Overview of CFD activities @ POLIMI/DAER

From turbulence modeling with DNS to adjoint optimization

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HPC Methods for Engineering
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Introduction

A rather personal (!) interpretation of:

1. DAER
2. CFD
3. HPC
4. Engineering

Topics

- Turbulence and Flow Control
- Adjoint-based shape optimization in OpenFOAM
- The OpenNOSE project

Flow Control

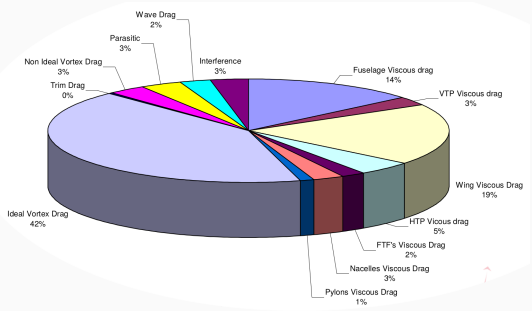
Control of turbulent flows

Focus on skin-friction drag reduction

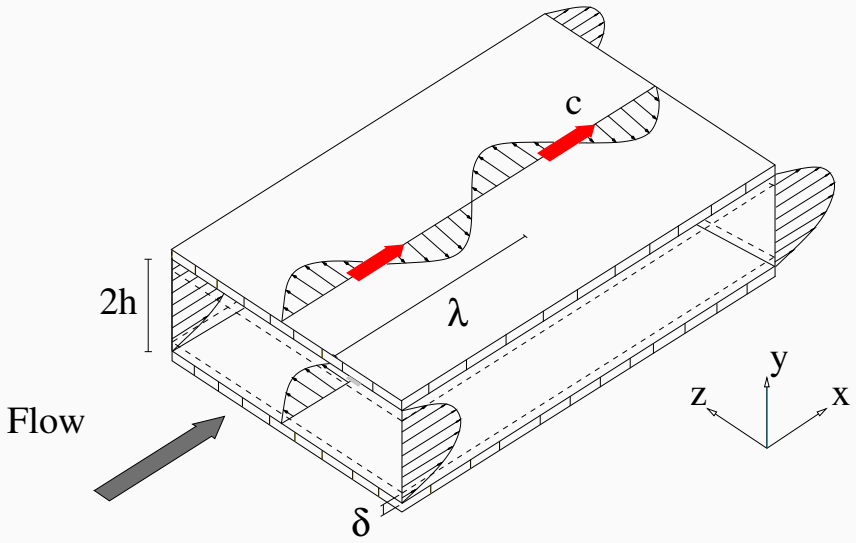
Challenges in:

- physical understanding;
- technological developments;
- control-theoretical methods.

