Control of unsteady wake flows using local oscillation of body surface: a data assimilation study

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Abstract

Variational data assimilation (DA) can expand active flow control techniques to design wall actuators such as synthetic jets or plasma discharges which are difficult to model computationally due to ambiguous boundary conditions at the wall. Here, the control vector for the DA problem is formed by the initial flow and the solid boundary conditions for the body, that means its tangential speed at all times where no particular form is prescribed to the body motion. The control domain takes into account the modeled body surface by means of a direct forcing immersed boundary method (IBM). We consider a configuration of reference flow past a rotationally oscillating cylinder given by Mons & Sagaut, 2017, *J. Fluid Mech.*. The proposed methodology is applied to the reconstruction of a reference flow generated by a partial control restricted to an upstream part of the cylinder surface as given by Bergmann & Cordier, 2006, *Phys. Fluids*. DA is also employed to build wall conditions for a direct numerical simulation (DNS) of flow around an airfoil with local oscillation, from synthetic observations of the wake flow downstream the body.

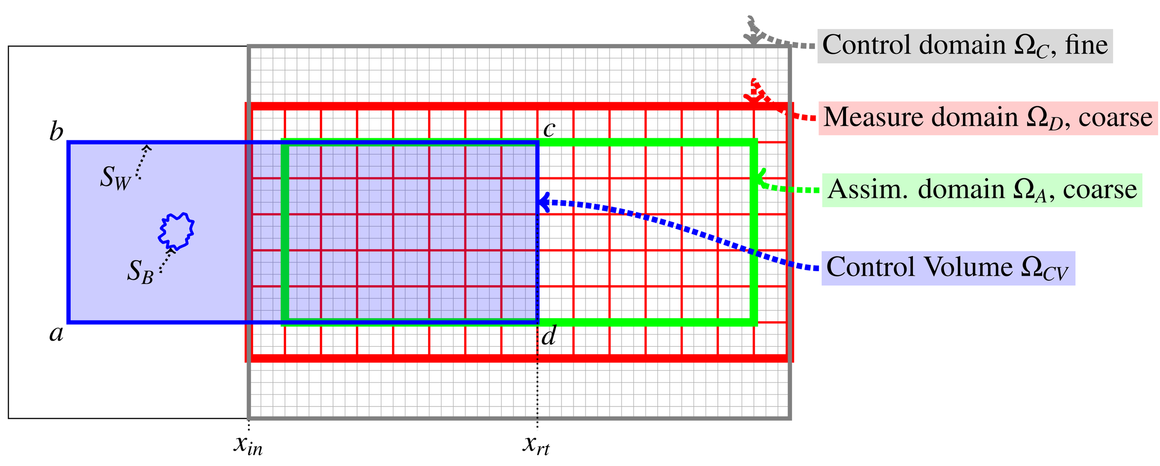
Data assimilation for flow spatio-temporal reconstruction

Goal Provide a DA technique integrating experimental data and DNS to reconstruct the flow dynamics around complex stationary or moving geometries

Control volume technique
Lack of info outside Ω_D
⇓
Not be able to evaluate unsteady term $\frac{\partial}{\partial t}\int_{\Omega_{CV}} \rho \mathbf{u} \, dV$
⇓
Partial estim. of C_D^{rms}, C_L^{rms}

Present strategy
body boundary cond. $\mathbf{u}(x\rfloor_{S_B}, t)$ in DA control vector

Force estimation by body wake data assimilation
Gronskis et al., to appear in *Exp. Fluids*



Boundary forcing estimation through VDA

Problem Recover a system's state X obeying a dynamical law $\mathbb{M}$, given observations at t^* separated by Δt_{obs}

$$\partial_t X(\mathbf{x},t) + \mathbb{M}(X(\mathbf{x},t),\eta(t)) = 0$$
$$X(\mathbf{x},t_0) = X_0(\mathbf{x}) + \epsilon(\mathbf{x})$$

Dynamical model

$$\nabla \cdot \mathbf{u} = 0$$
$$\frac{\partial \mathbf{u}}{\partial t} = -\nabla p - \frac{1}{2}[\nabla(\mathbf{u}\otimes\mathbf{u}) + (\mathbf{u}\cdot\nabla)\mathbf{u}] + \nu\Delta\mathbf{u} + \mathbf{f}$$

