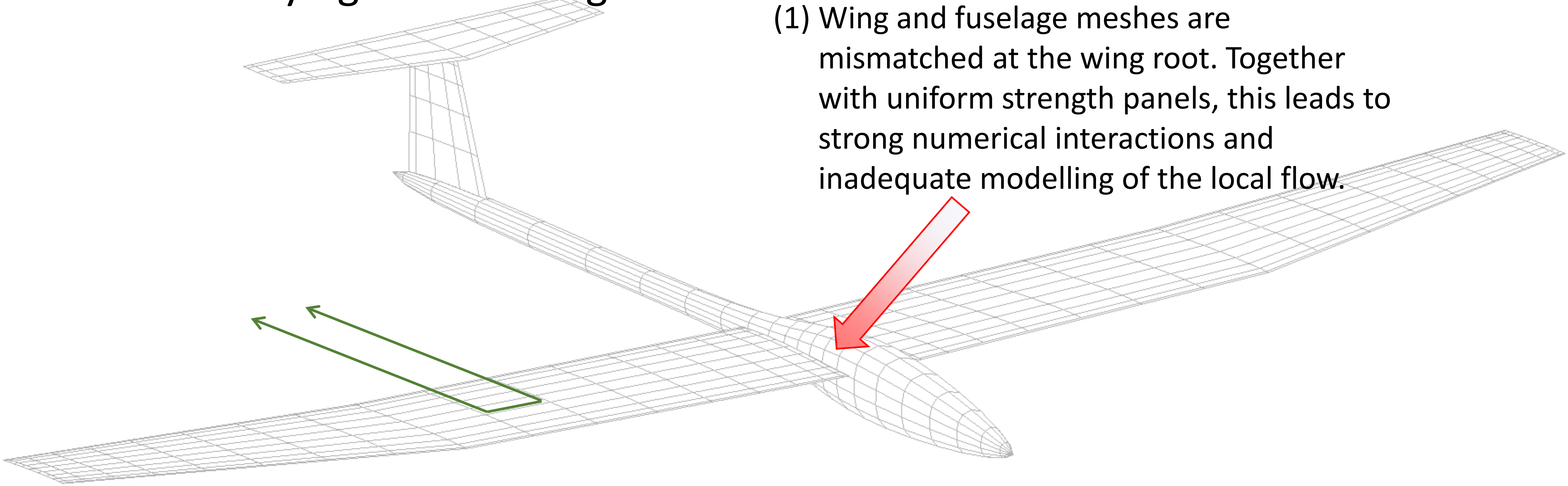
On the long term, the flat-quad, uniform-strength, panel method needs to be replaced by triangle-based Galerkin formulations of linear or quadratic order.

