Simulation of starting/stopping vortices for a lifting airfoil

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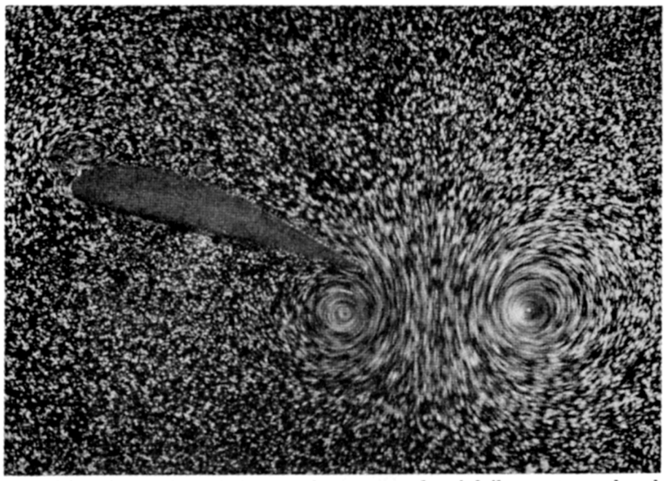


FIG. 55.—After formation of the starting vortex the airfoil was stopped and then the picture was taken.

Prandtl & Tietjens

Prandtl's experiments

Prandtl & Tietjens

FIG. 48.—Streamlines round an airfoil the very first moment after starting.

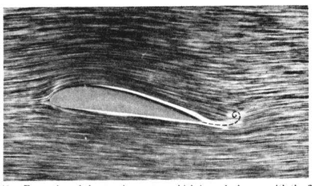


FIG. 49.—Formation of the starting vortex which is washed away with the fluid.

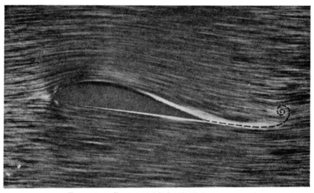


FIG. 50.—Growing of the starting vortex.

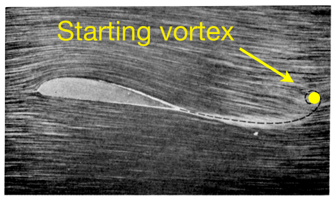
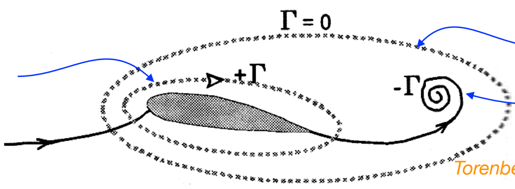


FIG. 51.—Taken somewhat later than Fig. 50.



Torenbeek & Wittenberg

Prandtl & Tietjens

FIG. 54.—Like Fig. 52, but with greater angle of attack and consequently stronger starting vortex. Also shorter exposure of plate.

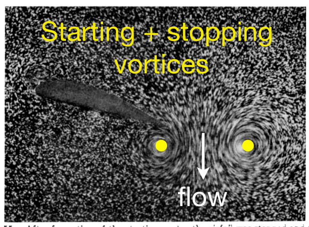
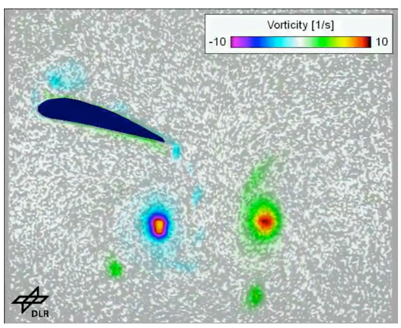


FIG. 55.—After formation of the starting vortex the airfoil was stopped and then the picture was taken.