Passive vs. open-loop vs. closed-loop approach



The streamwise-traveling waves

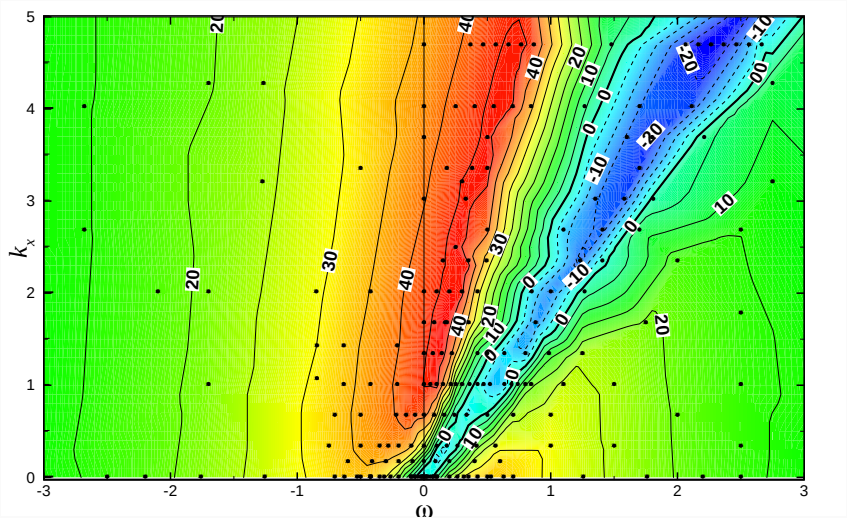


No ”engineering” yet

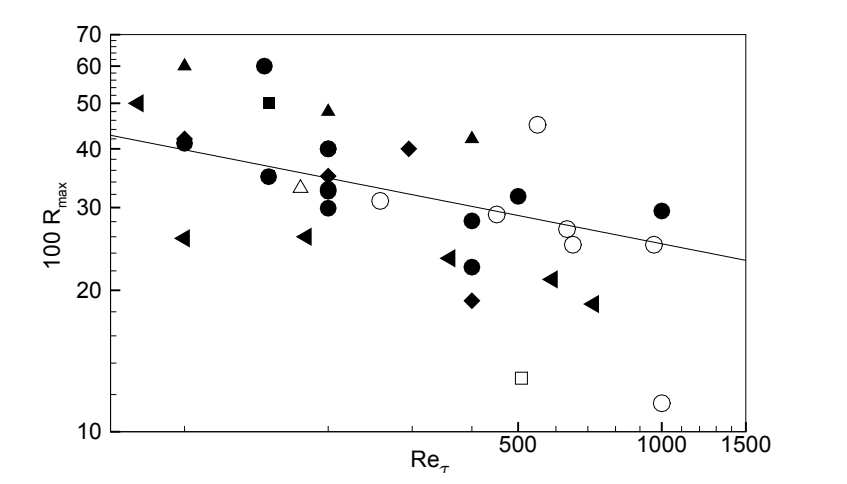
- Channel flow, low *Re*, simple geometry
- DNS required (cost!)
- fundamental study

The starting point

Quadrio et al, J Fluid Mech 2009

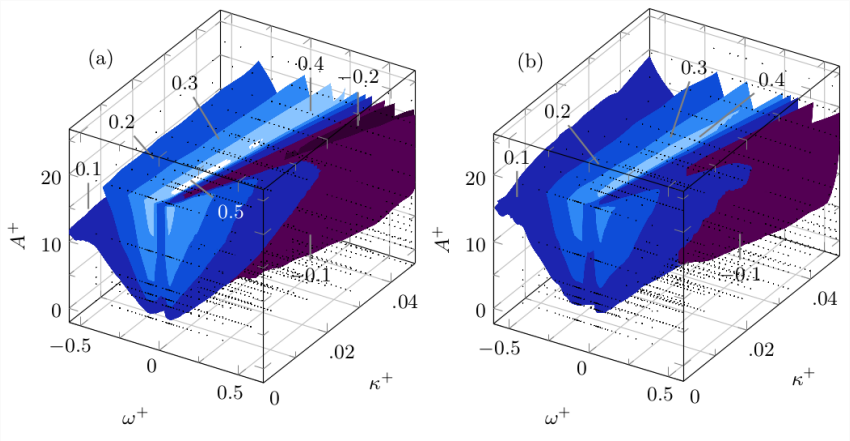


Q1: What about flight Re?

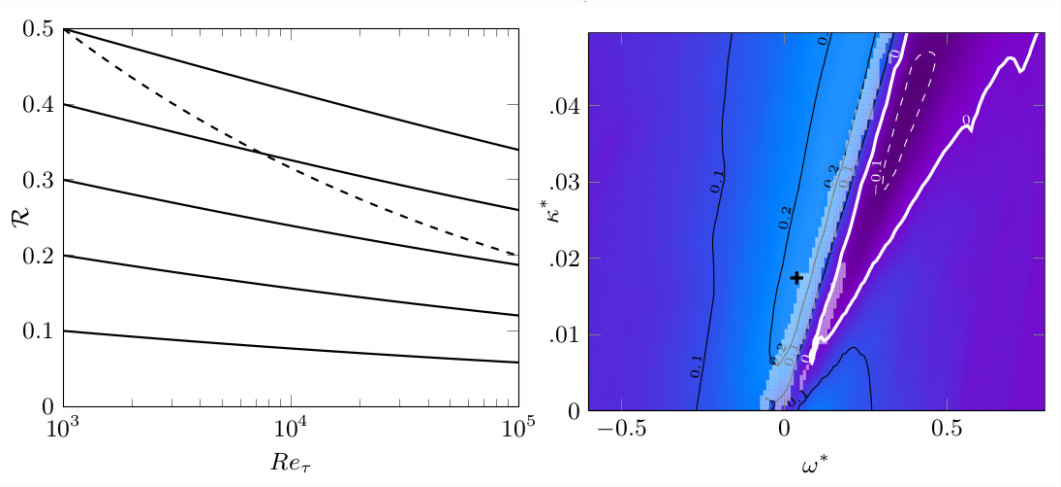


Huge study at $Re_\tau = 200$ and $Re_\tau = 1000$

4020 DNS cases: this is HTC, right?

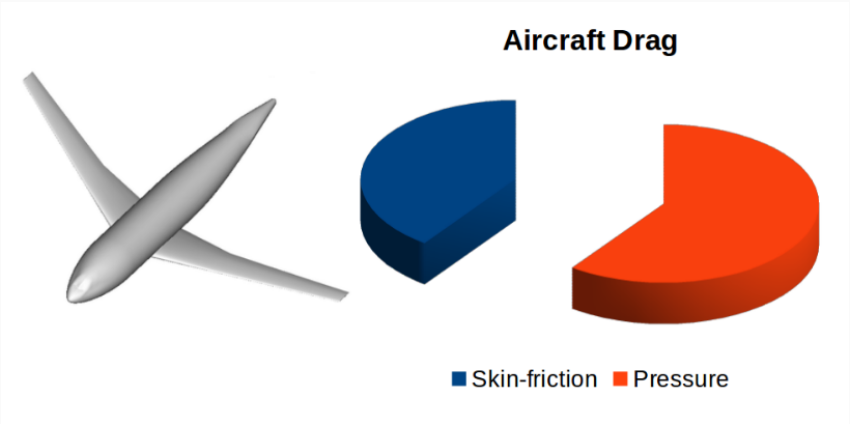


Extrapolation to flight *Re*



Very interesting news for industry, but ...

