DIRECT FEM-SIMULATION OF TURBULENT (BLUFF BODY) FLOW

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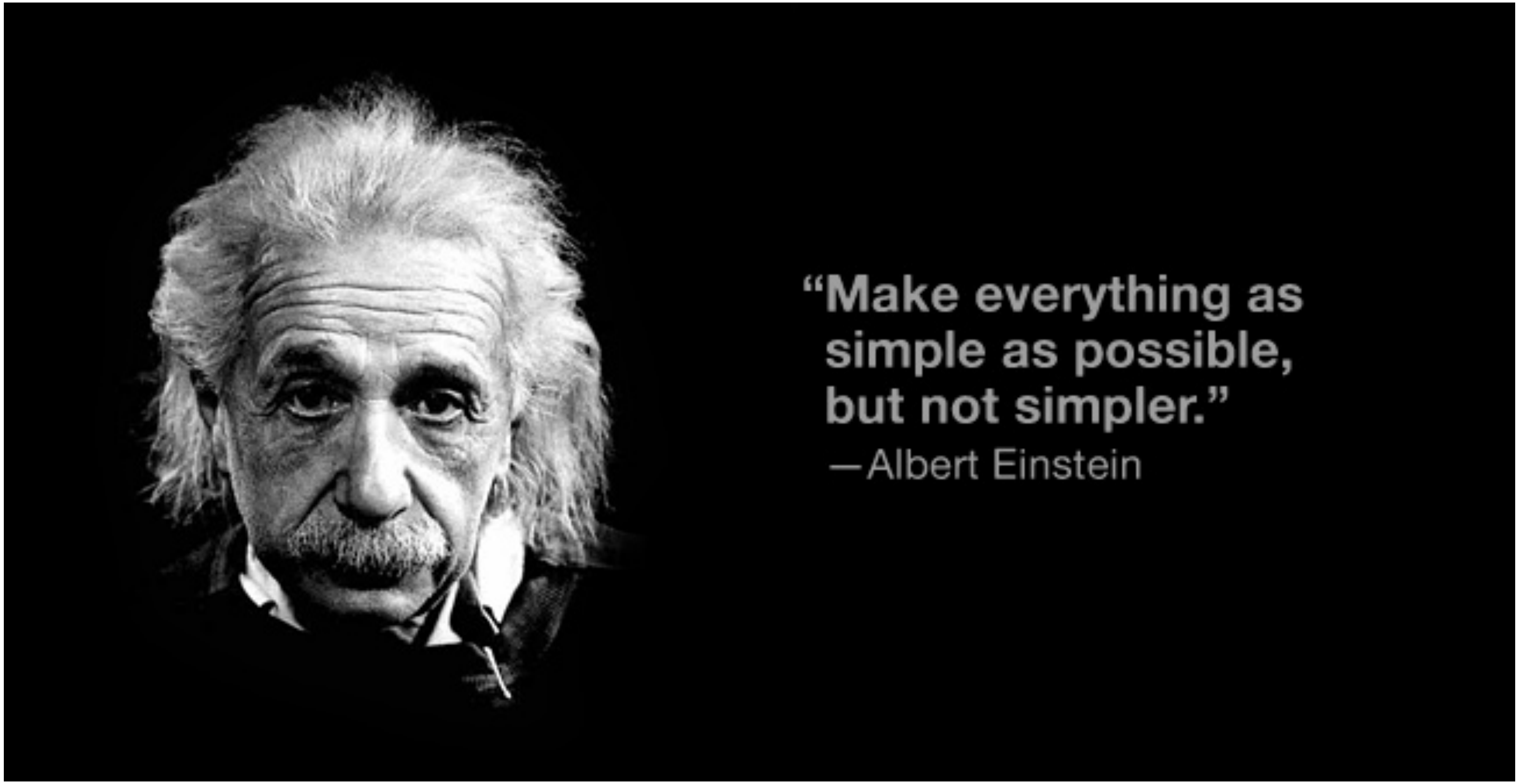
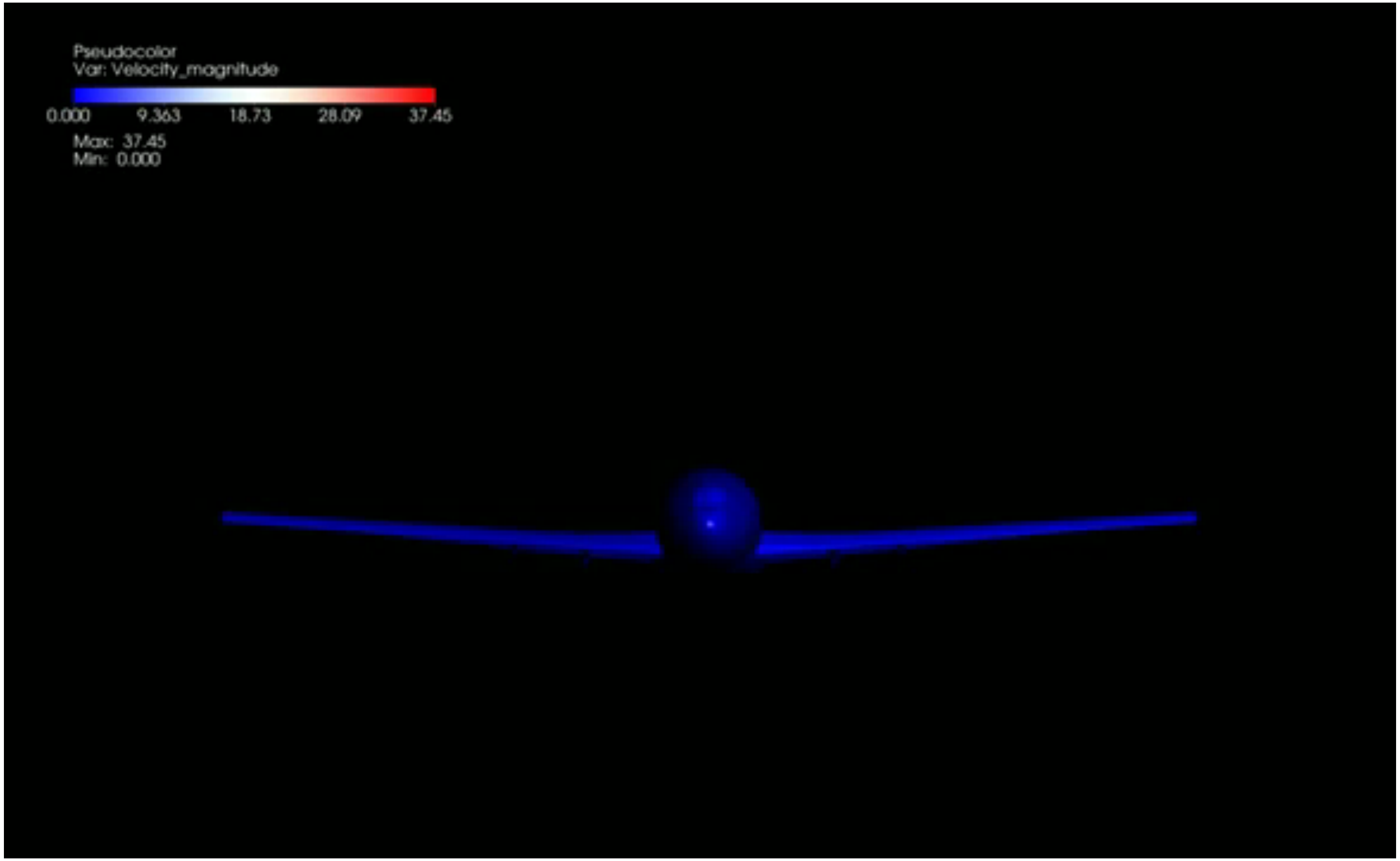
PLAN: MAKE FLUID MECH AS SIMPLE AS POSSIBLE, BUT NOT SIMPLER



THE TRUTH: G2: NAVIER-STOKES



G2 = GENERAL GALERKIN: UNICORN

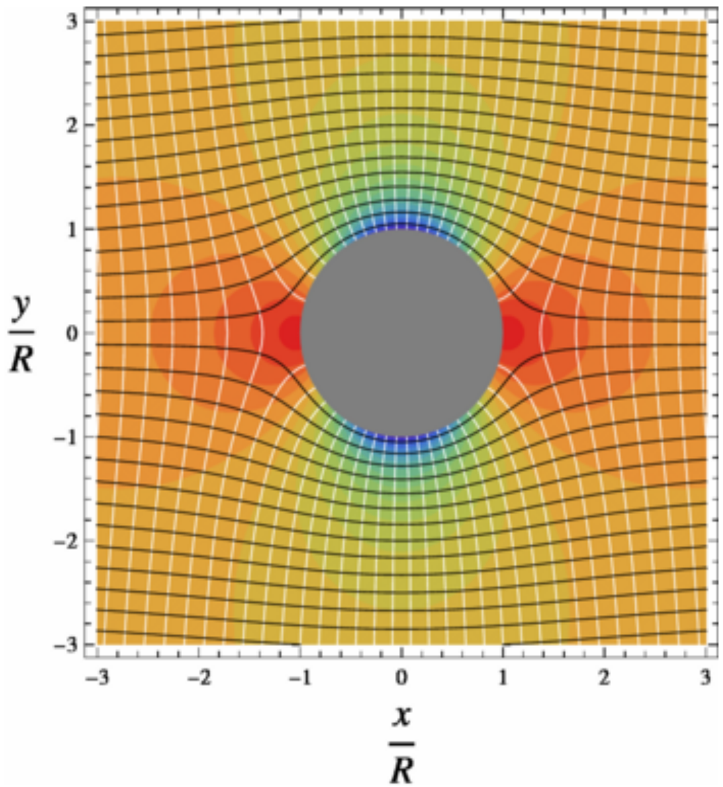
- RESIDUAL STABILIZED GALERKIN FEM:
- NAVIER STOKES EQUATIONS

- ADAPTIVE, PARALLEL, FLUID-STRUCTURE
- DUALITY-BASED A POSTERIORI ERROR CONTROL:
- DRAG LIFT FORCE DISTRIBUTION

EULER EQUATIONS 1745 - 55: INCOMPRESS + NEWTON'S 2ND LAW

Everything that the theory of fluids contains is embodied in the two equations I have formulated. It is not the laws of mechanics that we lack in order to pursue this research, only the analysis which has not been sufficiently developed for this purpose.

POTENTIAL FLOW:
INCOMPRESS + IRROTATIONAL:
SOLUTION OF EULER'S EQUATIONS



D'ALEMBERT'S PARADOX 1752: ZERO DRAG

It seems to me that the theory (potential flow), developed in all possible rigor, gives, at least in several cases, a strictly vanishing resistance, a singular paradox which I leave to future Geometers to elucidate.

THEORY vs OBSERVATION

D'Alembert's paradox separated fluid mechanics from its start into theoretical fluid mechanics explaining phenomena which cannot be observed and practical fluid mechanics or hydraulics observing phenomena which cannot be explained.

CYRIL HINSHELWOOD
NOBEL PRIZE IN CHEMISTRY 1956

- POTENTIAL FLOW NOT OBSERVED
- POTENTIAL FLOW USELESS:
- COLLAPSE OF FLUID MECHANICS FROM START
- SIMPLY TOO SIMPLE!!

BIRKHOFF 1950: PROBLEM: THE LACK OF DEDUCTIVE RIGOR SO COMMON AMONG FLUID DYNAMICISTS

NO REASON TO BELIEVE THAT ANY POTENTIAL FLOW IS STABLE

BIRKHOFF 1950

- I think that to attribute d'Alembert's paradox to the neglect of viscosity is an unwarranted oversimplification The root lies deeper, in lack of precisely that deductive rigor whose importance is so commonly minimized by physicists and engineers....

256 YEARS TO RESOLVE D'ALEMBERTS PARADOX 1752 - 2008

- HOFFMAN-JOHNSON 2008 JMFM

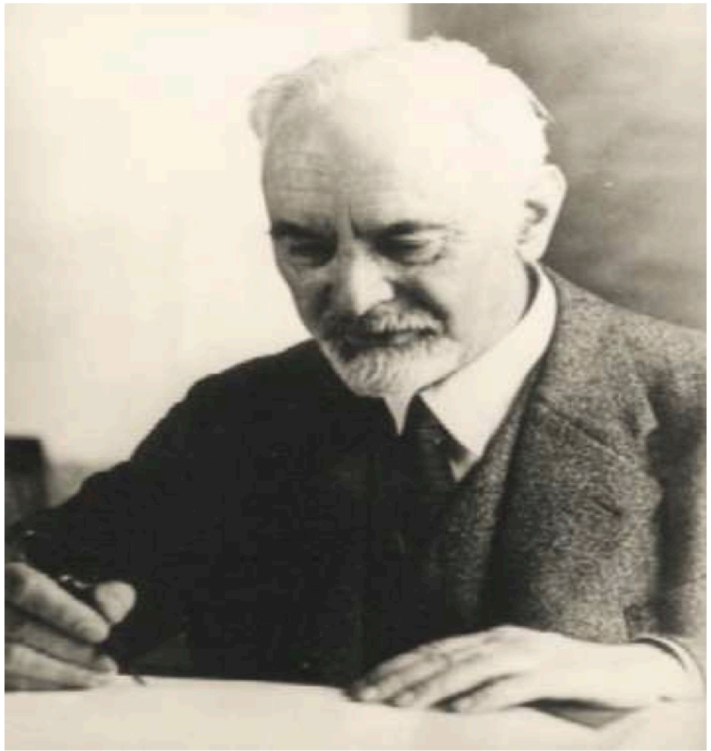
- BIRKHOFF WAS RIGHT 1950!