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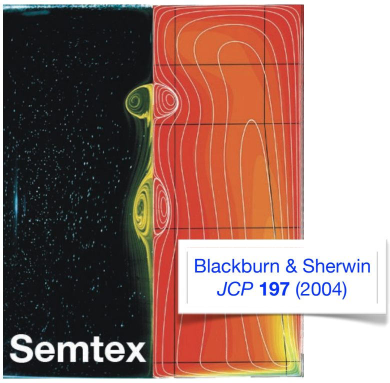
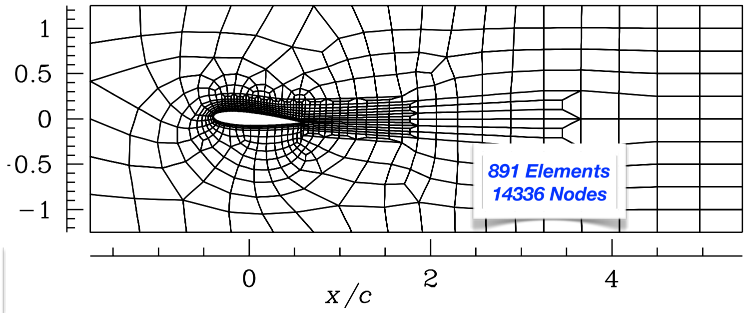
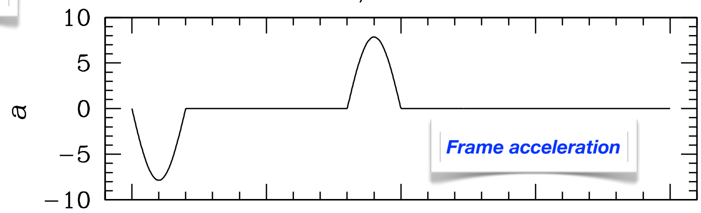
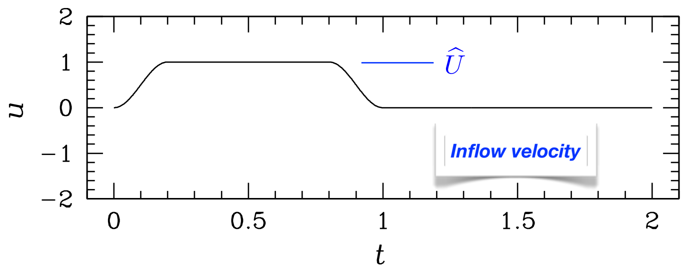
Spectral element DNS

$$\partial_t \boldsymbol{u} + \boldsymbol{u}\cdot\boldsymbol{\nabla}\boldsymbol{u} + \boldsymbol{a} = -\rho^{-1}\boldsymbol{\nabla}p + Re^{-1}\nabla^2\boldsymbol{u} \qquad \boldsymbol{\nabla}\cdot\boldsymbol{u} = 0$$