Q2: What about an airplane?



How to put waves into RANS of the airplane

A model for control is needed!

- Streamwise-travelling waves produce a vertical shift ΔB of the logarithmic portion of the mean velocity profile
- Drag redution is linked to ΔB
- ΔB^+ is Re-independent

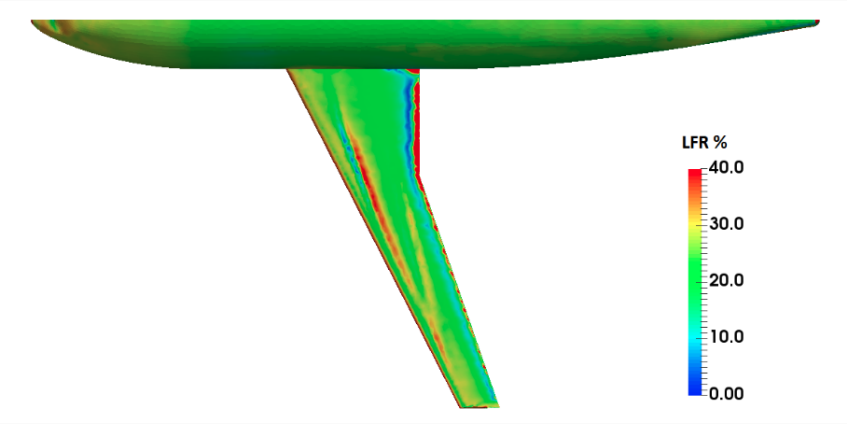
$$U^+ = \frac{1}{\kappa} \log y^+ + B^+ + \Delta B^+$$

The test case

- Taken from AIAA second Drag Prediction Workshop
- DLR-F6 (wing-body)
- RANS with Spalart-Allmaras model
- $Re = 3 \cdot 10^6$ and $Ma = 0.75$
- Code: AeroX (CPU+GPU)
- 2M elements, polar in one afternoon

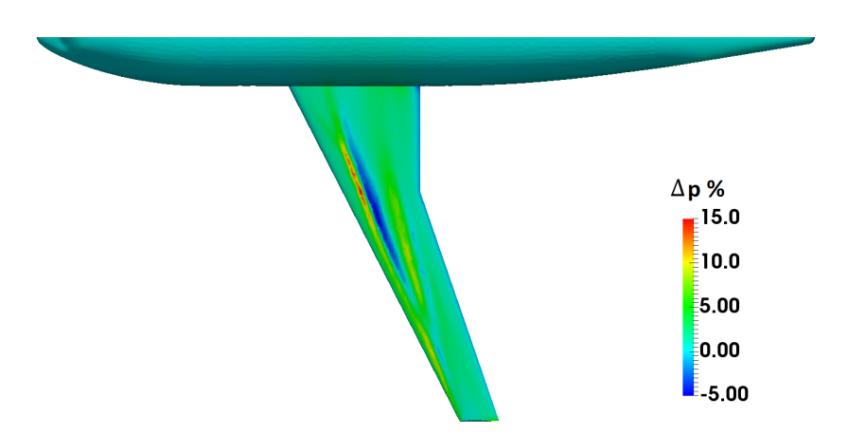
Friction

As expected on the fuselage ...

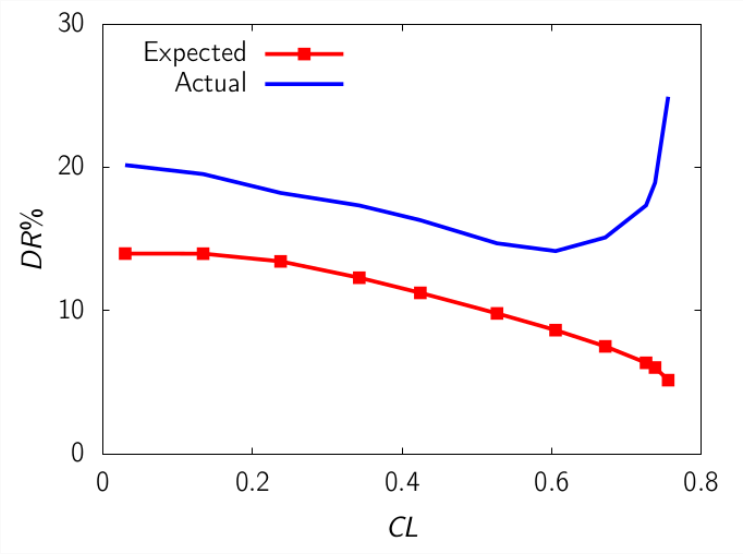


Pressure

Zero on fuselage only!