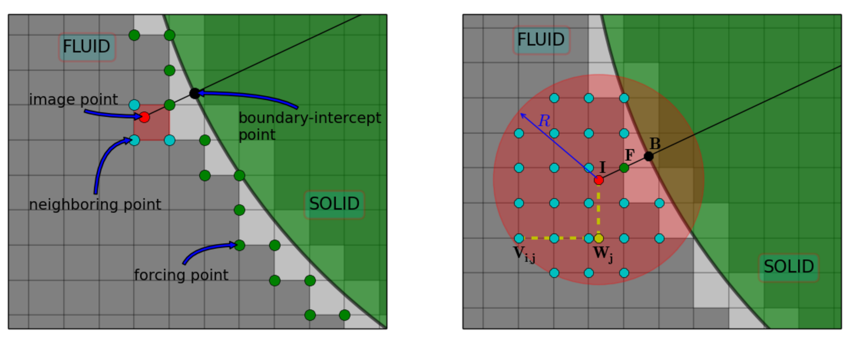
Numerical method ↦ `Incompact3d`

Evaluation of forcing

Force applied in a neighborhood of the solid boundary:

$$\tilde{\mathbf{f}}^{n+1} = \frac{\mathbf{u}_F - \hat{\mathbf{u}}}{\Delta t}$$
$$\tilde{\mathbf{f}}^{n+1} \cong -\sum_{k=1}^{nf} \tilde{f}_x(\mathbf{x}_{F_k}) \, \Delta x \, \Delta y$$

IBM for simulating flows with moving rigid boundaries
Gronskis et al., 2016, *Comput. Fluids*