PRANDTL RESOLUTION 1904:

EVERYTHING FROM BOUNDARY LAYER

WRONG:

UNPHYSICAL UNMATHEMATICAL



RESOLUTION 2008:
NOTHING FROM BOUNDARY LAYER
POTENTIAL FLOW:

- UNSTABLE UNPHYSICAL

- IRROTATIONAL 2D SLIP SEPARATION:
  UNSTABLE UNPHYSICAL

1904 – 2008 RESOLUTION

- PRANDTL 1904:
- POTENTIAL FLOW NOT OBSERVED BECAUSE IT HAS NO BOUNDARY LAYER (SLIP BC)

- HJ:
- POTENTIAL FLOW NOT OBSERVED BECAUSE IT IS UNSTABLE

REAL FLOW

- POTENTIAL FLOW MODIFIED BY
- ROTATIONAL 3D SLIP SEPARATION
- STABLE PHYSICAL
- AS SIMPLE AS POSSIBLE BUT NOT SIMPLER
- EULER’S DREAM COME TRUE

SMALL VISCOSITY:
HIGH REYNOLDS NUMBER

- INCOMPRESSIBLE NAVIER-STOKES
- SMALL SKIN FRICTION:
- SLIP BOUNDARY CONDITION
- NS/SLIP
- TURBULENT SOLUTIONS

SLIP = SKIN FRICTION = 0

- SLIP
- FORCE BOUNDARY CONDITION
- NEUMANN CONDITION

- FORCE KNOWN: SKIN FRICTION = SMALL

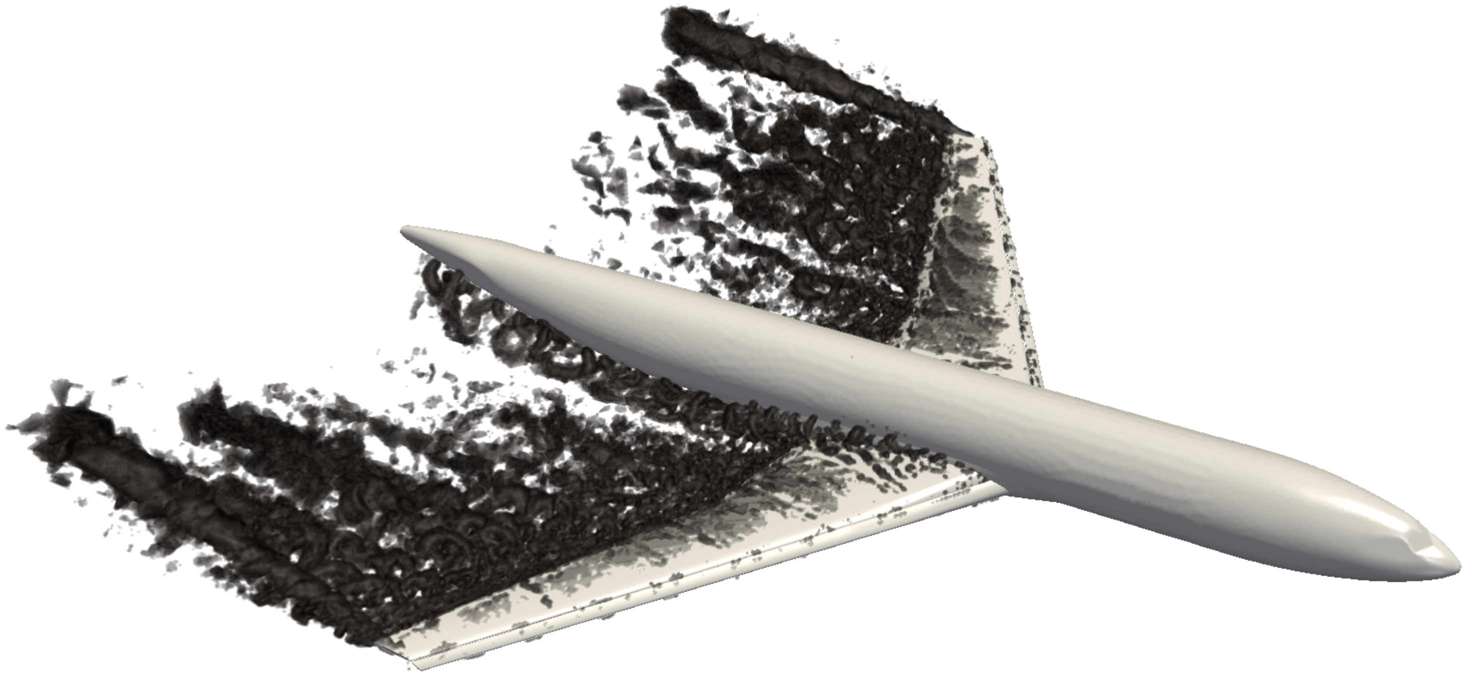
SLIP: NO BOUNDARY LAYER:
NOTHING FROM BOUNDARY LAYER

- WE DO NOT SPEAK ABOUT BOUNDARY LAYER
- NATURE OF BOUNDARY LAYER IRRELEVANT
- EFFECT OF BOUNDARY LAYER IRRELEVANT
- WE DO NOT SPEAK ABOUT QUANTUM MECH…

TURBULENT SOL OF NS/SLIP =

POTENTIAL FLOW MODIFIED BY

3D ROTATIONAL SLIP SEPARATION



BLUFF BODY FLOW:
90% OF FLUID MECHANICS:
FORCES ON BODY

EXTERIOR FLOW:

- AIRPLANE, CAR, BOAT…

INTERIOR FLOW:

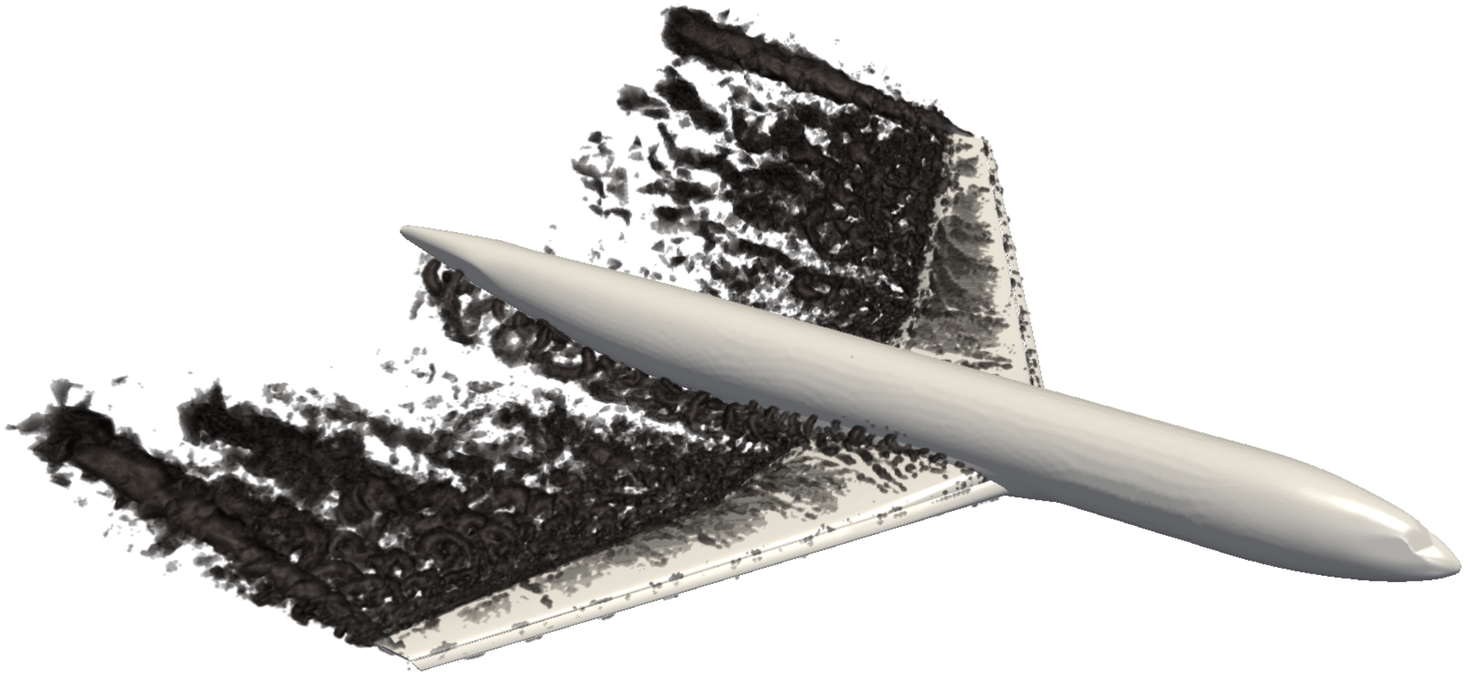
- ENGINE, HEART…

FORCES ON BODY

TURBULENT SOL OF NS/SLIP =

POTENTIAL FLOW MODIFIED BY

3D ROTATIONAL SLIP SEPARATION



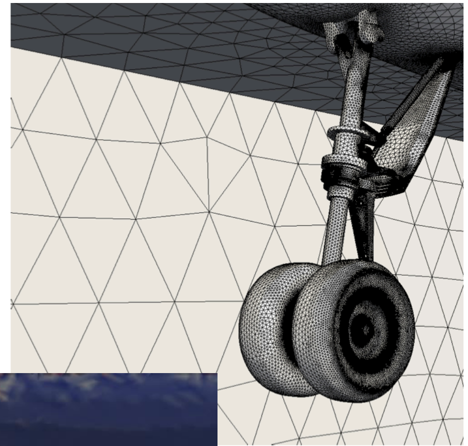
SECRET OF FLIGHT

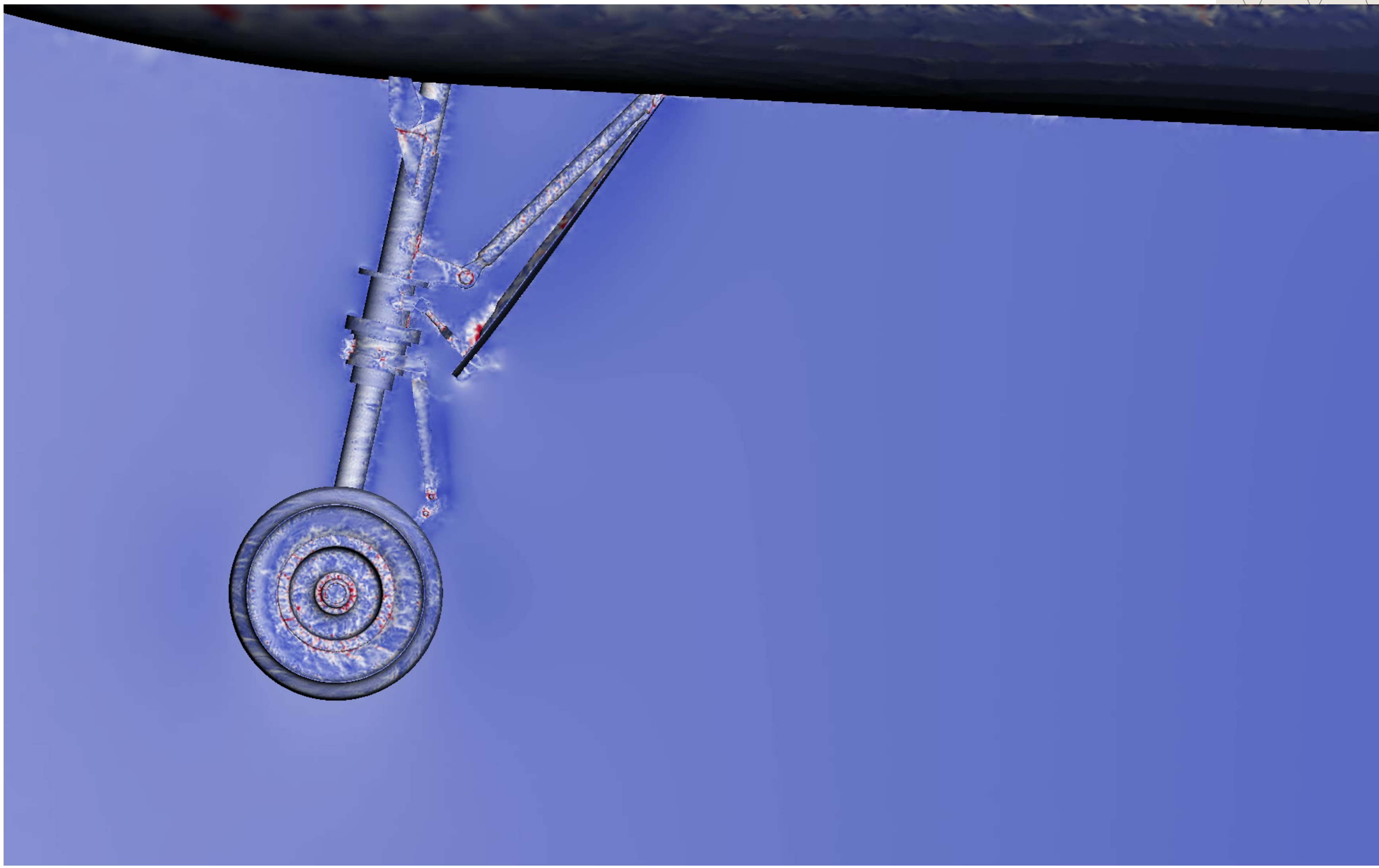
- NEW THEORY OF FLIGHT
  JMFM 2013 ??

- OLD THEORY OF FLIGHT
  WRONG

BANC-II 2012

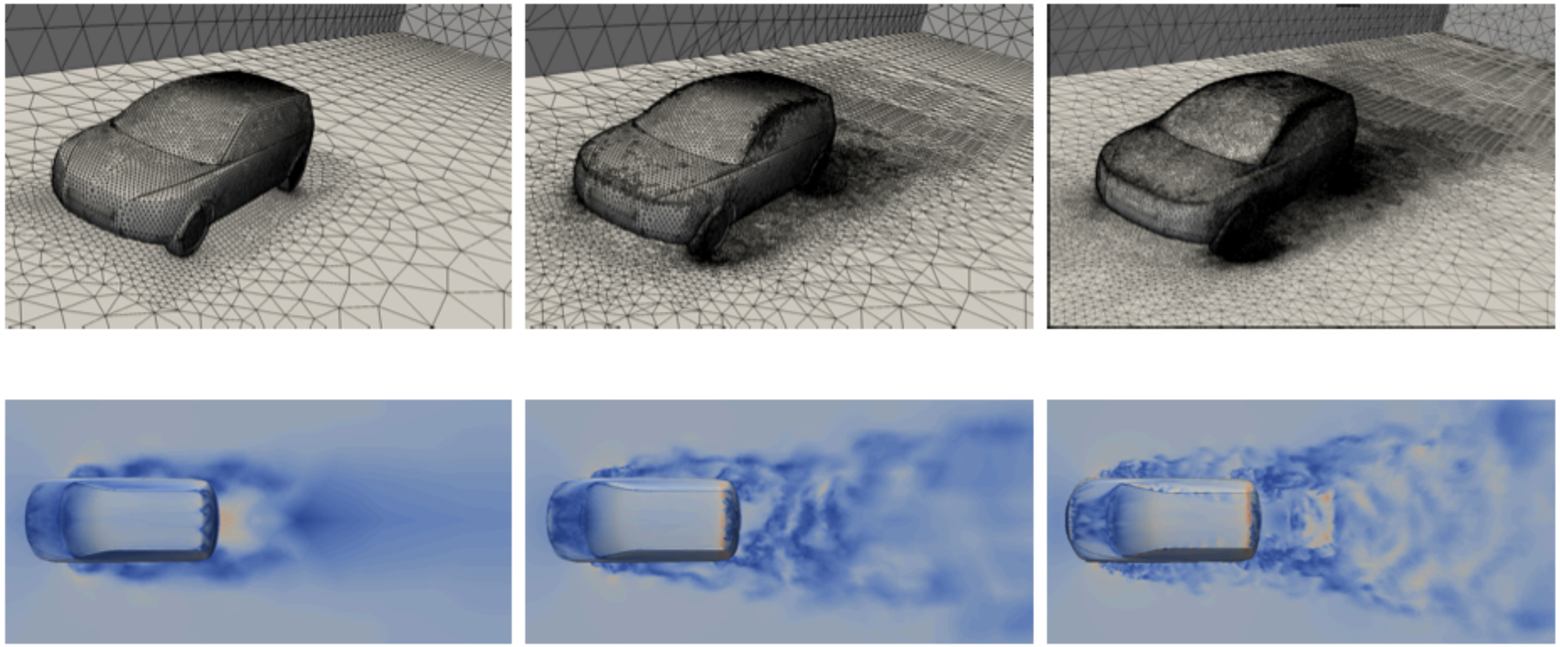
[Vilela De Abreu/Jansson/JH BANC-II, AIAA conference 2012





Refinement wrt acoustic sources

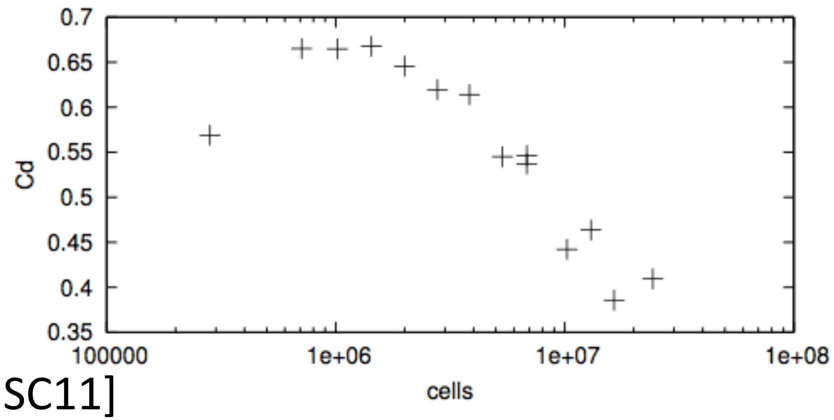
Full Car model (VRAK)