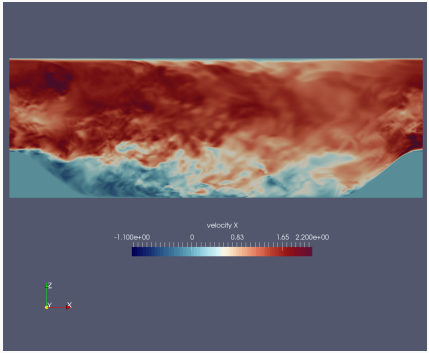


Drag reduction (at constant lift)



Where are we now

- Back to step zero: DNS of an incompressible duct flow over a bump
- Interaction between skin-fricton drag reduction and pressure



Example video: $Re = 5600$, $nx = 360$, $ny = 200$ and $nz = 461$

Adjoint

Dual problem of a PDE system (continuous formulation)

Primal equations

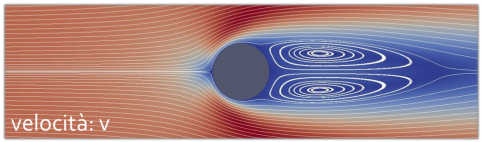
$$\begin{cases} \text{Incompressible steady NS} \\ \text{primal BC} \end{cases}$$

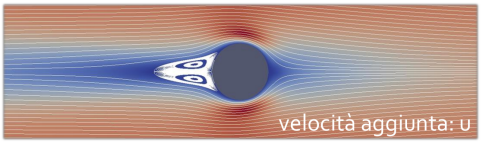
- control field
- cost function

Adjoint equations

$$\begin{cases} \text{Adjoint inc. steady NS} \\ \text{dual BC} \end{cases}$$

- primal solution
- sensitivity derivative





Adjoint: where's the benefit?

Efficient computation of sensitivity gradients

With 1 cost function and N control variables ($N \gg 1$ in shape optimization!):

- direct optimization: N+1 solutions required
- adjoint optimization: 2 solutions suffice

OpenFOAM vs SU2

OpenFOAM

- large user base
- focus: incompressible
- no adjoint

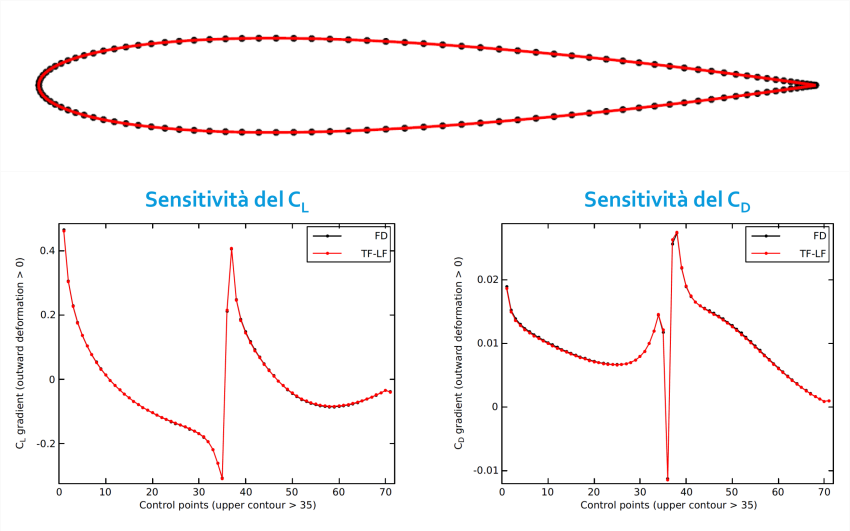
SU2

- small (growing) user base
- focus: compressible
- built-in adjoint!