2.3 Incomplete modelling of body-wing interactions

VLM and panel methods excluding LLT

Incomplete modelling of body-wing interactions

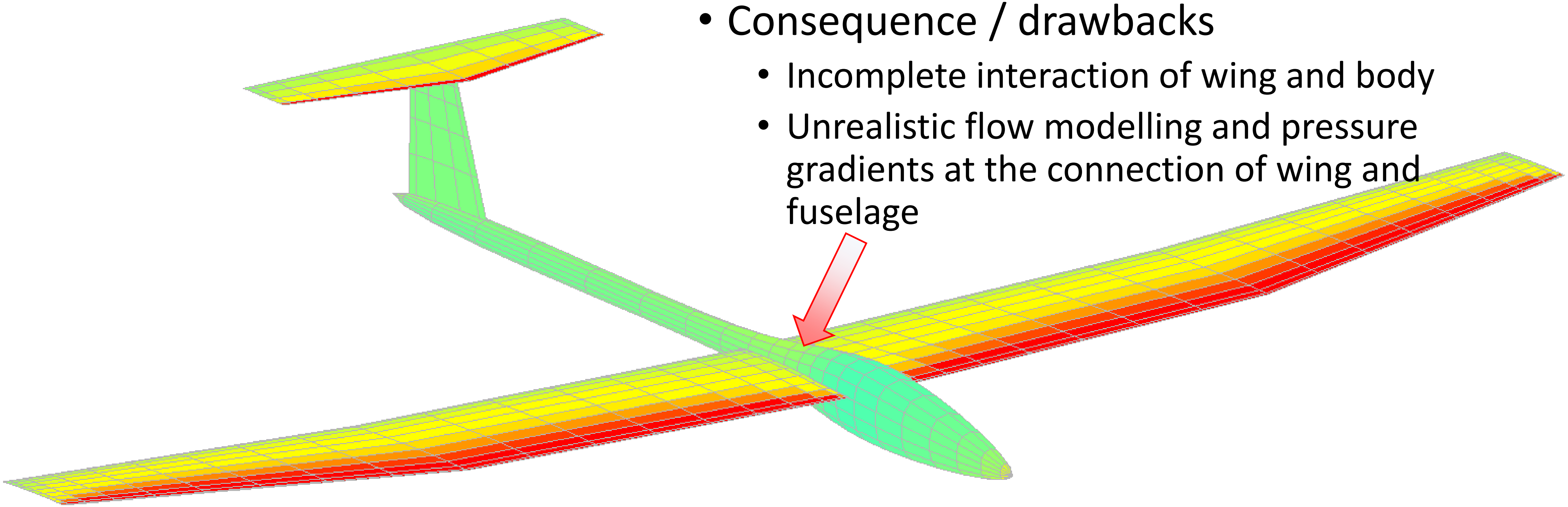
- Two underlying shortcomings



(1) Wing and fuselage meshes are mismatched at the wing root. Together with uniform strength panels, this leads to strong numerical interactions and inadequate modelling of the local flow.

(2) There is no convenient way to evaluate the potential function associated with the vortices on the thing wings, therefore the Dirichlet BC which are required for the fuselage are incomplete.

Incomplete modelling of body-wing interactions



- Consequence / drawbacks
  - Incomplete interaction of wing and body
  - Unrealistic flow modelling and pressure gradients at the connection of wing and fuselage

Incomplete modelling of body-wing interactions

- What can be done about it
  - Not much…

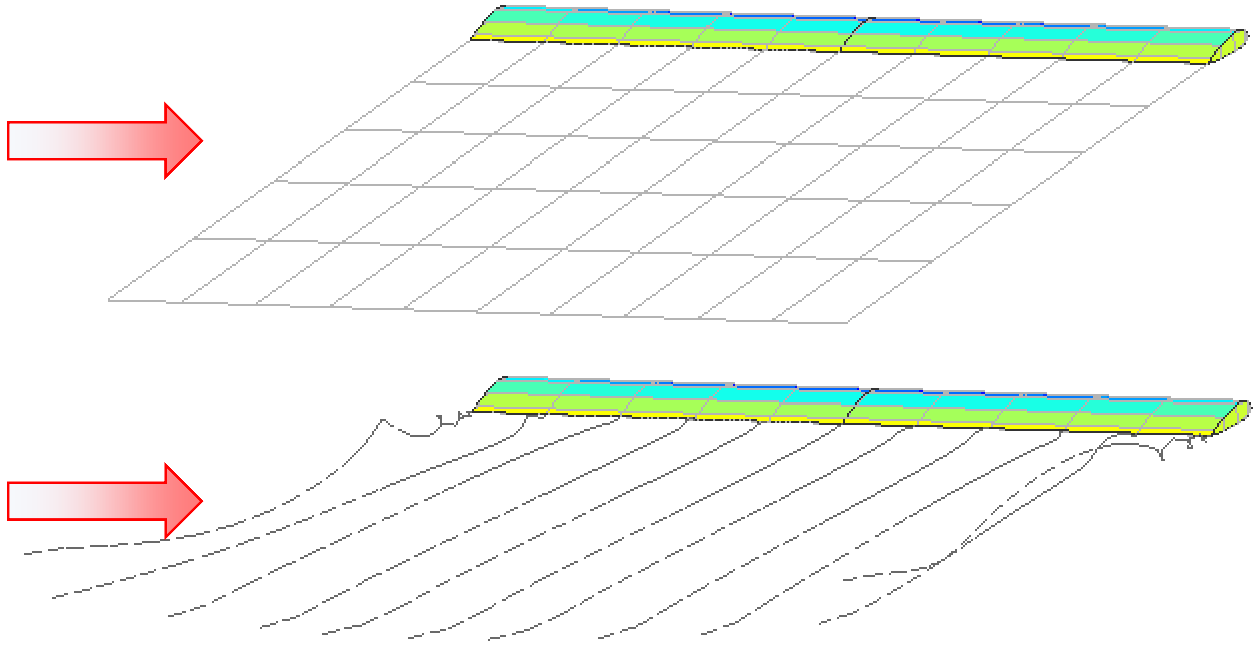
→ Do not include the fuselage in the analysis