[Geometric model from of Volvo Cars]

Aerodynamic drag

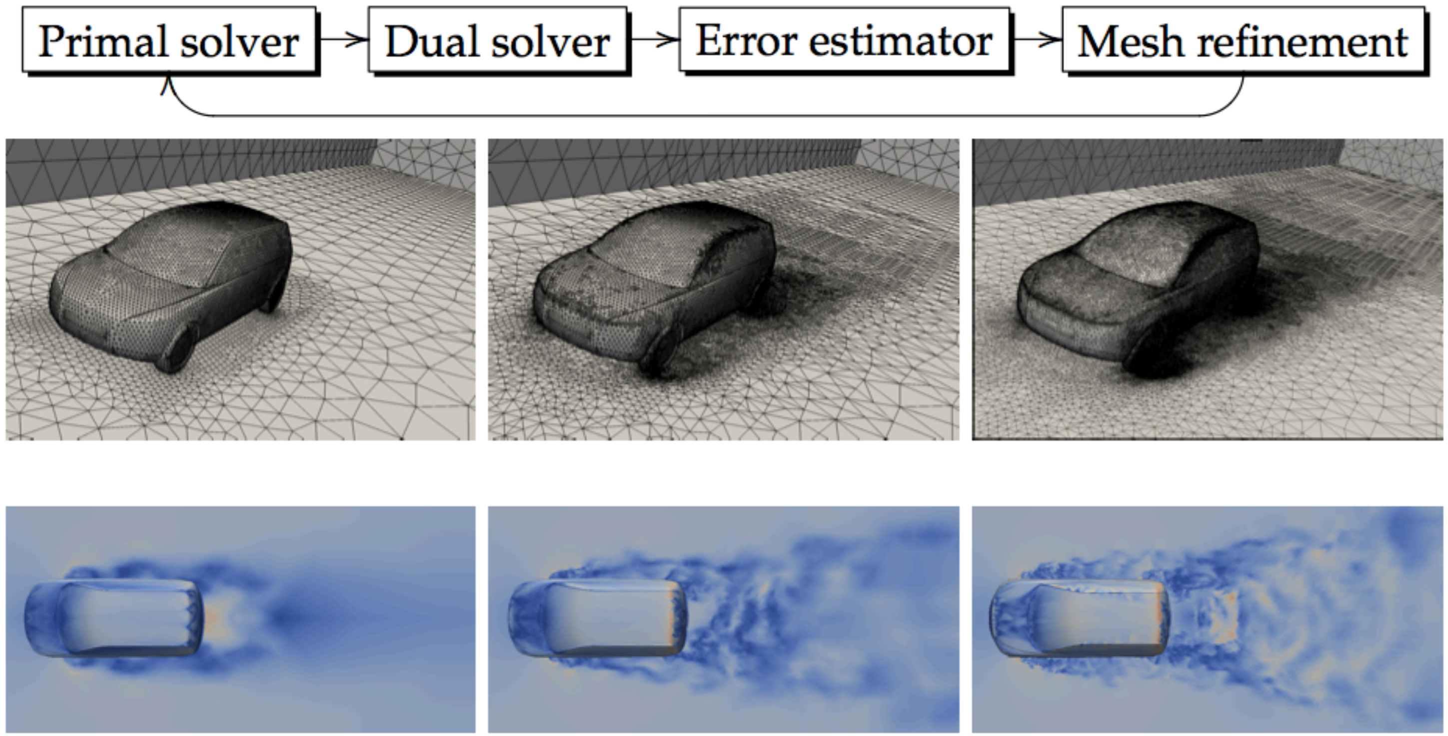
- Refine w.r.t error in drag
- Reference value $C_D = 0.359$



[N.Jansson/J.Hoffman/M.Nazarov Supercomputing SC11]

G2 Adaptive FEM Implicit LES

- A posteriori error estimate: $|M(u) - M(U)| \leq \sum_K E_K$ (cells K)
- Error indicator $E_K = S_K \times h_K|R_K|$ (S_K stability weight, R_K residual)
- Output sensitivity of $M(\cdot)$ by adjoint equation: stability weight S_K
- Adjoint equation: $-\partial\phi/\partial t - (u\cdot\nabla)\phi + \nabla U^T\phi + \nabla\theta = \psi$, $\nabla\cdot\phi = 0$

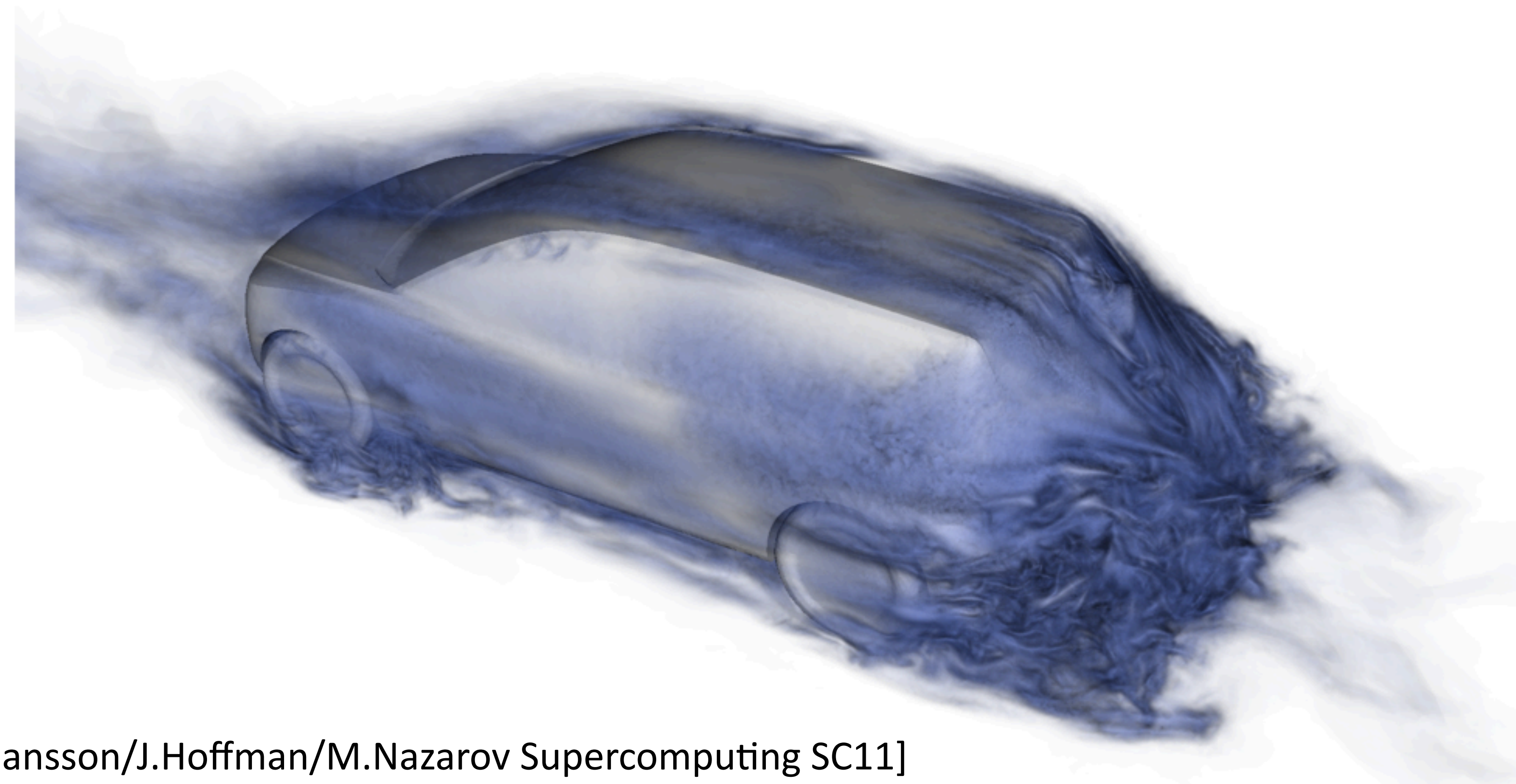


FLOW AROUND A VOLVO

Full Car model (VRAK)

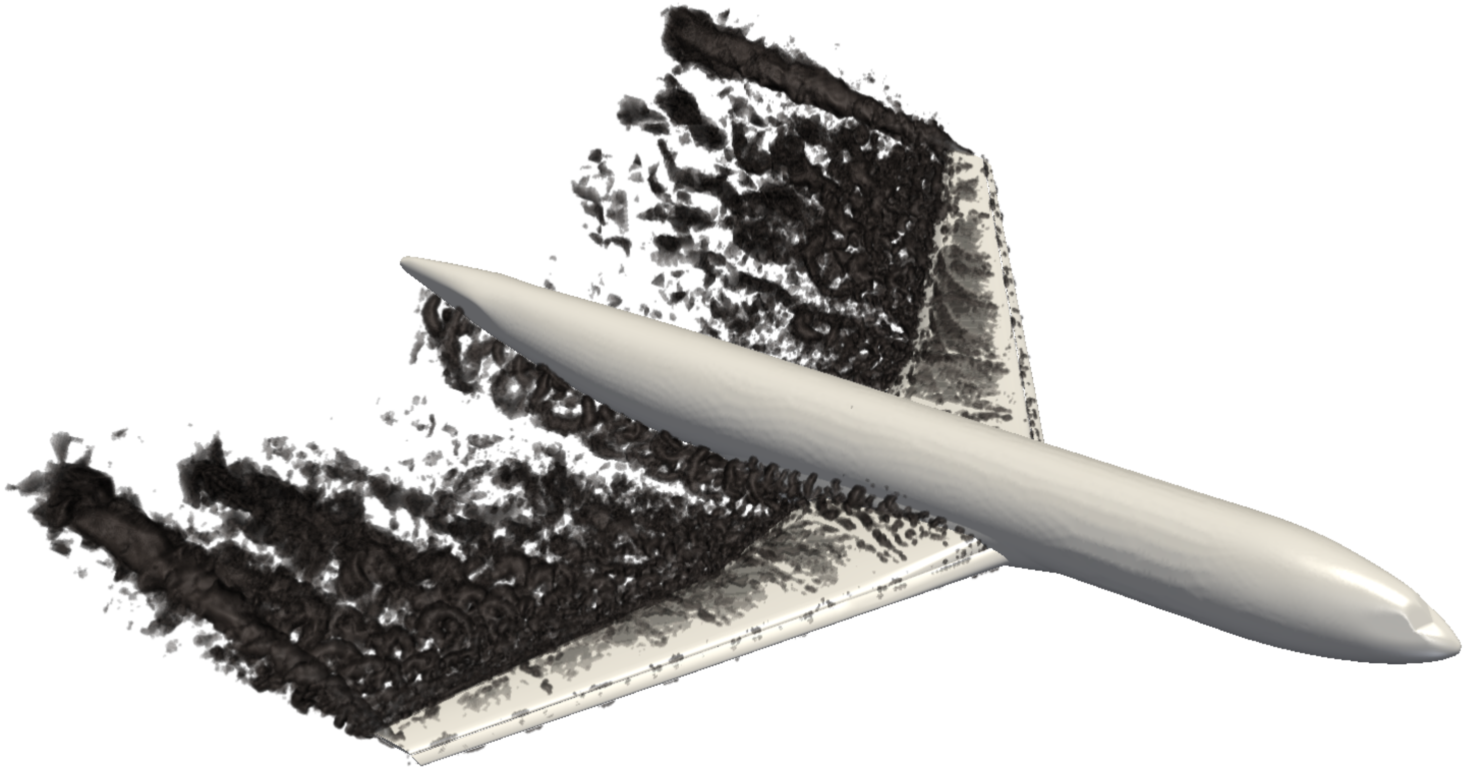
Dual solution

The solution charaterize sensitivty in the output (drag)



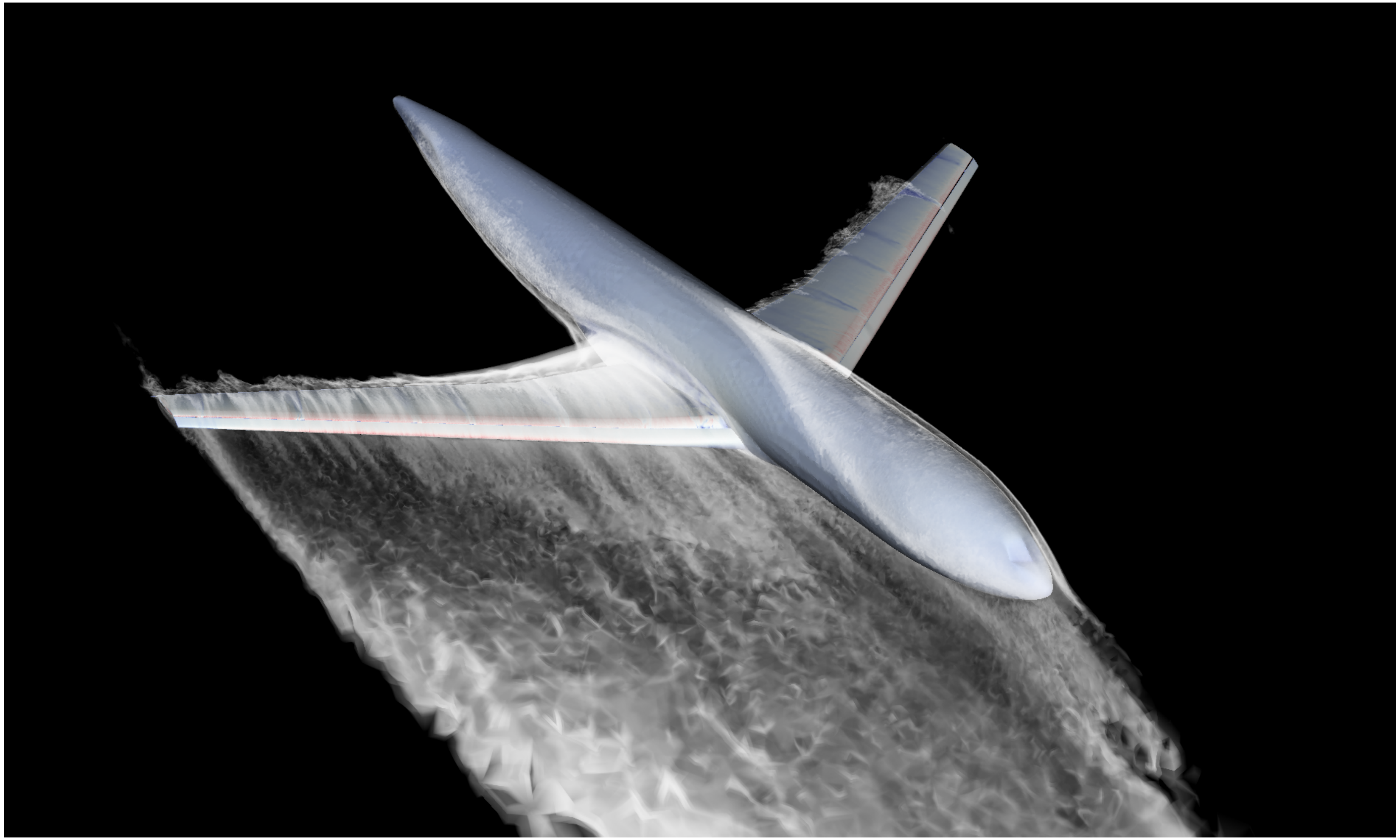
[N.Jansson/J.Hoffman/M.Nazarov Supercomputing SC11]