Our goal: open-source implementation of a continuous-adjoint toolbox in OpenFOAM

Need for robust, simple, numerically-accurate formulation

LAMINAR NACA 0012

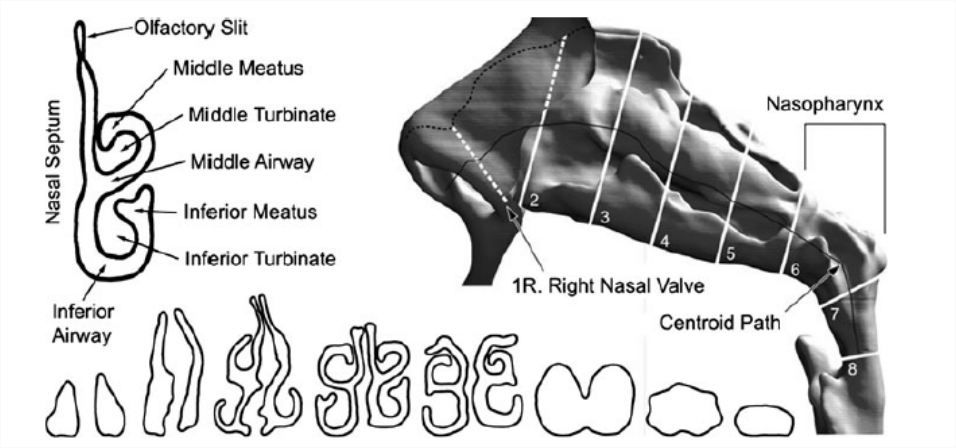


The nose

The human nose: a complex system with "industrial" interest

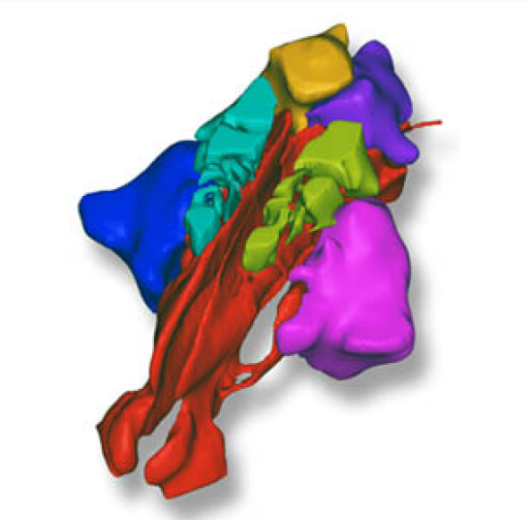
- Fundamental interest
- Nasal breathing diffisulties are very widespread
- Strong economical impact

Significant longitudinal variations



A 3D view

Topologically simple, morphologically complex

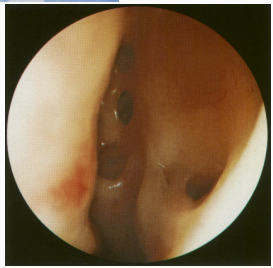


How to study the nasal airflow?

CFD improves over *in-vivo* or *in-vitro* approaches

- Beginning to appear in early 2000
- Long times (weeks/months) for producing a mesh
- Questionable (but never questioned!) modellistic approaches
- Non-validated results

FESS



The state of the art

Nowadays functional endoscopic sinus surgery (FESS) is the gold standard for chronic NBD treatment. The operation generally involves inferior/middle turbinoplasty and uncinate and ethmoid excision, sometimes followed by opening of the maxillary, sphenoid and frontal sinuses. A correction of a nasal septal deviation can also be necessary.

...

However, we are currently unable to assess the relevance of every single anatomic anomaly and its surgical modification on the overall nasal flow quality and nasal obstruction.

Quadrio et al, Eur. Arch. Oto-Rhino-Laryngology Head Neck, 2014

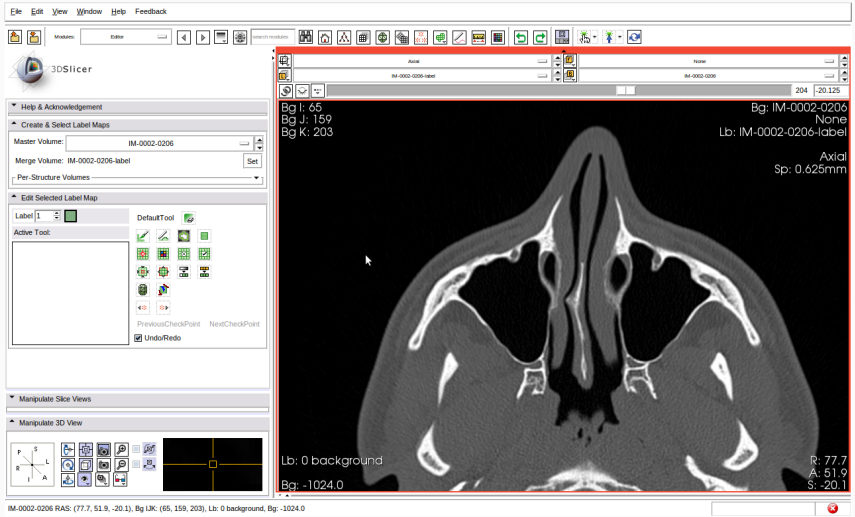
Our vision: a patient-specific nearly-automated procedure

- *Patient-specific* procedure
- CFD results from a CT scan
- Virtual surgery
- Reliable results
- Robust and feasible procedure (time and cost)
- Goal: support / reduce / optimize surgery