Data Assimilation - Cost Functional

Minimization problem constraint ⇒ state dynamics ⇒ dependence of the system's state variable X on the control variable γ

$$X \equiv \mathbf{u}(\gamma), \quad \gamma = \{\epsilon(\mathbf{x}), \eta(t)\} \equiv \{\mathbf{u}(\mathbf{x},t_0), \mathbf{u}(\mathbf{x}\rfloor_{S_B}, t)\}$$

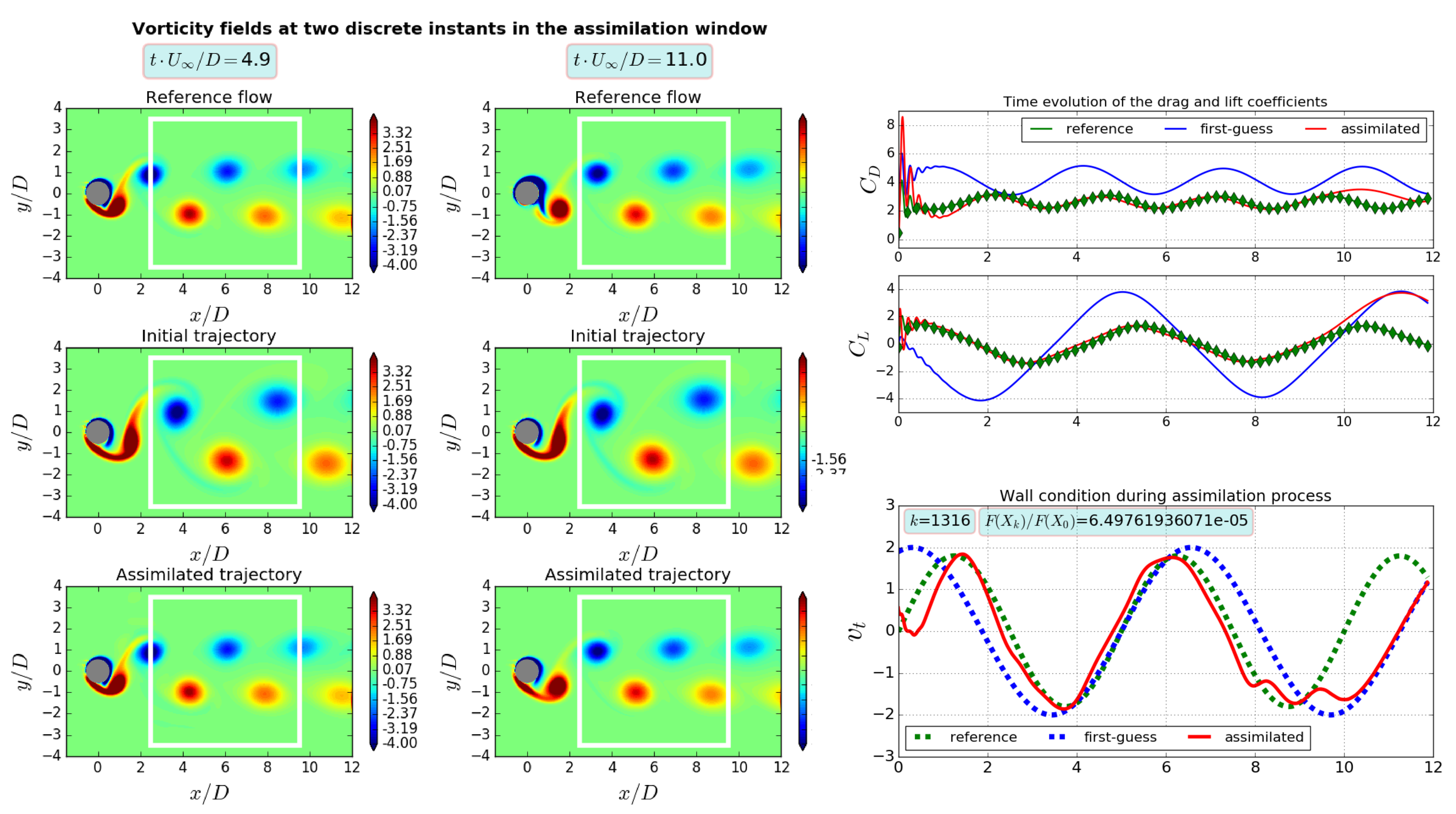
Objective lowest discrepancy between observations and state variable