HiLiftPW-2 (2013) - preliminary results
aoa=12; Lambda 2 visualization in box



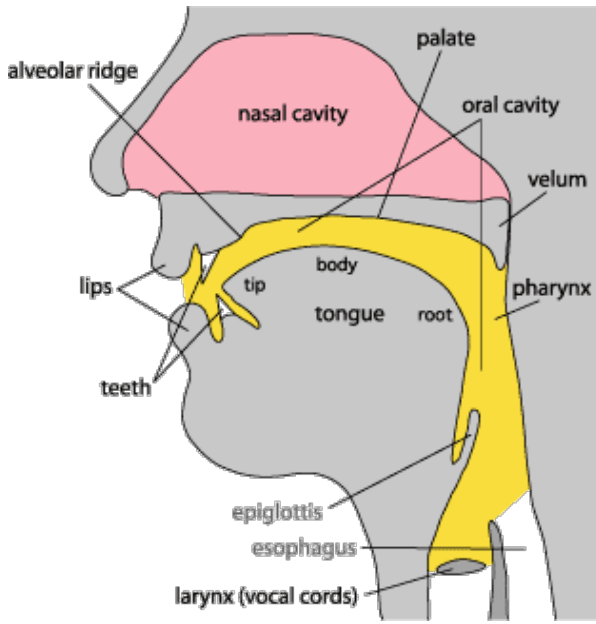
Adaptive mesh refinement with respect to drag/lift for right half plane

Adjoint solution

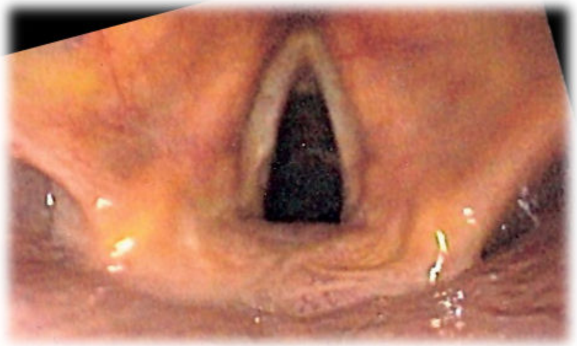


Simulation of the human voice

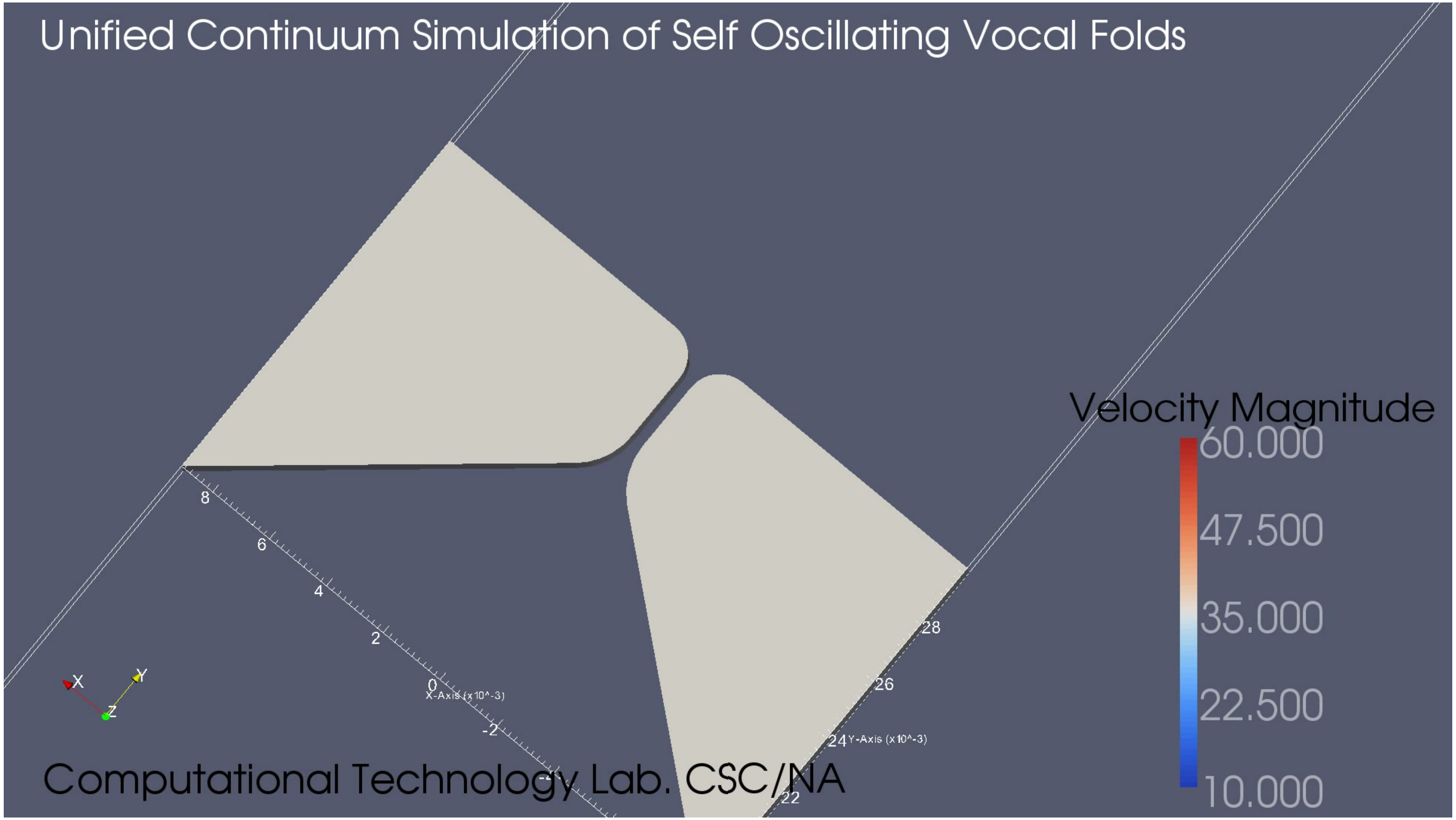
- FSI model of flow through vocal folds
- Contact model as part of UC-FSI
- Next: acoustic propagation through vocal tract, with neural control



- KTH, Grenoble (CNRS-GIPSA), Erlangen (FAU), Barcelona (CIMNE, La Salle),
- KTH: S.Ternström, J.Hoffman, J.Jansson, O.Engwall, Ö.Ekeberg

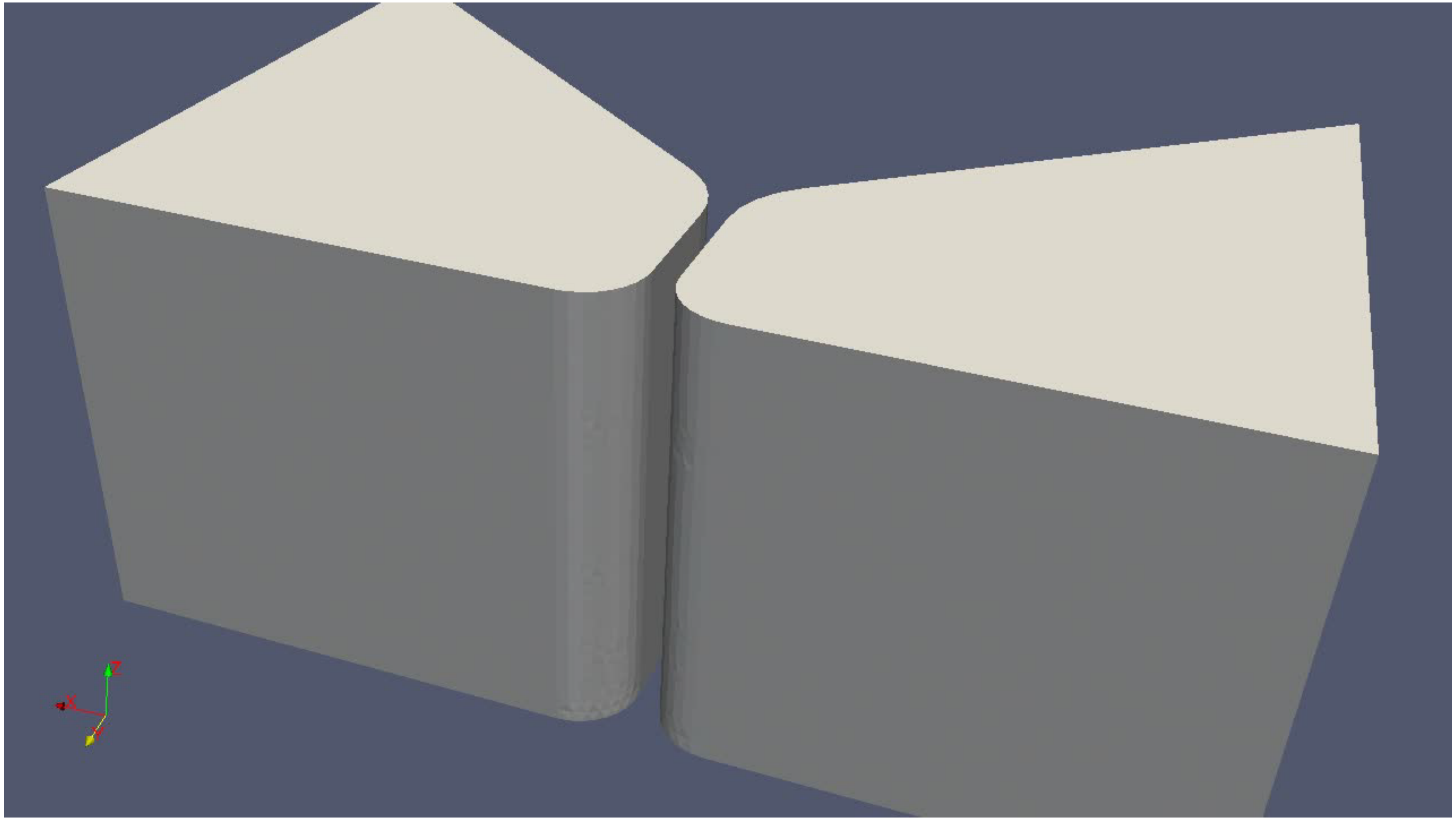


FSI: Self-oscillation with contact



[C.Degirmenci/J.Jansson/JH]

FSI: Self-oscillation with contact



[C.Degirmenci/J.Jansson/JH]

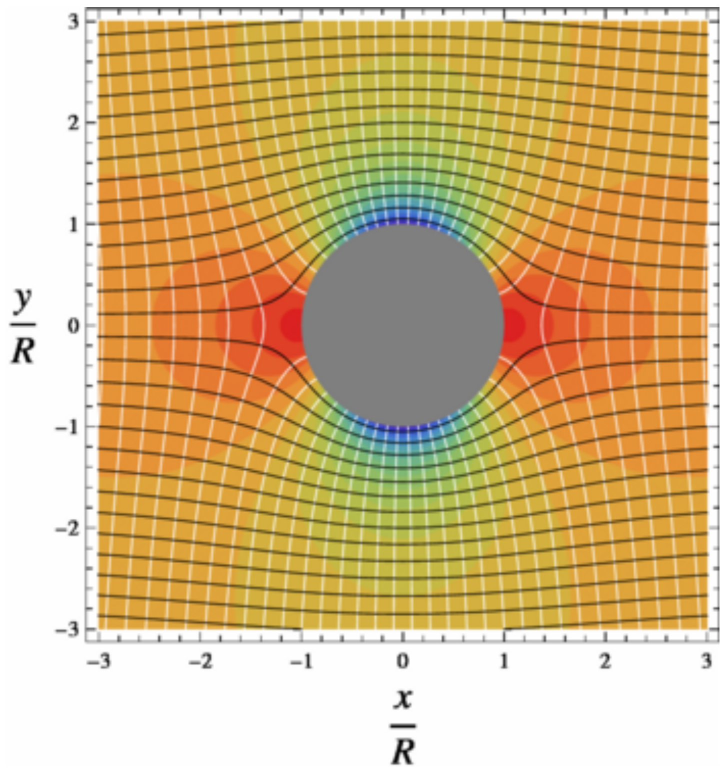
BLUFF BODY FLOW

= POTENTIAL FLOW

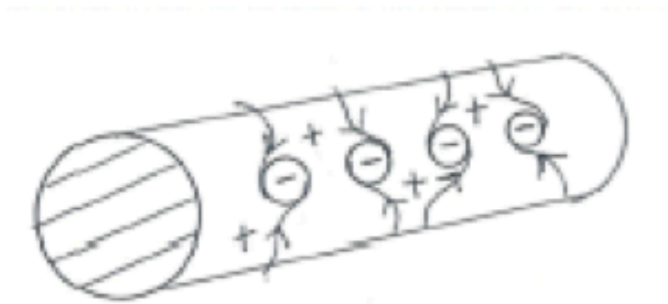
+ 3D ROTATIONAL SLIP SEPARATION

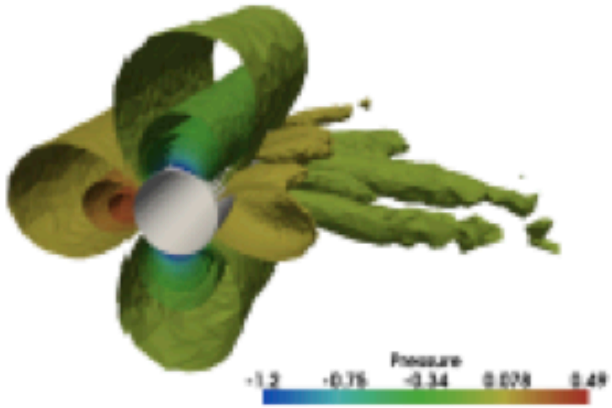
- COMPUTABLE
- UNDERSTANDABLE

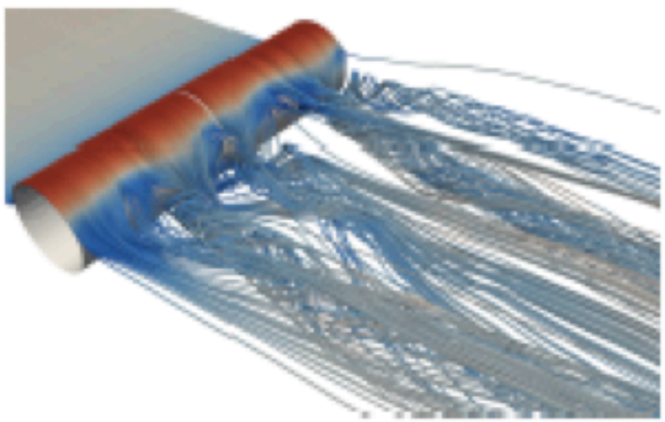
POTENTIAL FLOW:
SOLUTIONS OF LAPLACE'S EQUATION:
HIGH PRESSURE AT SEPARATION:
ZERO DRAG