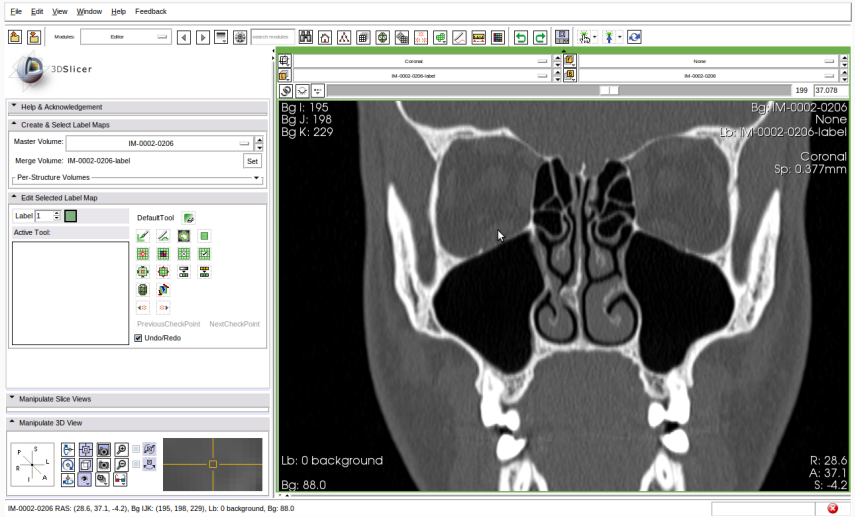
The toolchain

1. Analysis of CT scan (3DSlicer)
2. STL from CT scan (3DSlicer)
3. Volume mesh (OpenFOAM / snappyHexMesh)
4. CFD (OpenFOAM)
5. Visualization (ParaView)

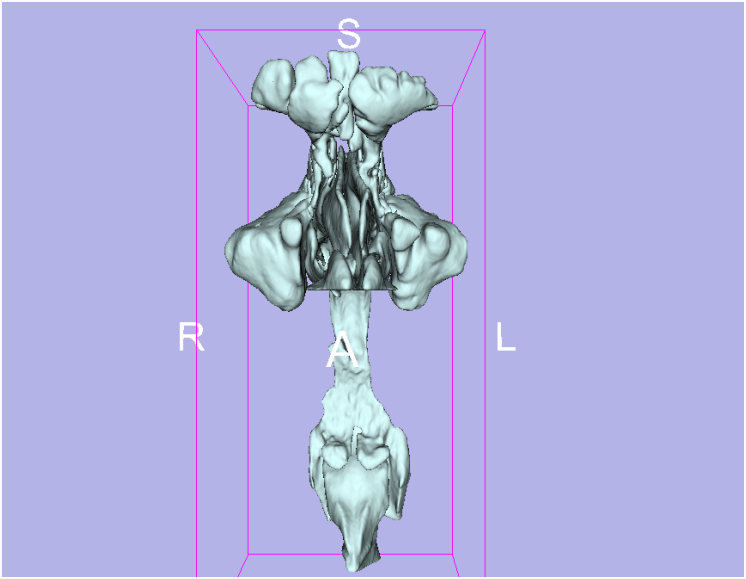
1/3 Analysis of the CT scan

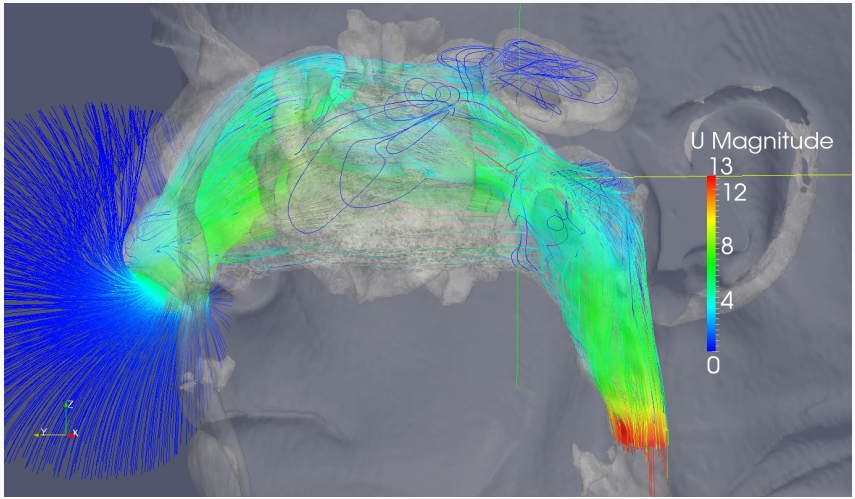


1/3 Analysis of the CT scan (2)