$$J(\gamma) = \int_{t_1}^{t_N}\int_{\Omega_A} \|\overline{\omega}(\mathbf{x},t) - \omega^{obs}(\mathbf{x},t)\|_R^2 \, dx \, \Delta_{t^*} dt + \nu(\mathbf{x})\int_{\Omega_C} \|\overline{\mathbf{u}}(\mathbf{x},t_0) - \mathbf{u}_{k=0}(\mathbf{x},t_0)\|^2 \, dx$$

$dx_{obs} > dx$
spatial avg model
background state

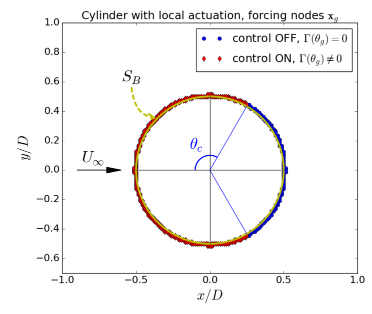
Control on the Initial and Wall Condition

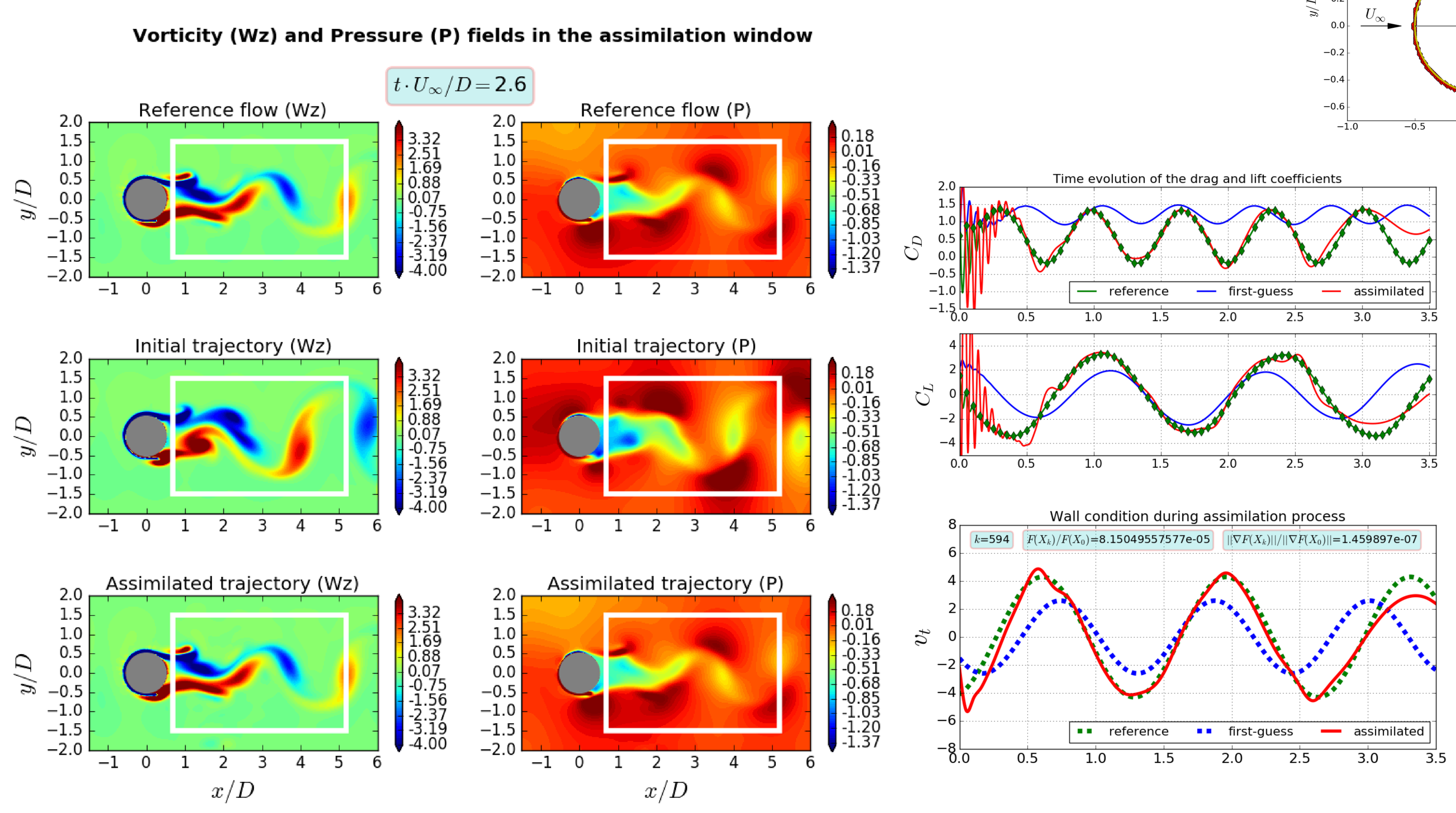
Flow configuration rotational speed of the cylinder at Re=100: $w_c(t) = A\sin(2\pi f t)$