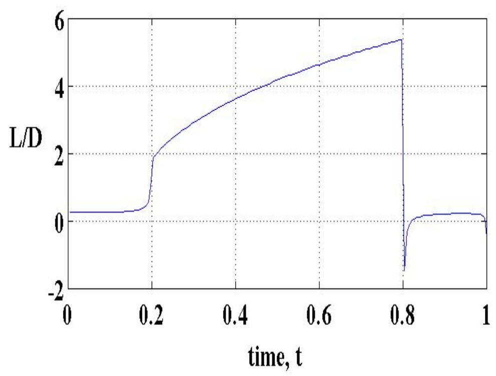




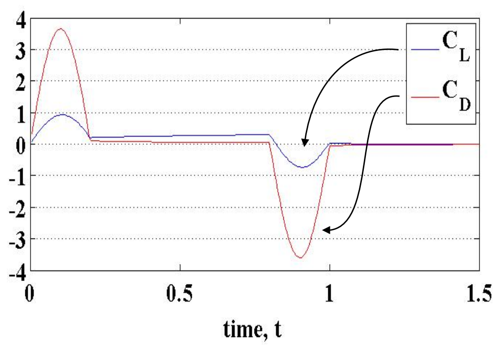
timescale $c/\widehat{U}$

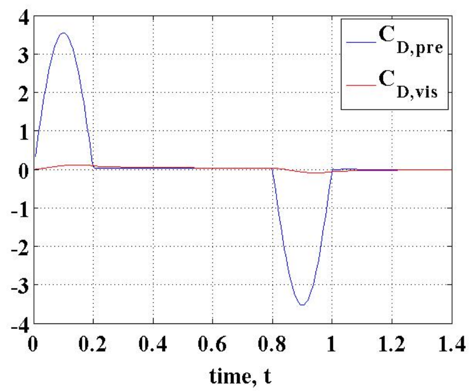
$Re = \widehat{U}c/\nu = 10\,000$

Time evolution



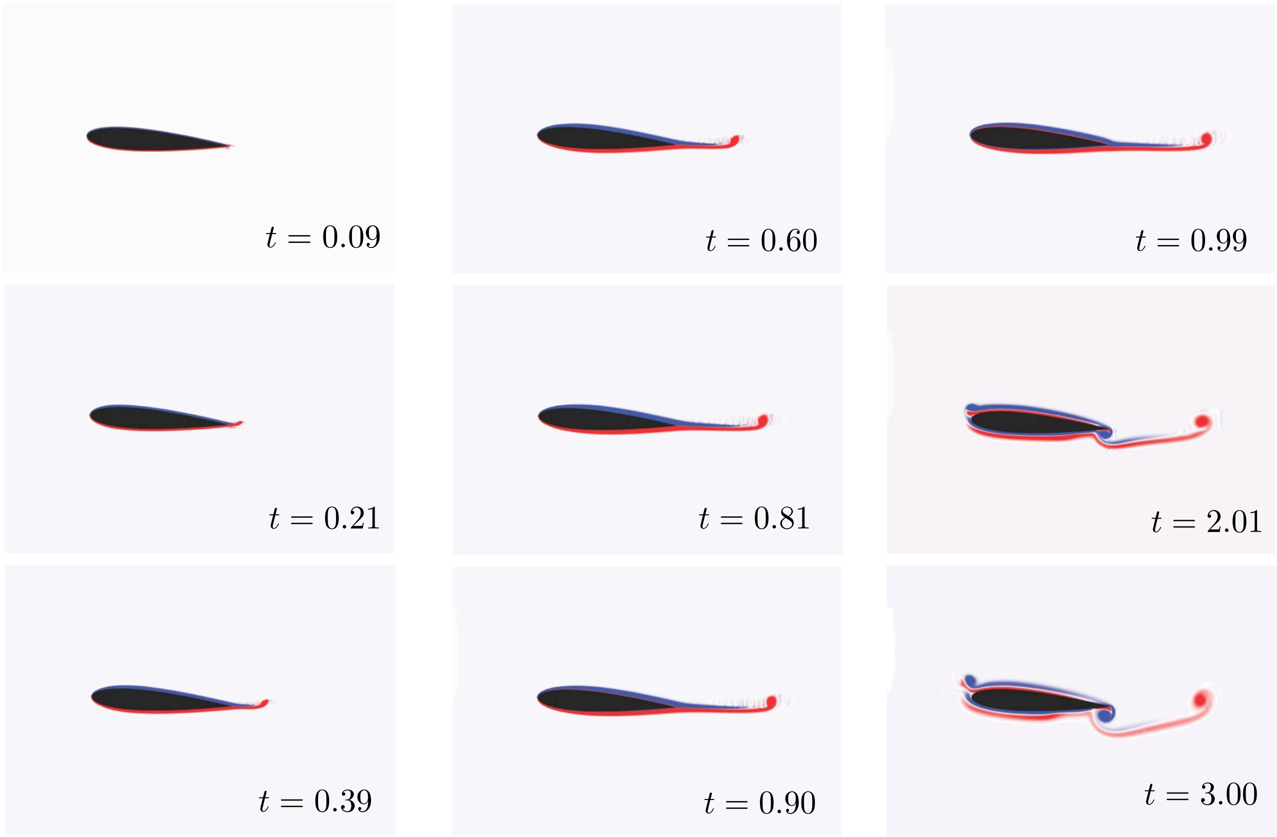
$$C_l = L'/\left(\tfrac{1}{2}\rho\widehat{U}^2 c\right) \qquad C_d = D'/\left(\tfrac{1}{2}\rho\widehat{U}^2 c\right)$$