STL FROM CT SCAN




U Magnitude
13
12
8
4
0
Z
Y
X

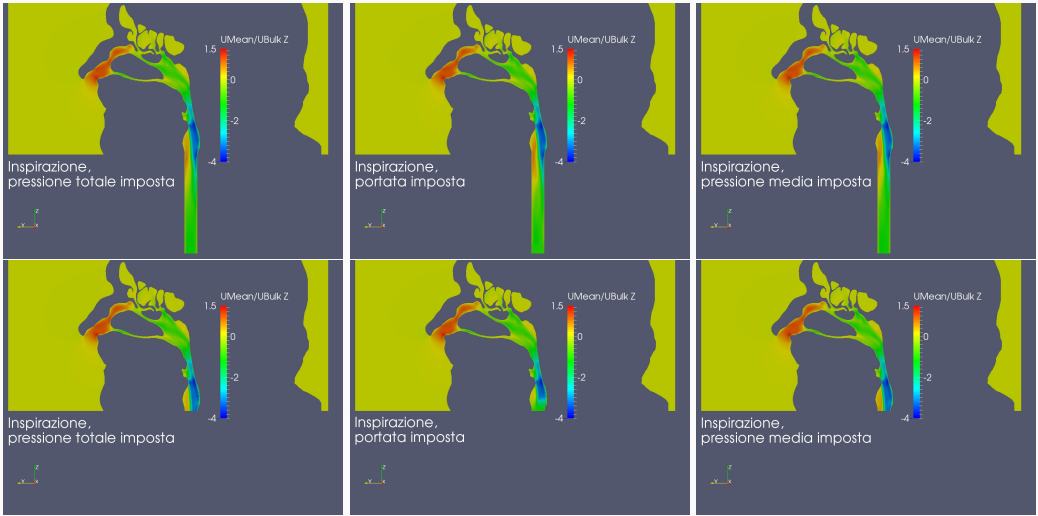
Example movie

Example movie

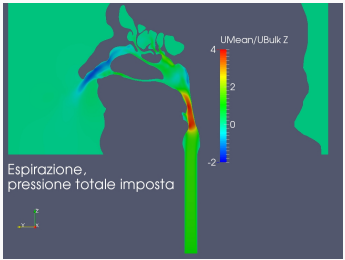
The role of OpenNOSE

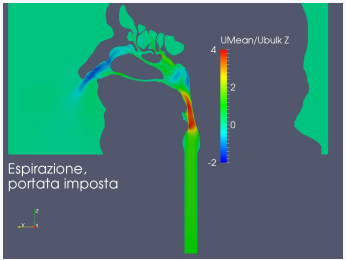
- World-first validation testbed
- Naturally open: open source, open data, open science
- Unique DNS and experimental dataset under construction

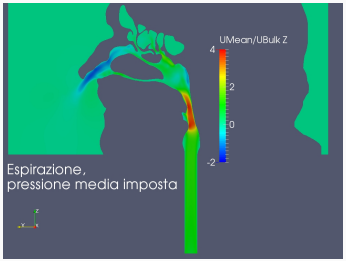
Which boundary condition(s)?

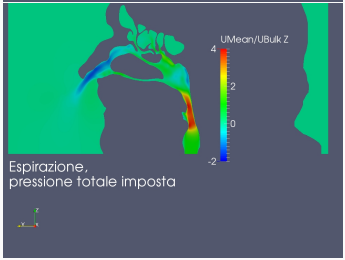


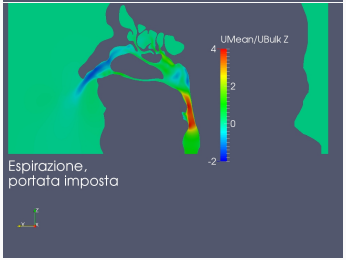
Which boundary condition(s)?