The long term fix is the implementation of a triangle-based Galerkin method which can fix both issues

3. Flat wake

Flat wake

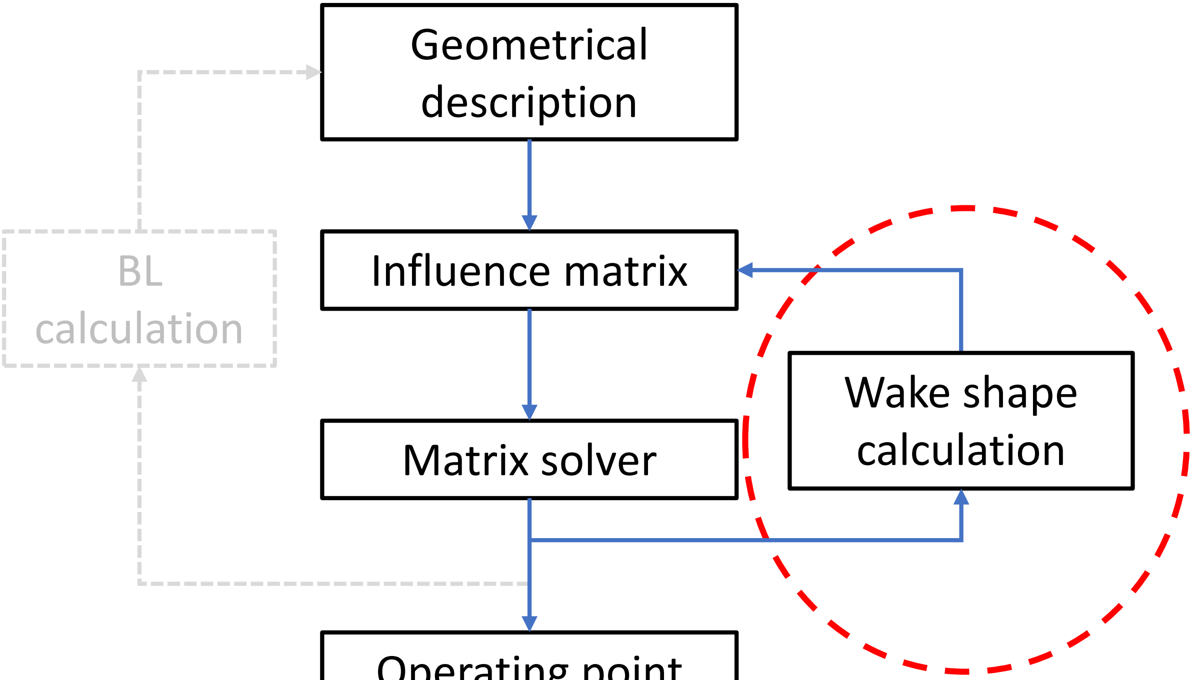
- In xflr5, the wake is modelled as a straight extension of flat panels or vortex lines behind the wing's trailing edge
- In practice, the wake takes the shape of the streamlines, and the wake panels should take the shape of the streamlines



This is known as the "wake roll-up"