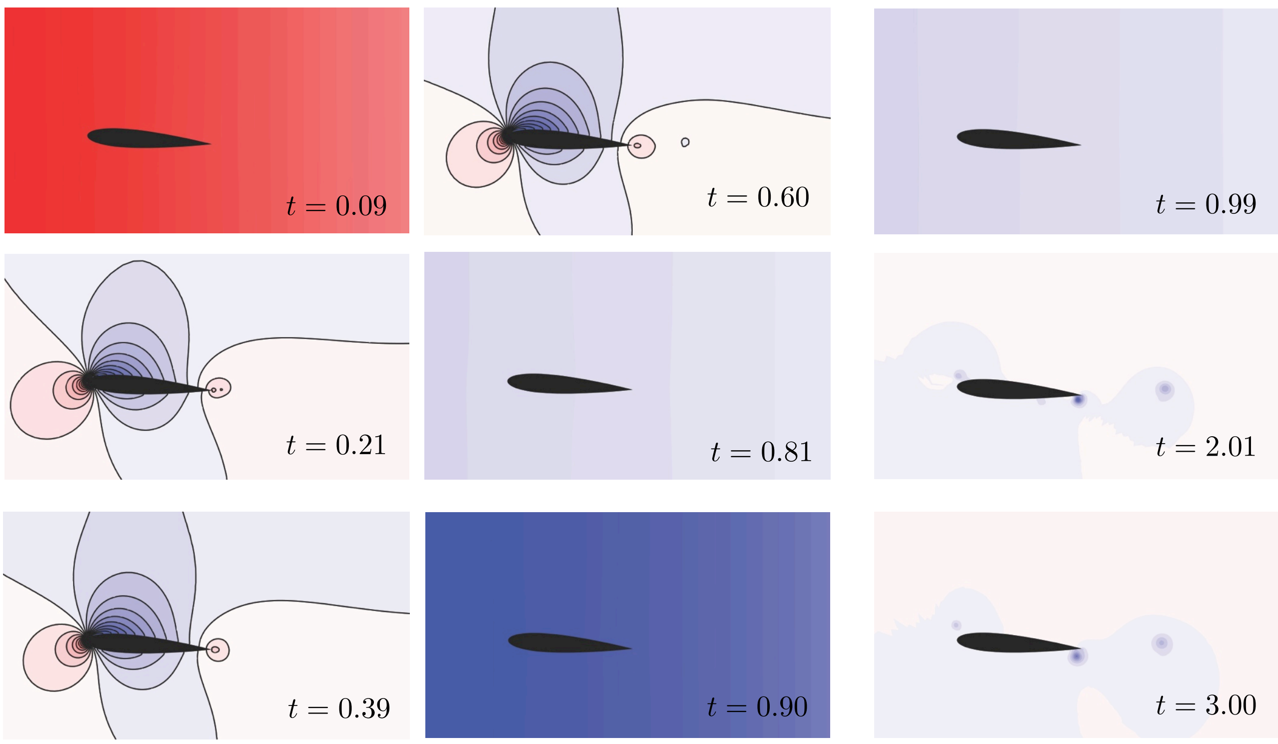


For $\dfrac{\partial C_l}{d\alpha} = 2\pi$ steady-state C_l = 0.438

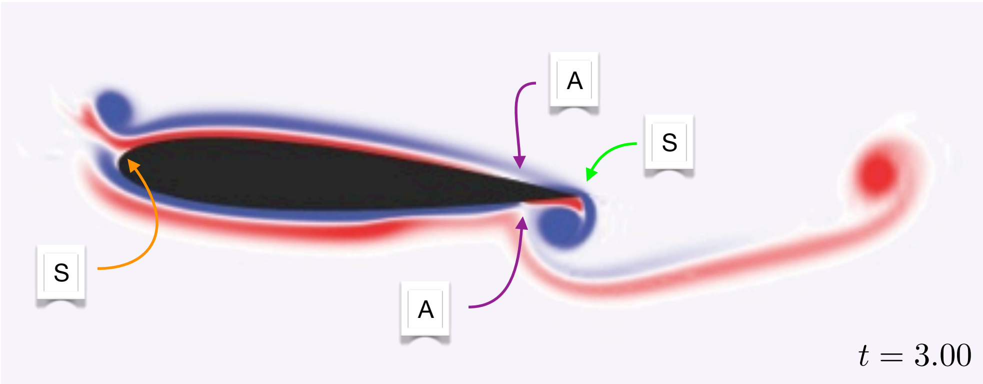
Vorticity



Pressure



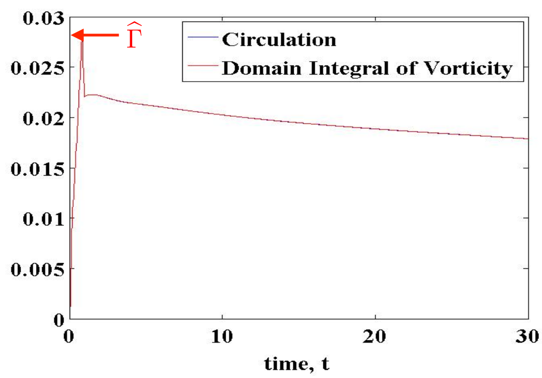
Flow topology



Circulation and vorticity

Kutta–Joukowsky theorem

$$\Gamma = \oint \boldsymbol{u} \cdot \mathrm{d}\boldsymbol{l} = \int \boldsymbol{n} \cdot \boldsymbol{\omega} \, \mathrm{d}S$$



Kelvin–Helmholtz theorem

$A = \Delta x \times \Delta y = 60.0c^2$ $\qquad \widehat{\Gamma} = 0.0183$

$A = \Delta x \times \Delta y = 17.5c^2$ $\qquad \widehat{\Gamma} = 0.0281$

Summary

1. Very similar to Prandtl's experiment
2. Additional detail: generation of vortex pair at leading edge
3. Global circulation approaches zero as domain size increases
4. Forces dominated by added mass effects