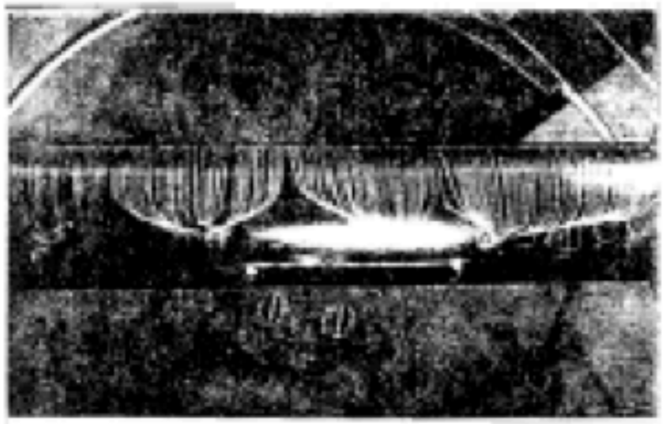


REAL FLOW: 3D ROT SEP:
NO HIGH PRESSURE AT SEP: DRAG



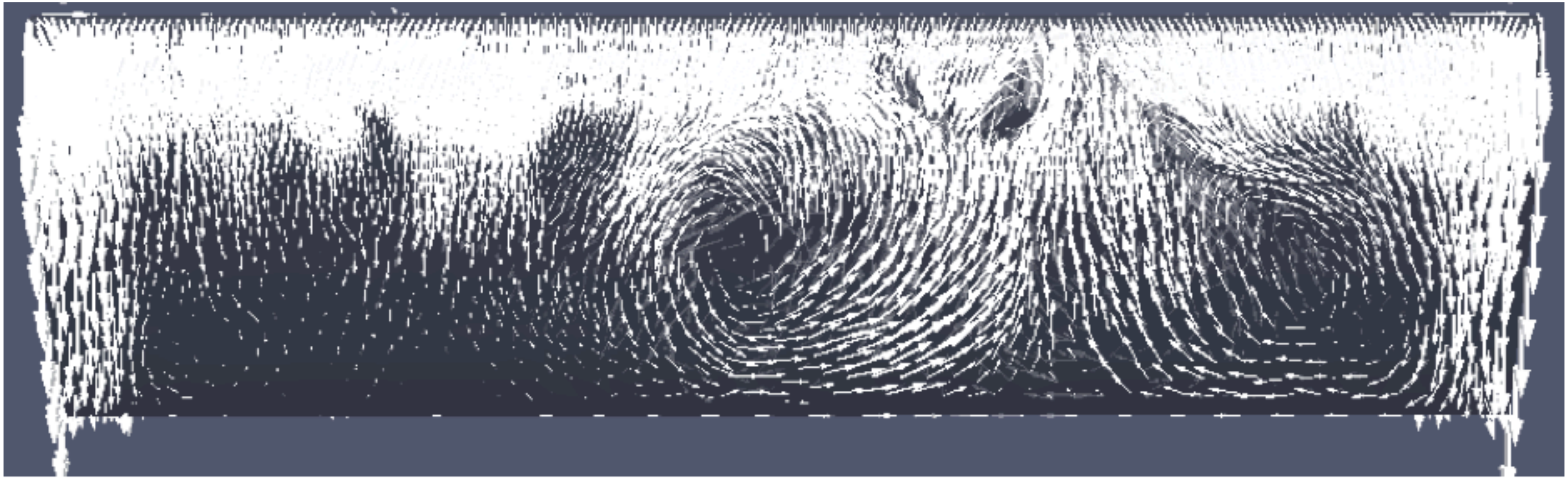


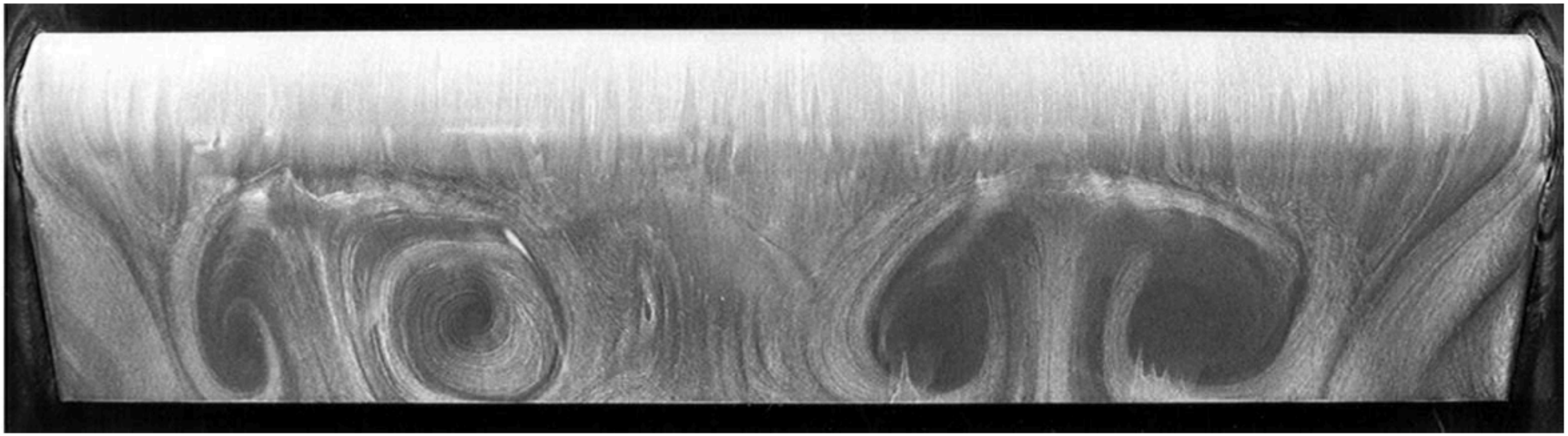




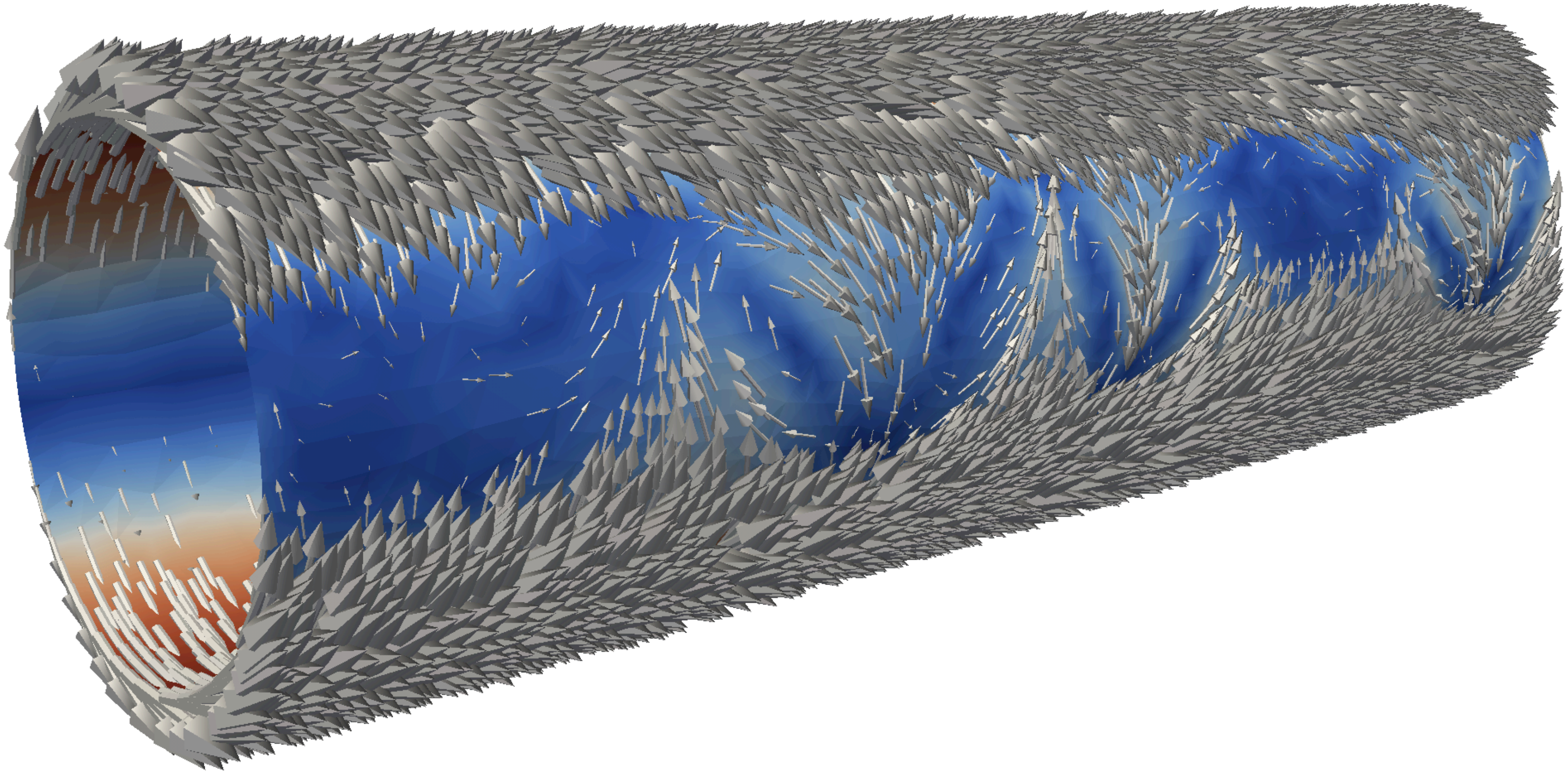
Stall: computation vs experiment

[K.Hedlund, 2010]