Partial control on the cylinder surface

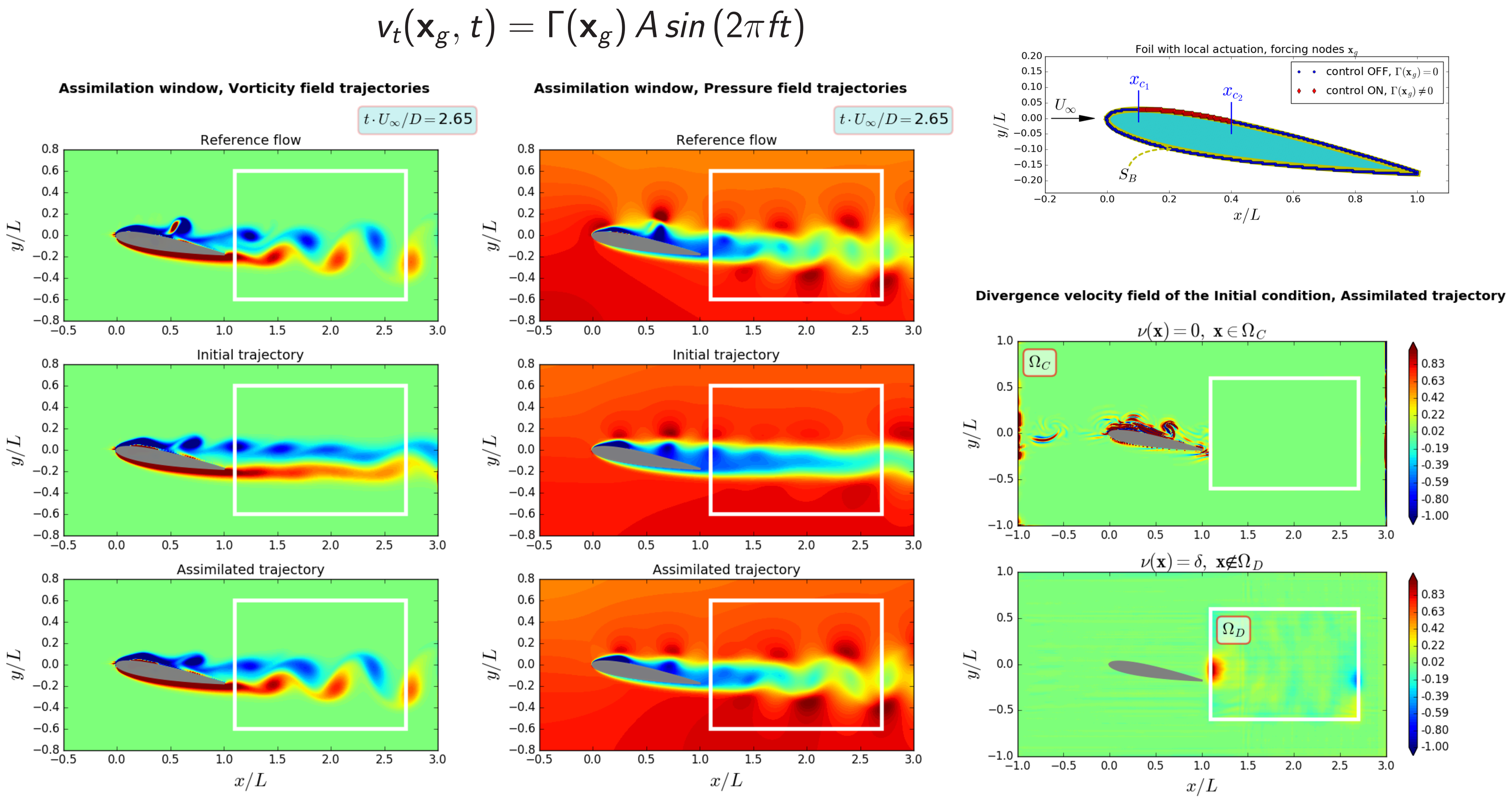
Flow configuration non-uniform rotational speed at Re=200 and θ_c=120°:
$$w_c(\theta_g, t) = \Gamma(\theta_g)\, A \sin(2\pi f t)$$





Local control on the airfoil upper surface

Flow configuration non-uniform tangential speed of the NACA0012 at Re=1000 and α=10°:
$$v_t(\mathbf{x}_g, t) = \Gamma(\mathbf{x}_g)\, A \sin(2\pi f t)$$