Flat wake

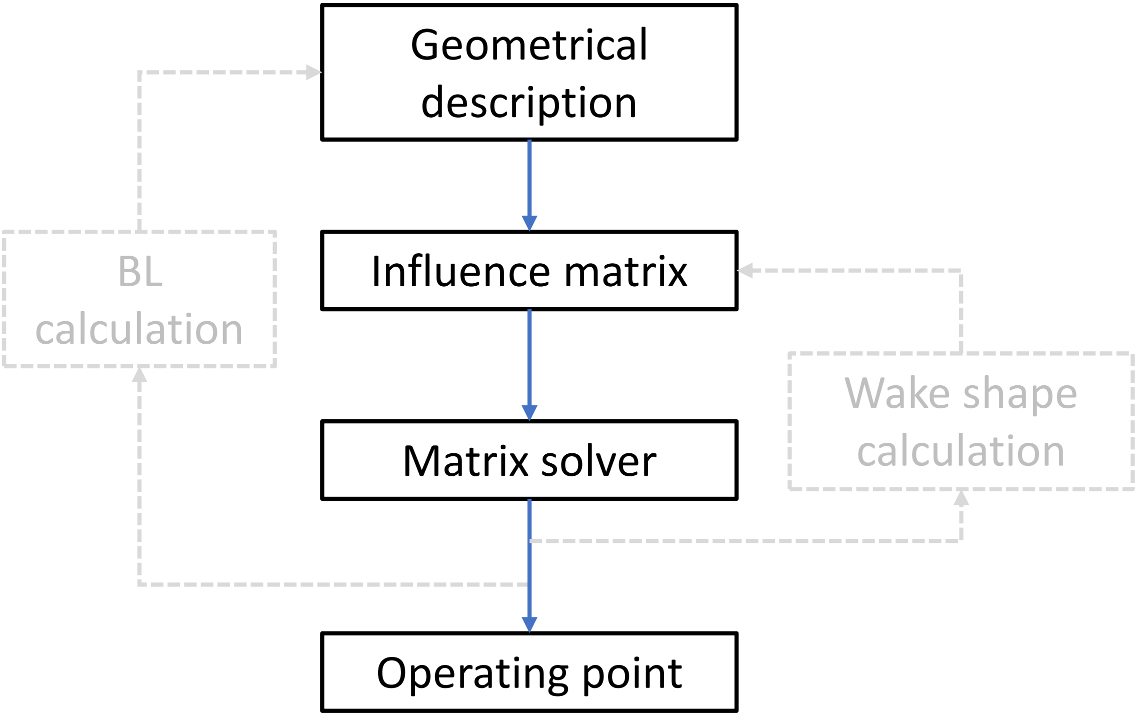
- The modelling of the wake roll-up requires the implementation of a loop
- It requires user-tuning of the wake settings on a case by case basis
- Tests have shown that this increases the complexity of the analysis by a huge factor
- Wake roll-up has therefore been disabled in xflr5



The wake roll-up loop is not implemented

Flat wake

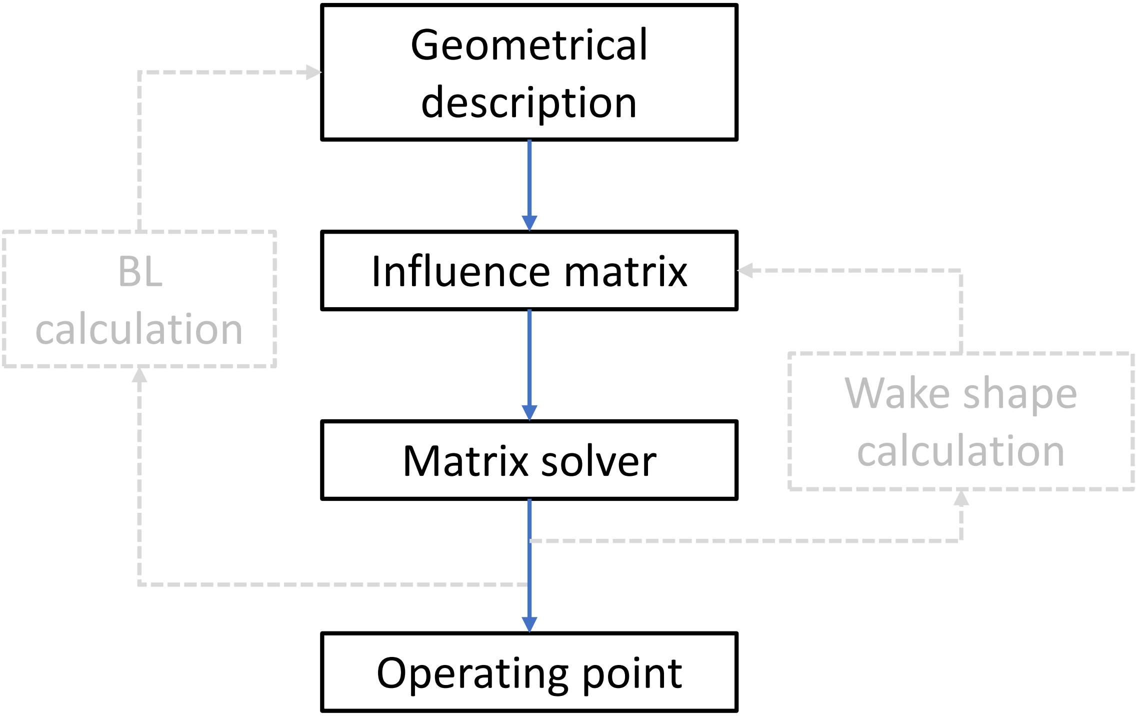
- Consequence / drawbacks
  1. Over-estimation of the vortex and doublet strengths, and over-estimation of the lift; for a stand-alone wing, the error can be in the order of magnitude of 1 to 10 % for the lift and induced drag
  2. The main wing's wake panels may intersect the elevator or fin's panels, leading to unwanted numerical interaction