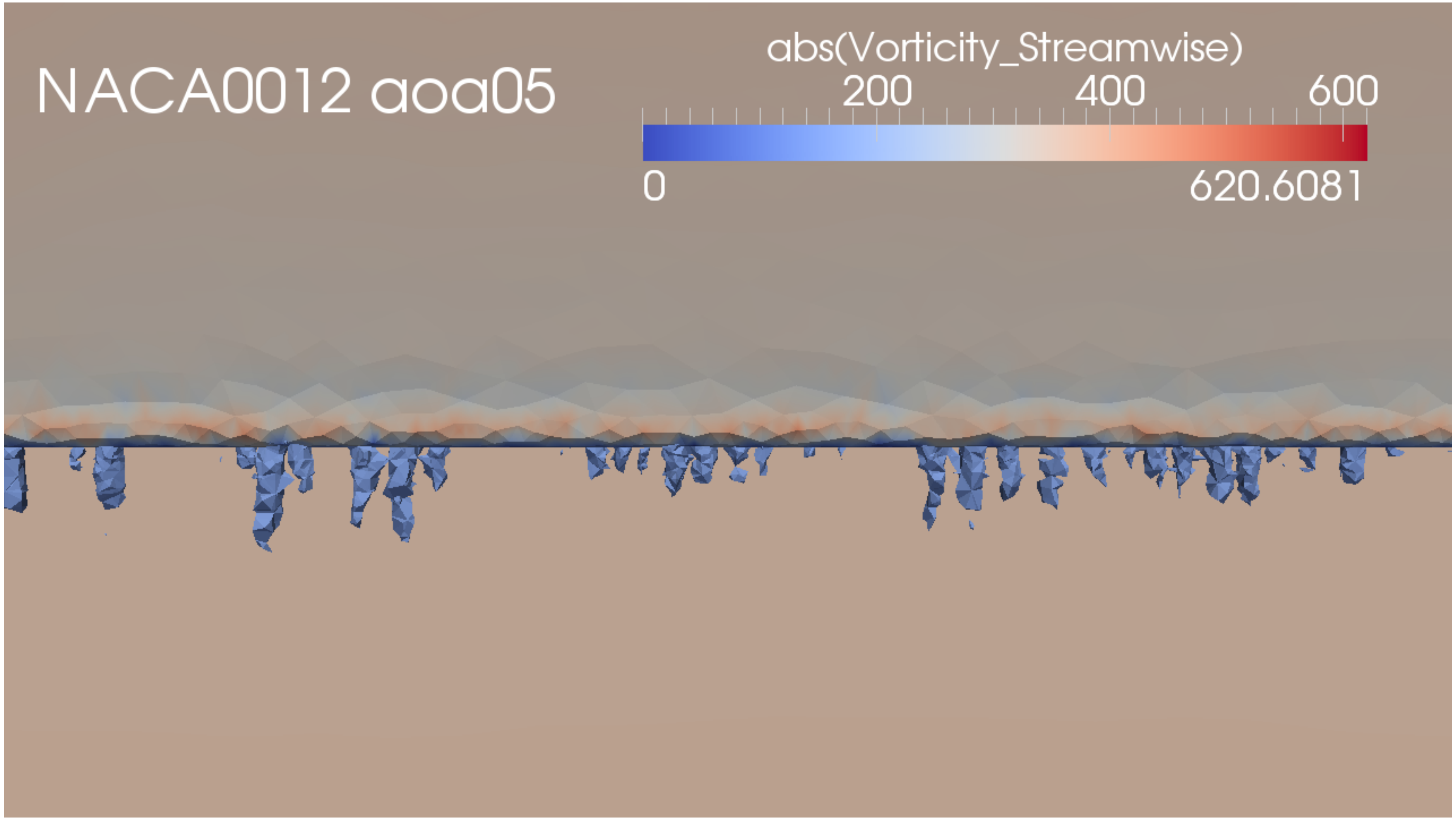




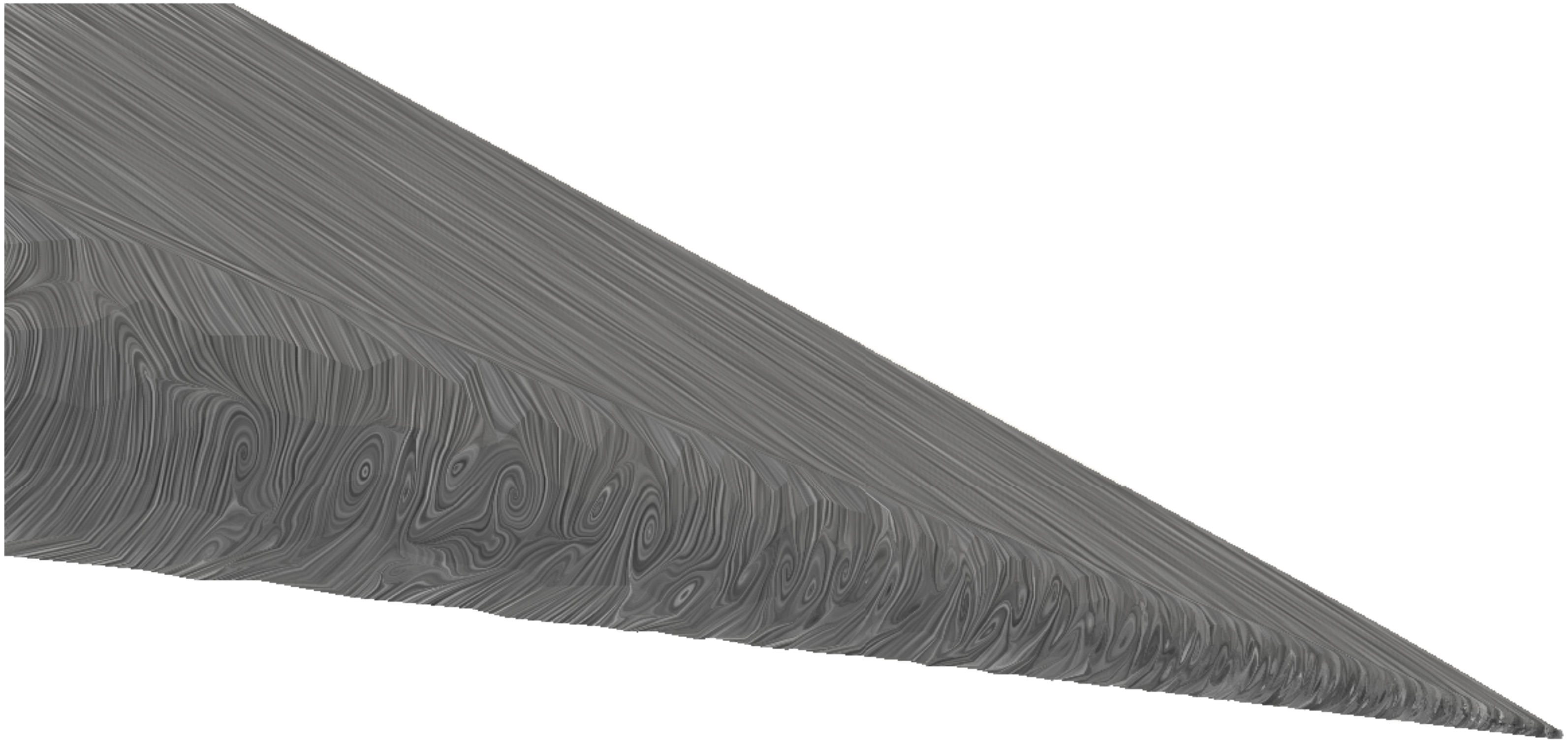
OPPOSING FLOW: RETARDATION



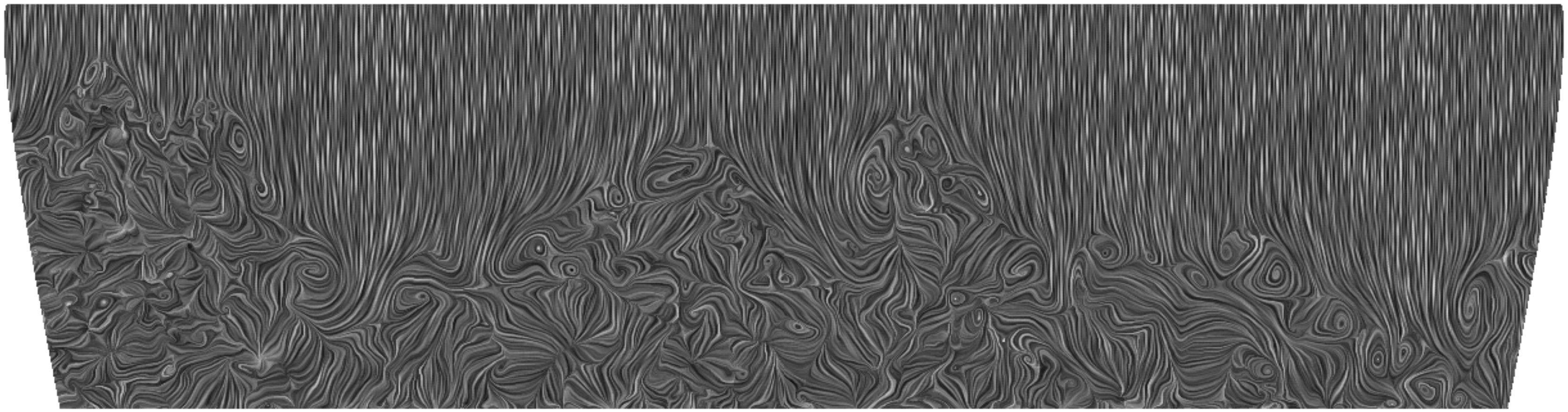
TRAILING EDGE STREAMWISE VORTICITY



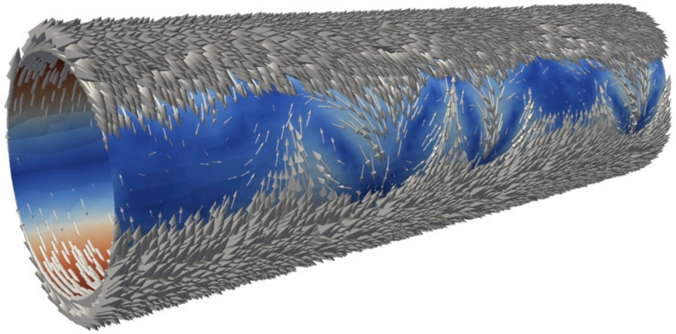
OILFILM FLOW: TRAILING EDGE
AOA = 4



OILFILM FLOW AOA = 17



Linear stability analysis

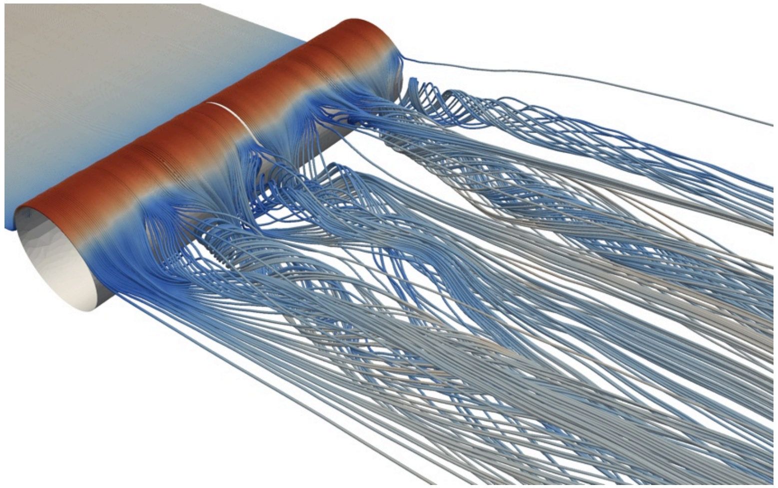


- Linearized equations:

$\partial\phi/\partial t + (u\cdot\nabla)\phi + (\phi\cdot\nabla)u + \nabla\theta = 0, \ \ \nabla\cdot\phi=0$

- Vorticity equations:

$\partial\omega/\partial t + (u\cdot\nabla)\omega - (\omega\cdot\nabla)u = 0, \ \ \omega=\nabla\times u$



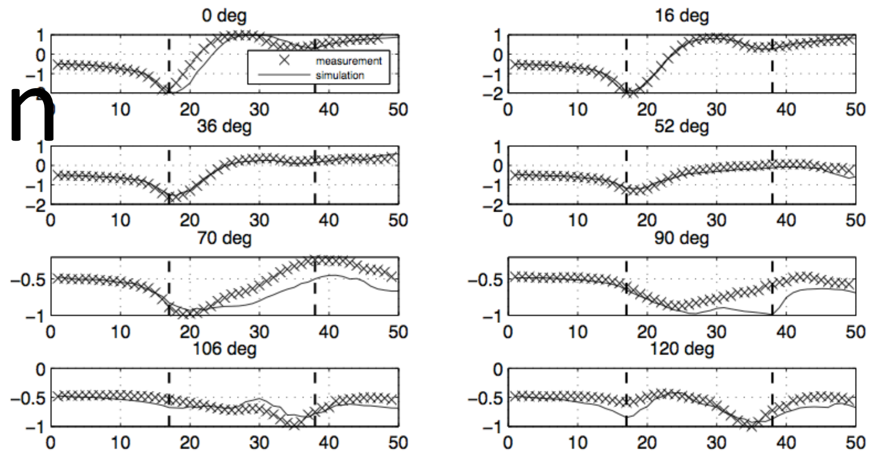
- Key for stability: solution gradient ∇u
- At separation: ∇u = [2 0 0; 0 -2 0; 0 0 0]

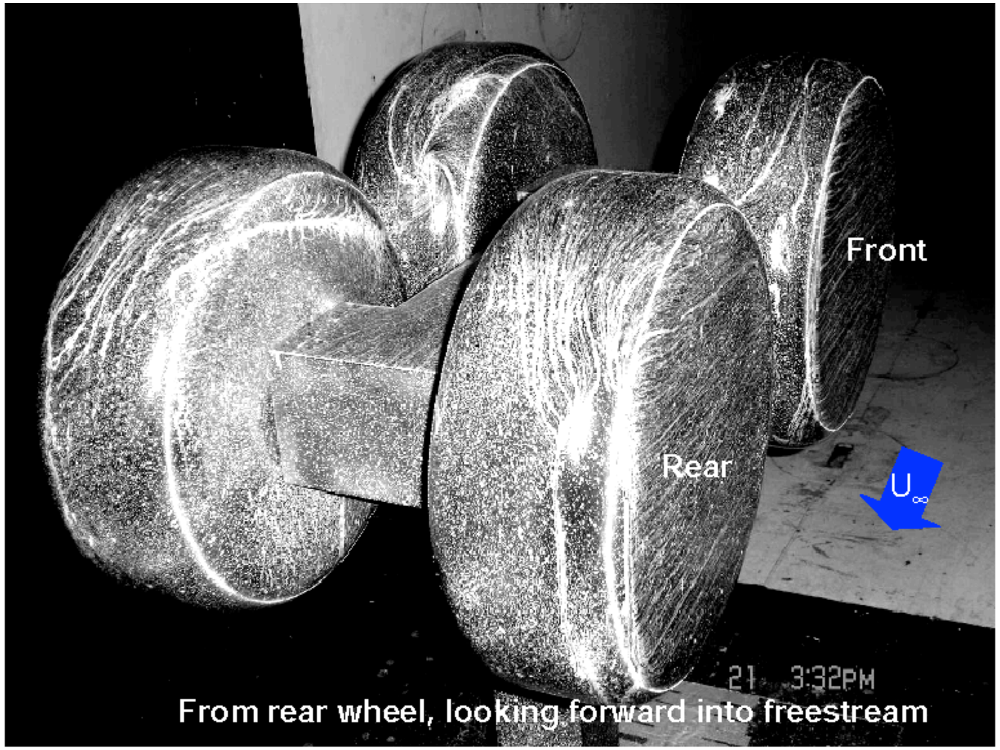
Potential solution is exponentially unstable at separation:

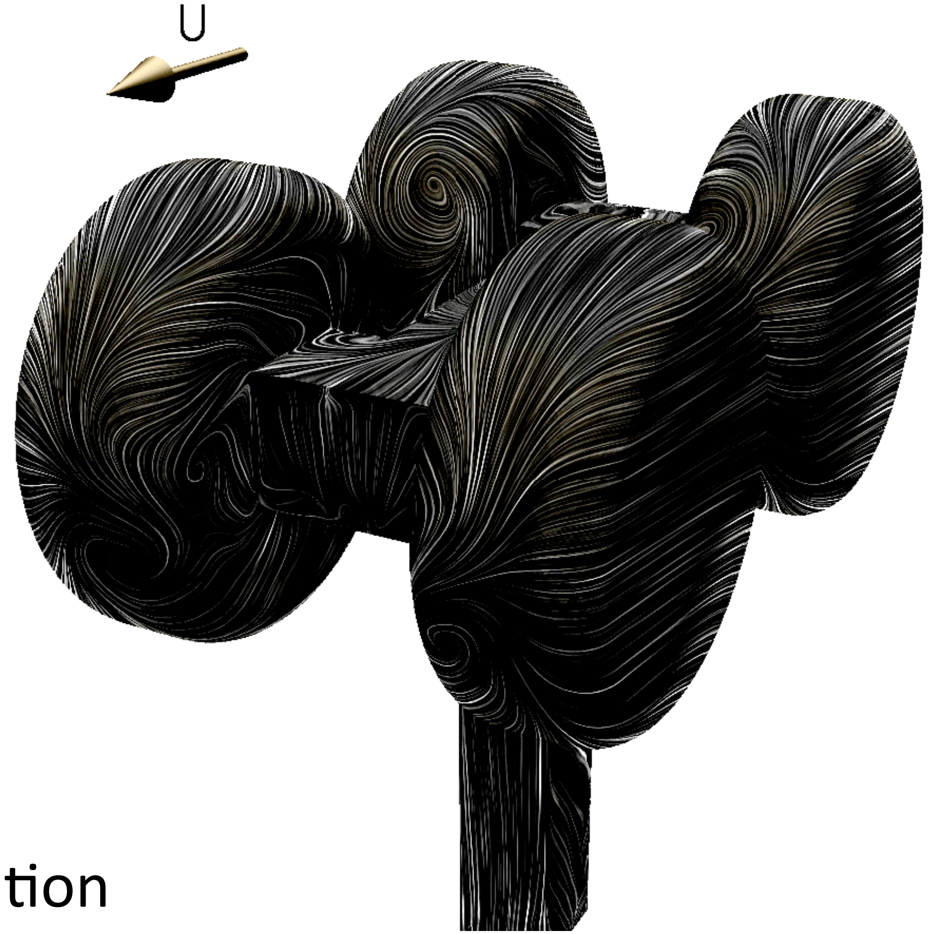
1. $\partial\phi_2/\partial t + (u\cdot\nabla)\phi_2 + \partial\iota/\partial_2 = 2\phi_2$ (exponential growth of ϕ_2)
2. $\partial\omega_1/\partial t + (u\cdot\nabla)\omega_1 = 2\omega_1$ (exponential growth of ω_1)

[J.Hoffman/C.Johnson, Springer 07, BIT 08, JMFM 08]