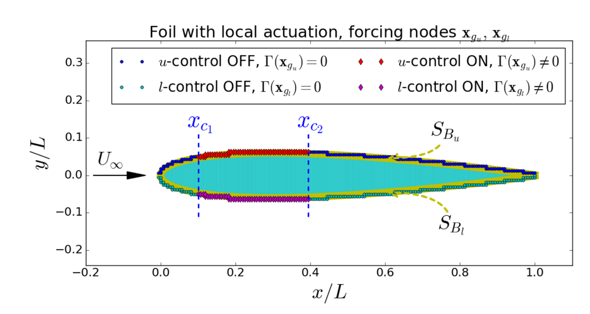


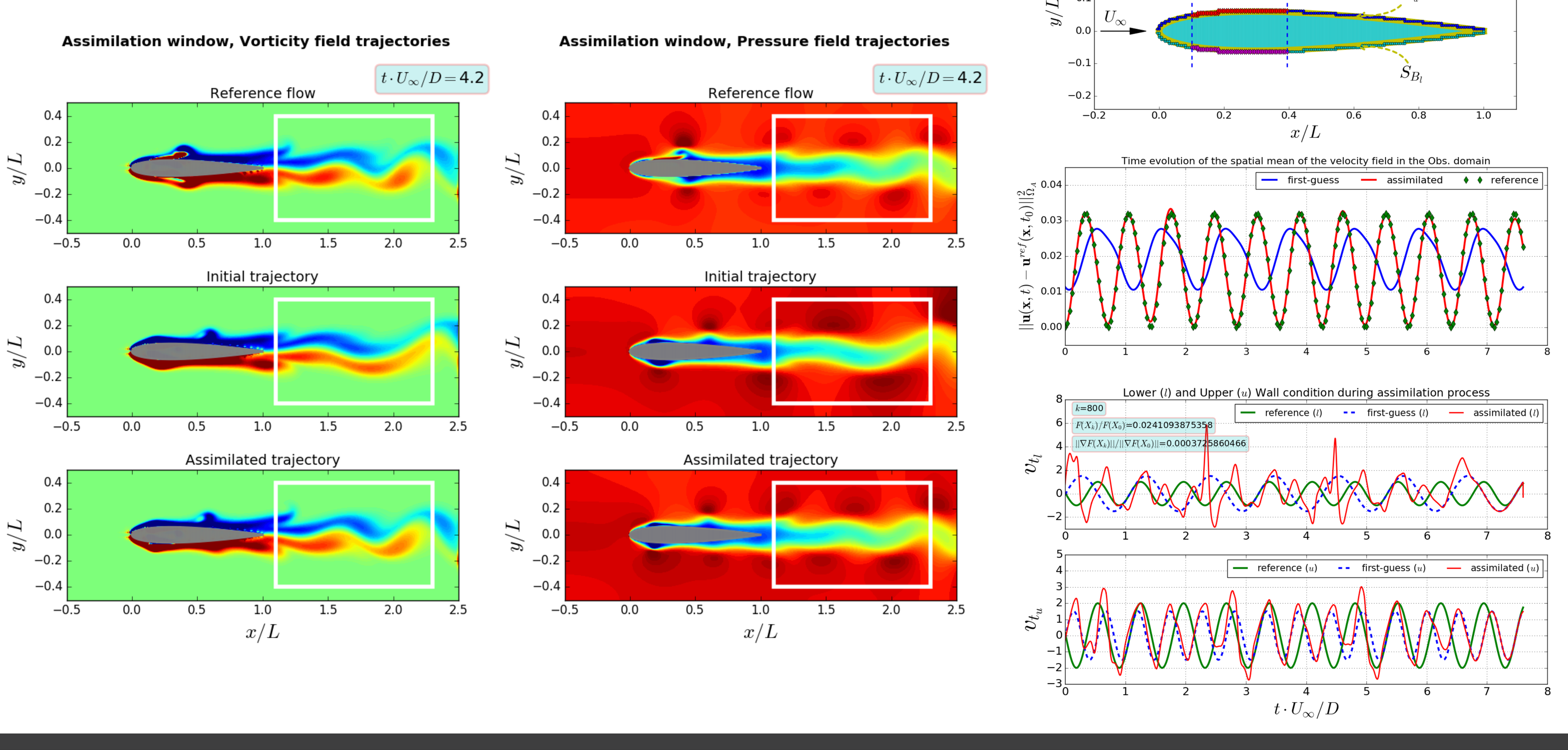
Controlled airfoil by arrays of actuators

Flow configuration non-uniform tangential speed of the NACA0012 at Re=1000:

upper wall: $v_{t_u}(\mathbf{x}_{g_u}, t) = \Gamma(\mathbf{x}_{g_u})\, A_u \sin(2\pi f_u t)$

lower wall: $v_{t_l}(\mathbf{x}_{g_l}, t) = \Gamma(\mathbf{x}_{g_l})\, A_l \sin(2\pi f_l t)$





Conclusion and Outlook

- A new method for reconstructing the flow field from limited measurements where no velocity information is available in a neighborhood of the solid boundary has been introduced.
- Though being restricted to reasonable mesh resolution at the body surface, present technique allows for an accurate pressure reconstruction in a region close to the solid boundary.
- The addition of a penalization term for the wall condition in the cost function will allows us to prevent drastic changes in the temporal solution during the optimization process.
- Introducing a moving boundary cond. as a control parameter will extend VDA to FSI.

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