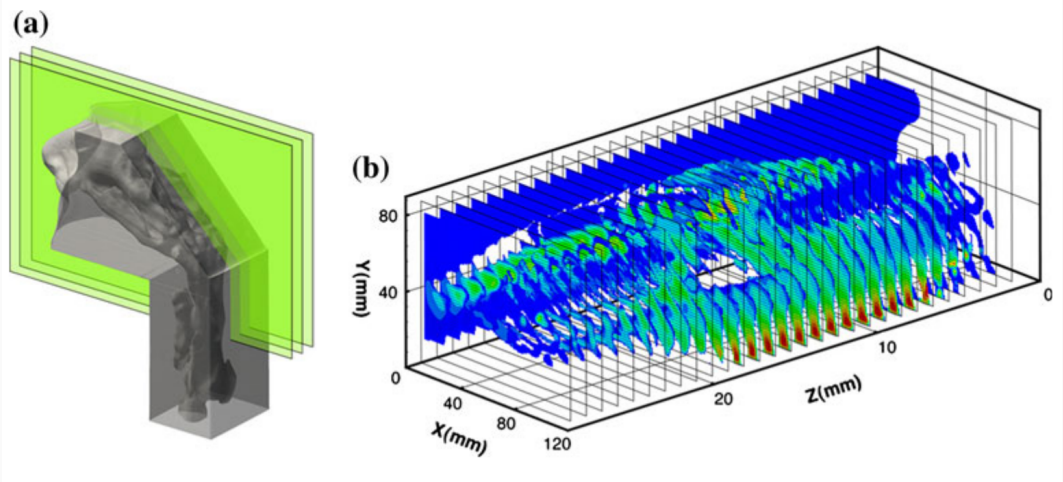




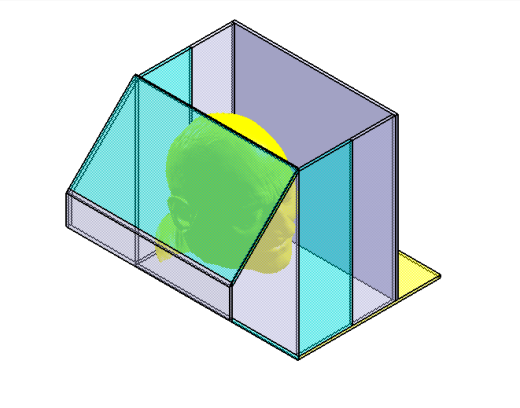


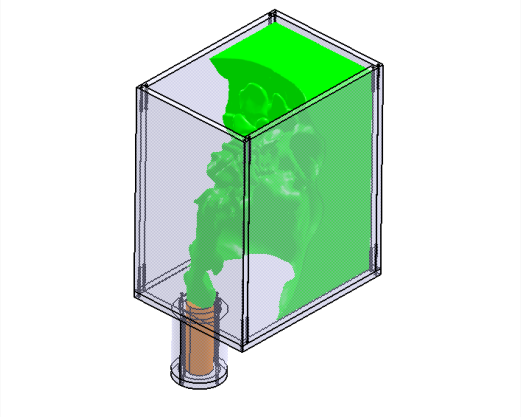


2D-3C PIV velocity measurements

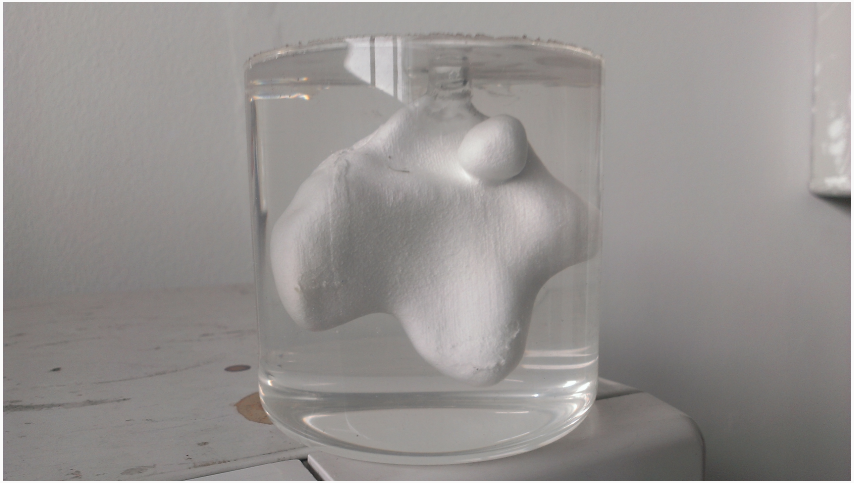


The experimental setup

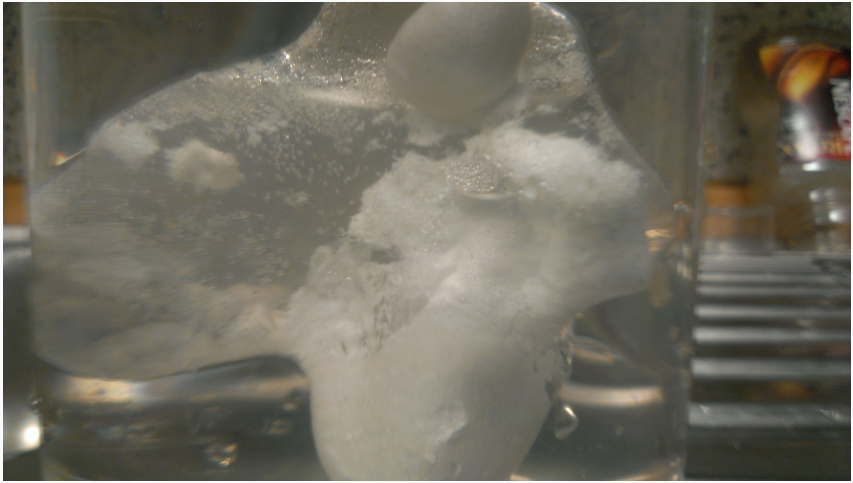




1) Dissoluble material coated and embedded in silicone



2) Removal of the dissoluble material by water



3) Filled with water + glycerine: the model is... phantom!

Conclusions

Credits

Adjoint

- CINECA: R.Ponzini
- POLIMI: F.Auteri
- Master students: F.Gritta, R.Pieri, M.Murari, L.Palma, R.Mosca, M.Pesarin, G.Sorgiovanni
- UNIGE: J.Pralits, A.Bottaro

OpenNOSE

- UNIMI: V.Covello + ENT group (G.Felisati, A.Saibene, C.Pipolo, E.Bujis)
- Regensburg: L.Krenkel
- Master students S.Corti, C.Pesci, E.Biondi, G.Lamberti, F.Manara, L.Sufrà, G.Vicenzotti, A.Schillaci

Credits: flow control

Davide Gatti, Yosuke Hasegawa, Betty Frohnapfel, Andrea Cimarelli, Jacopo Banchetti