Experiment/Simulation
- surface pressures
- oil film visualization





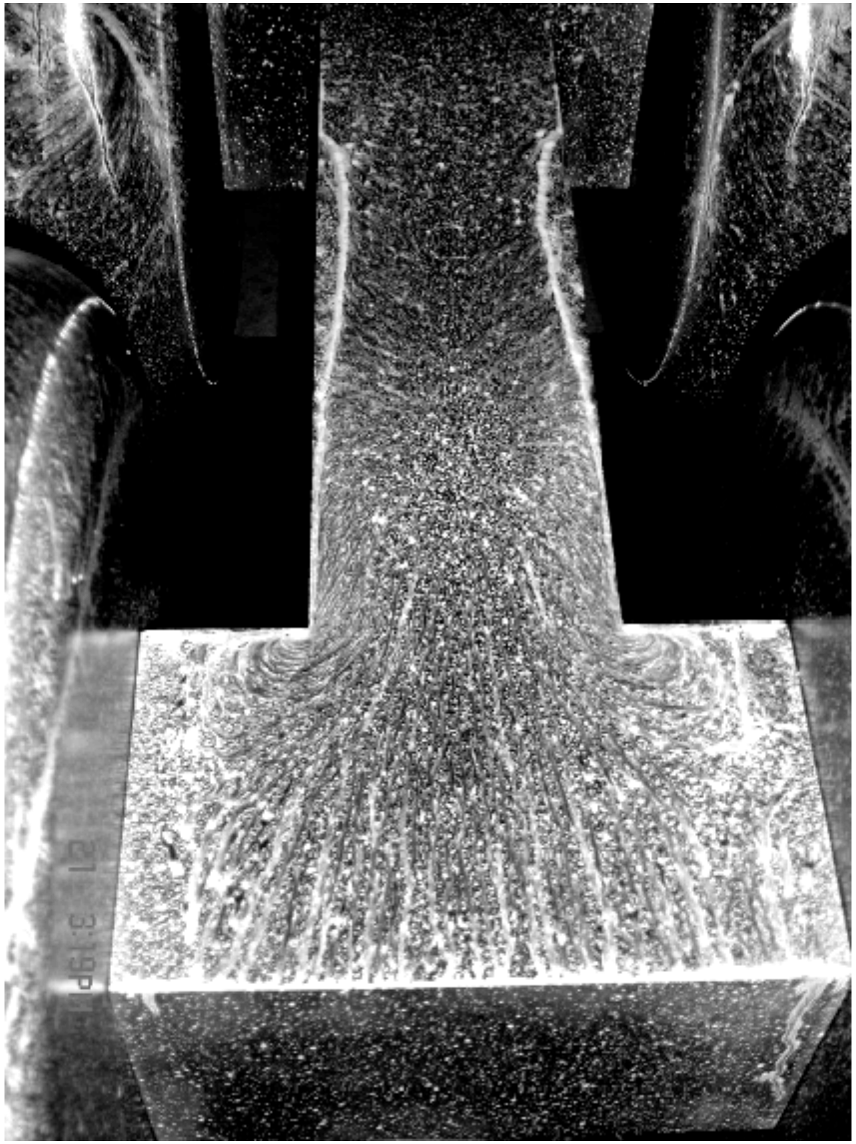


Surface flow separation patterns

No boundary layer - inviscid separation

3D ROTATIONAL SLIP SEPARATION

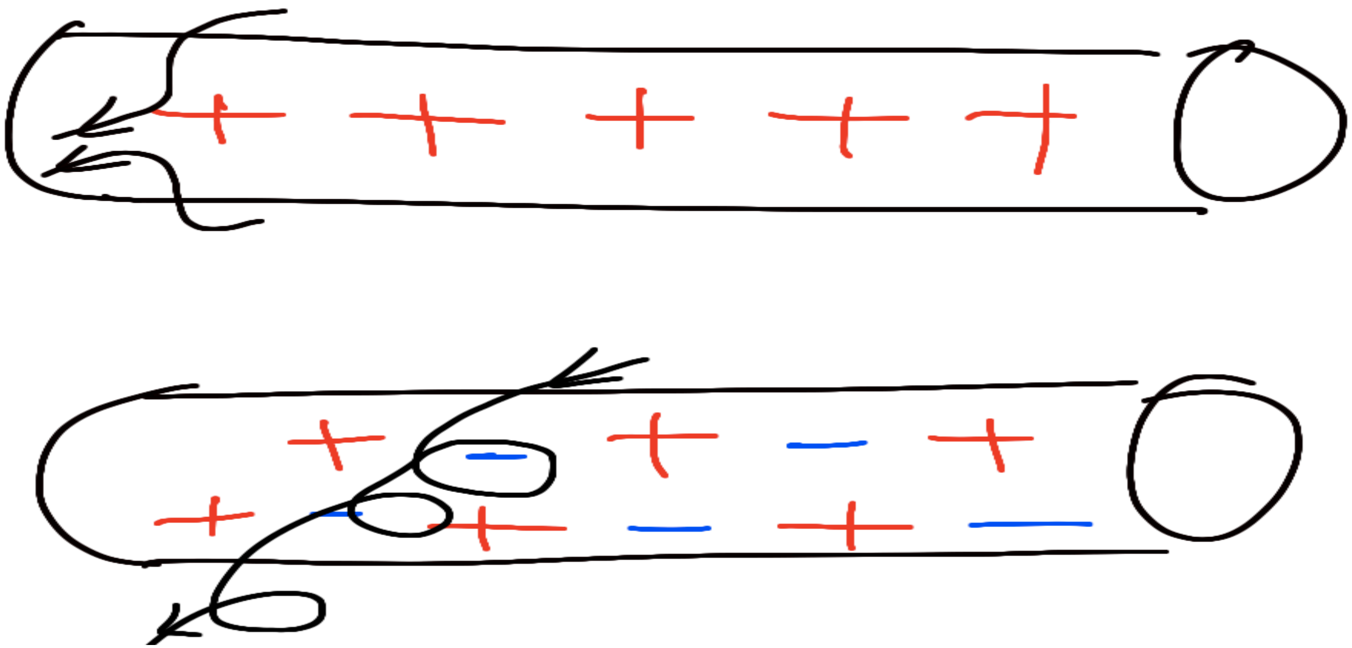
Experiment vs Simulation oil film visualization



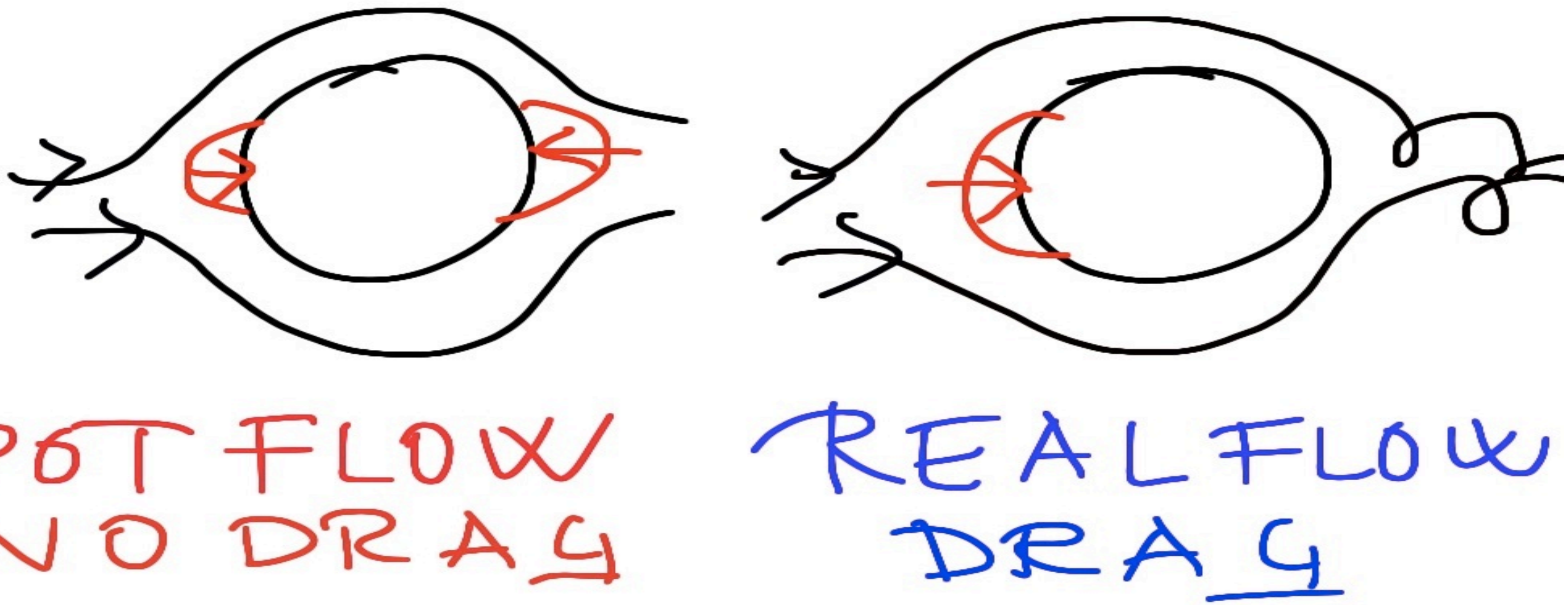
3D ROTATIONAL SLIP SEPARATION:

- COMPUTABLE
- UNDERSTANDABLE

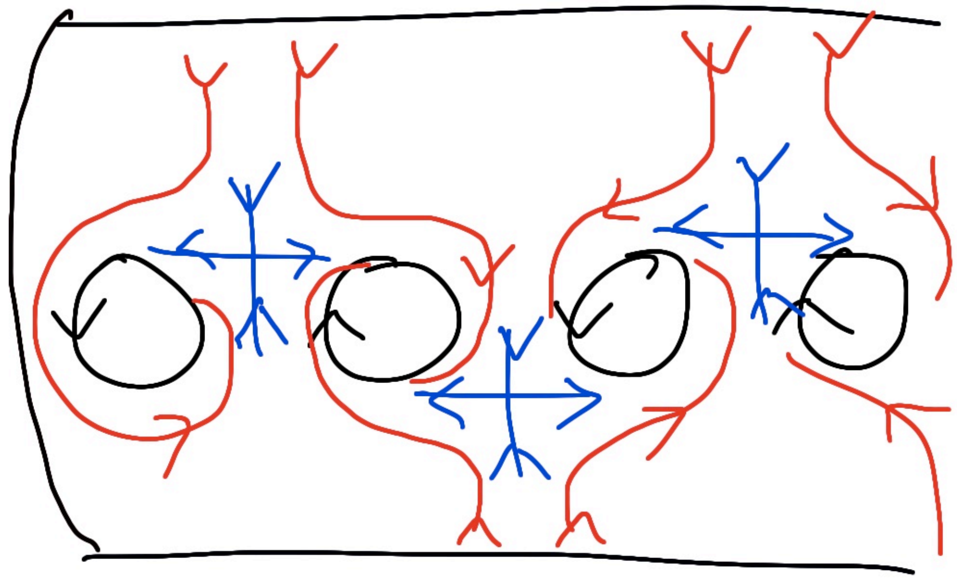
UNSTABLE HIGH PRESSURE REPLACED BY STABLE OSCILLATING PRESSURE PRESSURE ENERGY INTO KINETIC ROTATIONAL ENERGY BY BERNOULLI



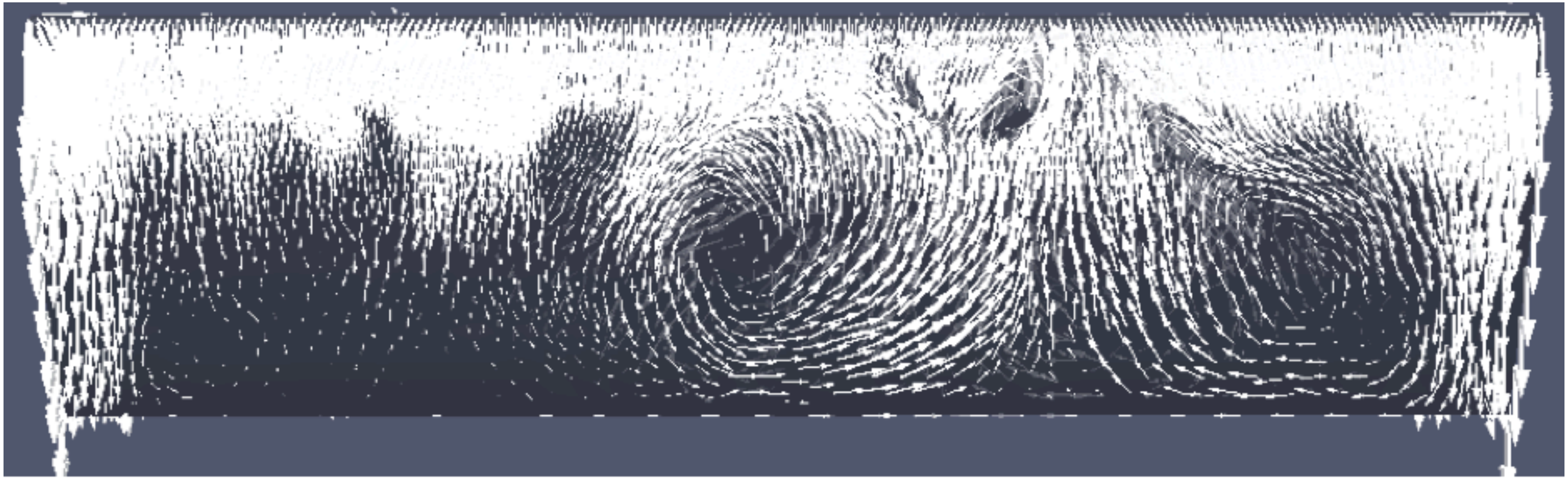
D'ALEMBERT'S PARADOX: ROTATIONAL SLIP SEPARATION WITHOUT PRESSURE RISE GIVES DRAG

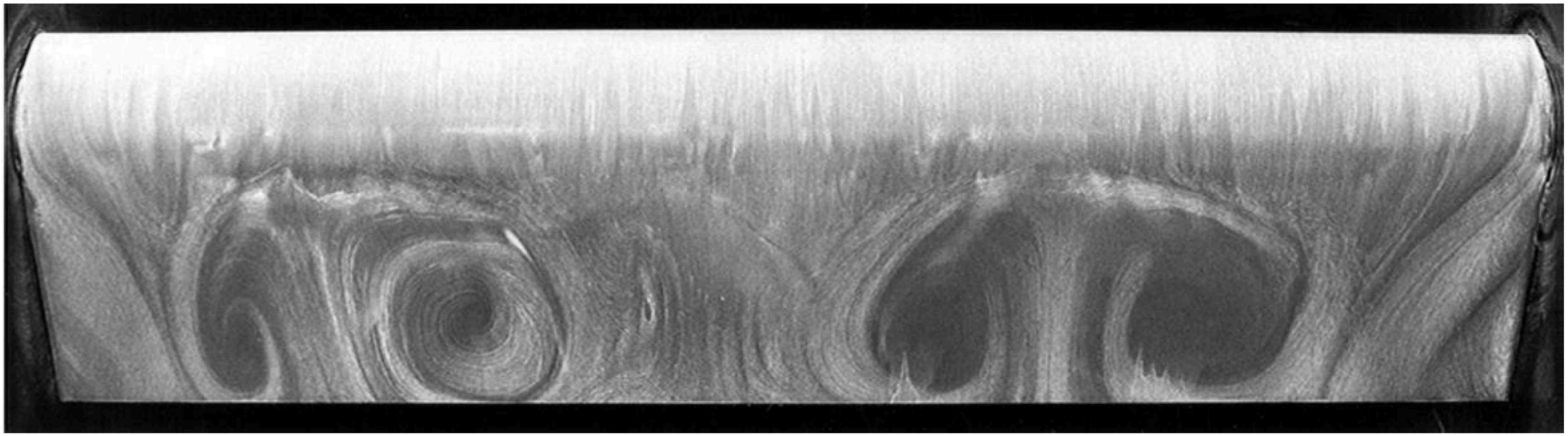


POT FLOW SEP REPLACED BY
3D ROTATIONAL SLIP SEPARATION



ROTATIONAL 3D SEPARATION





3D ROTATIONAL SLIP SEPARATION
= ELEGANT SEPARATION

- LARGE SCALE STRUCTURE: COMPUTABLE
- MINIMIZE OPPOSING FLOW INSTABILITY
- ELIMINATE HIGH PRESSURE SEPARATION

- KUTTA CONDITION AT TRAILING EDGE
- SMOOTH ELEGANT SEPARATION
- SECRET OF FLIGHT = ELEGANT SEPARATION

SLIP: NO BOUNDARY LAYERS TO RESOLVE = COMPUTABLE: 10^6

- SLIP CORRECT:
- BECAUSE SKIN FRICTION SMALL!

- NO-SLIP: BOUNDARY LAYERS TO RESOLVE = UNCOMPUTABLE: 10^16

TURBULENCE COMPUTABLE?

- NO

TURBULENCE UNDERSTANDABLE?

- NO

ASPECTS TURBULENCE COMPUTABLE?

- YES

ASPECTS TURB UNDERSTANDABLE?

- YES

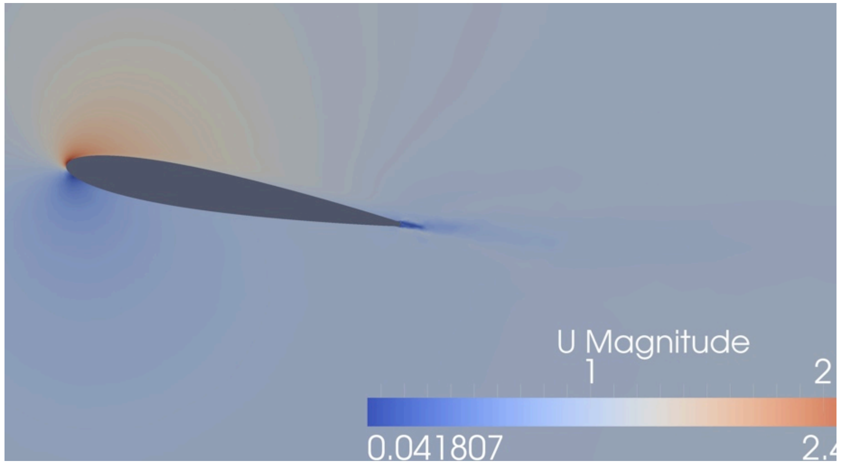
DRAG AND LIFT OF BLUFF BODY COMPUTABLE + UNDERSTANDABLE?