Flat wake

- What can be done about it
  - Not much…

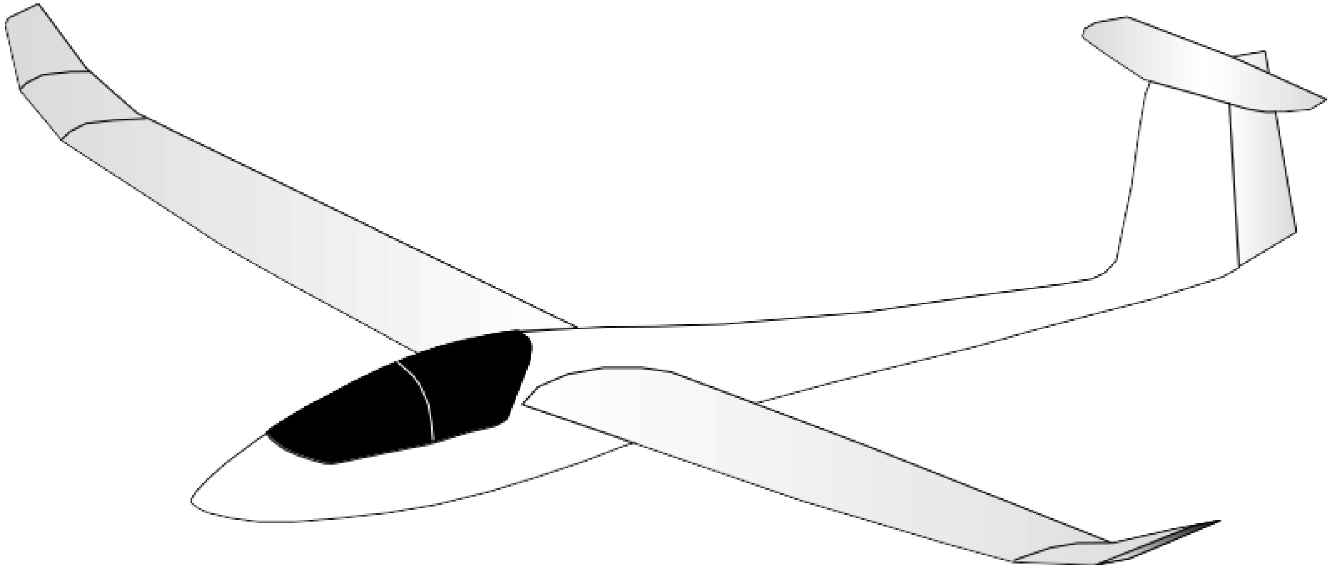
A minimum precaution is to make sure that the main wing’s wake panels do not intersect the elevator or fin



4. Recommendations

Recommendations

- Whatever the flow conditions, do not expect accuracy of xflr5 results
- Restrict the modelling and analysis to the conditions which have just been described
- Use xflr5 to get orders of magnitude, trends, and to understand sensitivity to design parameters



-That’s it-

In the hope that the concepts, wording, graphs, limitations and possibilities of XFoil and xflr5 are a little clearer now than they were at the start of these presentations.