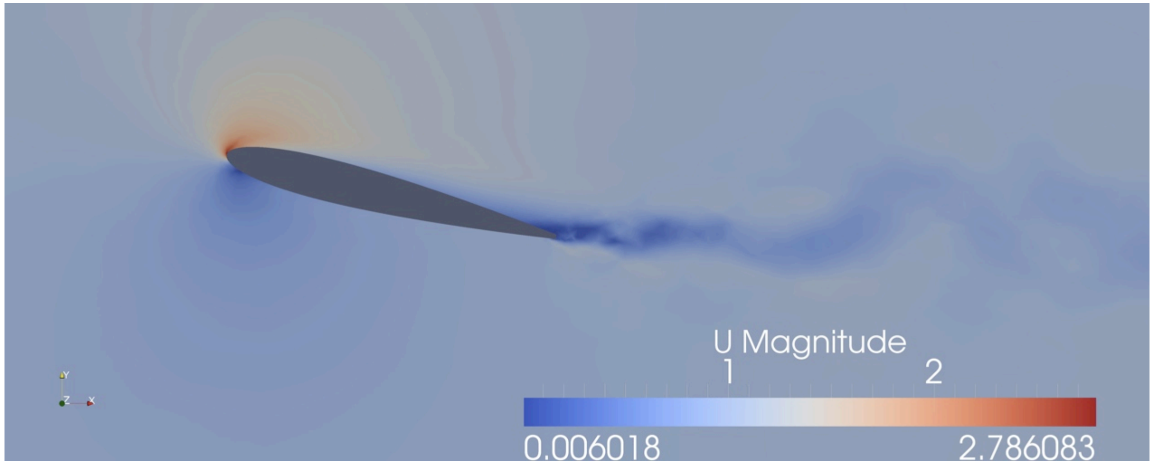
- YES

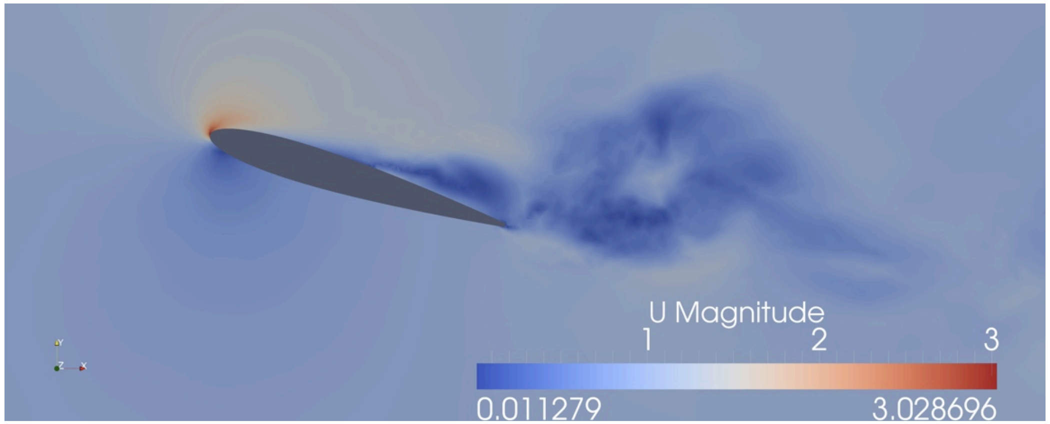
- BECAUSE POTENTIAL FLOW WITH WITH 3D ROTATIONAL SLIP SEPARATION IS

- COMPUTABLE + UNDERSTANDABLE

Naca 0012 : aoa = 10, 14, 17



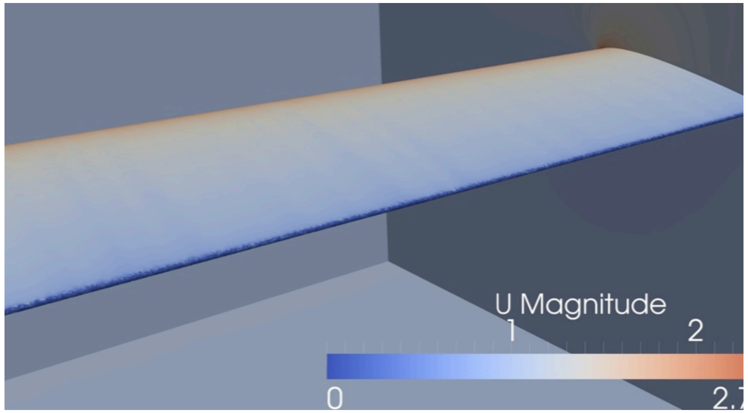


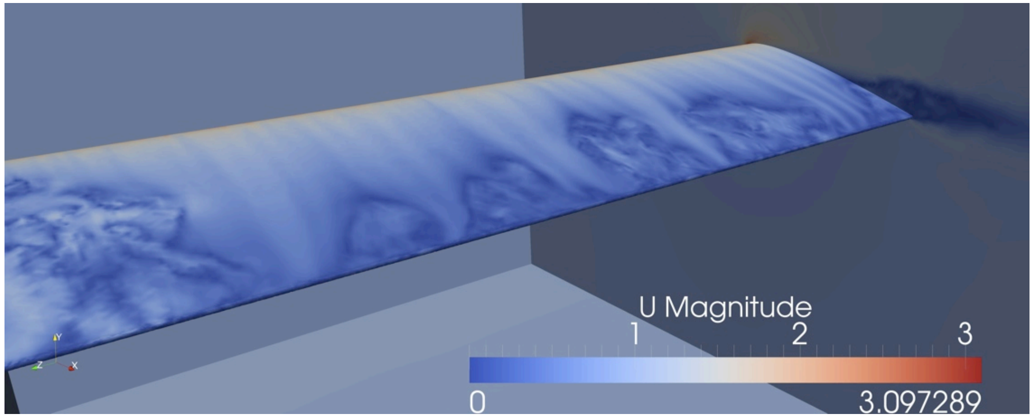


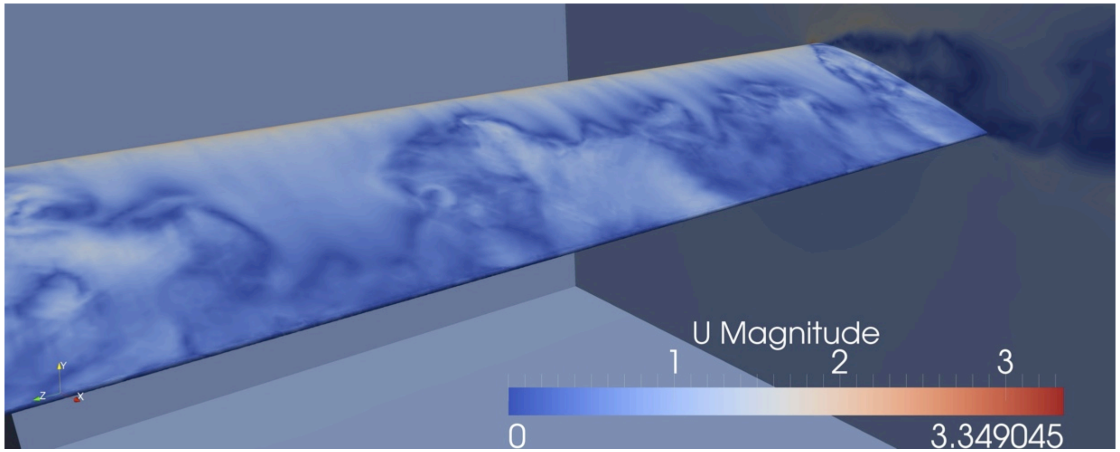
- separation -> stall
- zero wall skin friction
- no boundary layer
- inviscid separation

[J.Jansson/J.Hoffman/N.Jansson, 2011]

Naca 0012 : aoa = 10, 14, 17







- separation -> stall
- zero wall skin friction
- no boundary layer
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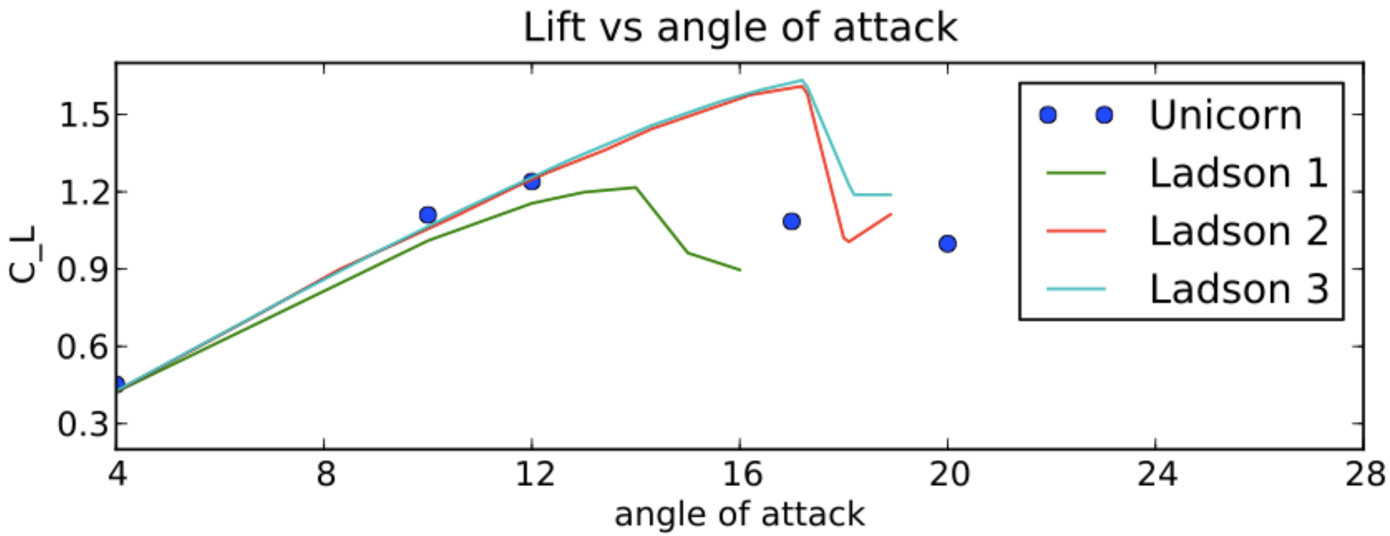
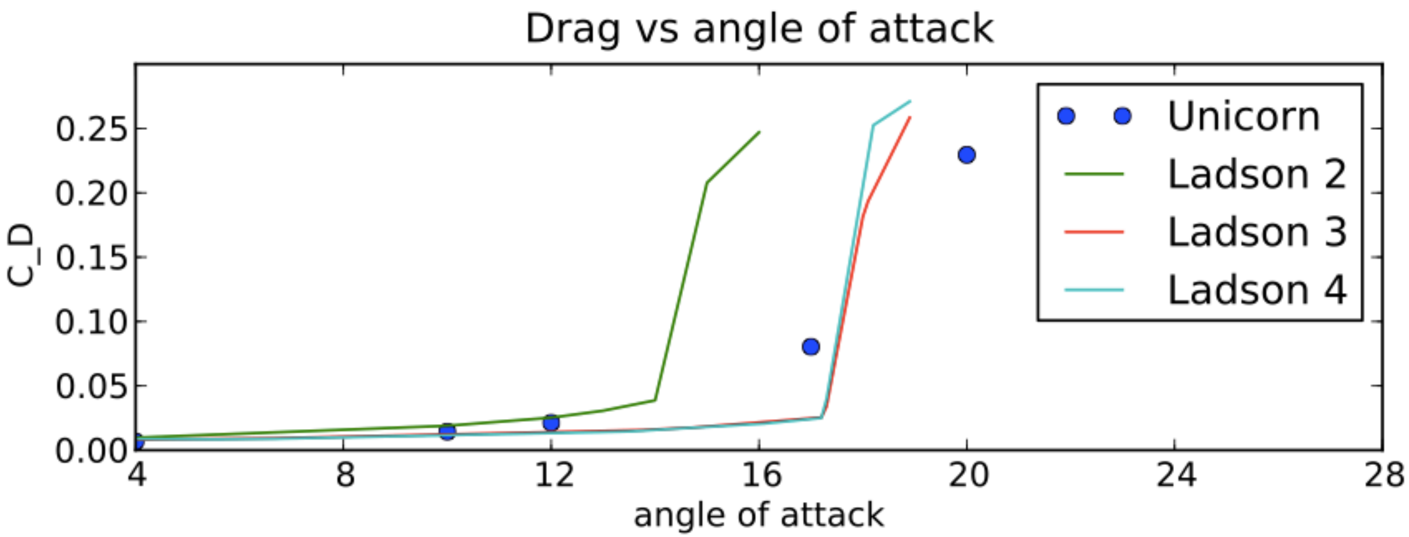
[J.Jansson/J.Hoffman/N.Jansson, 2011]

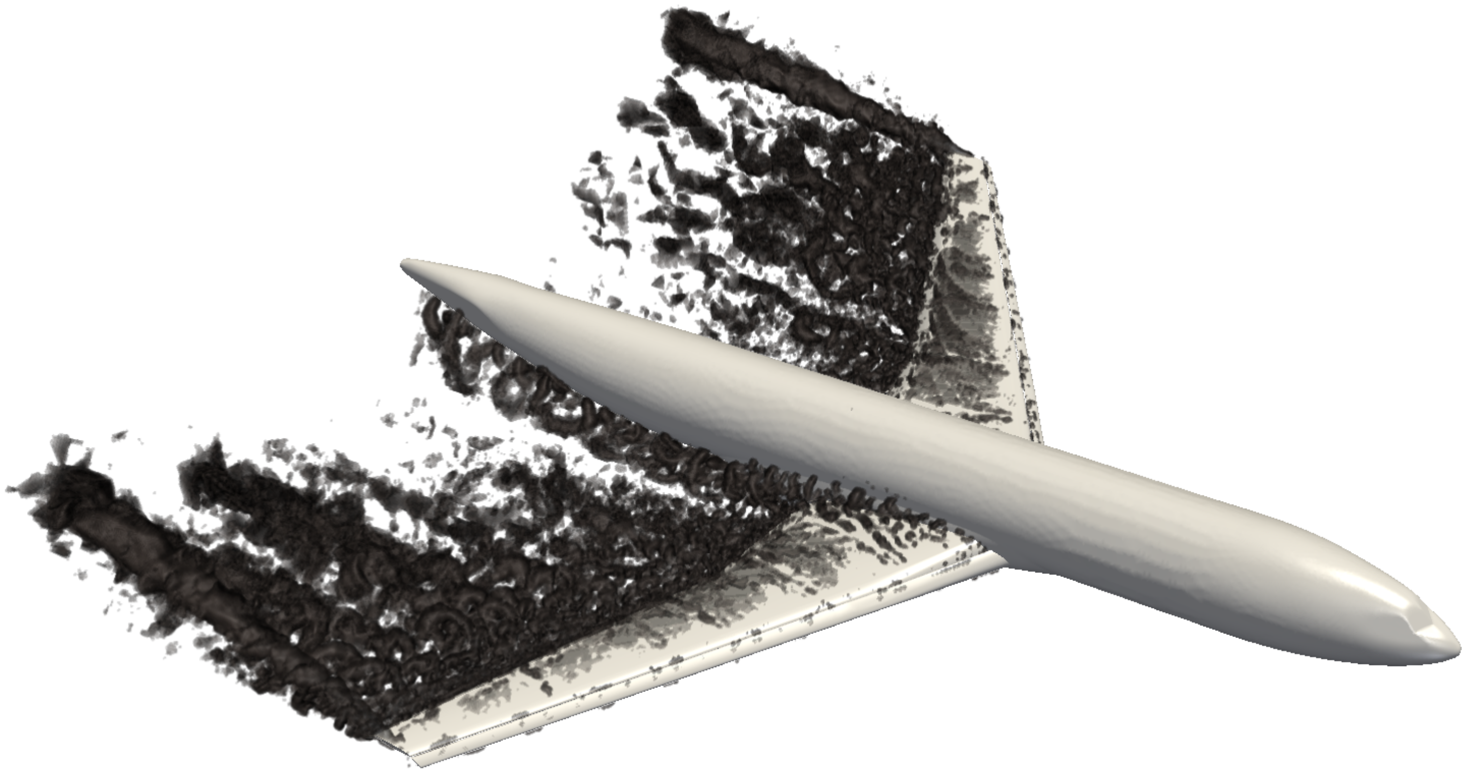
NACA 0012 wing : 0.8M mesh points





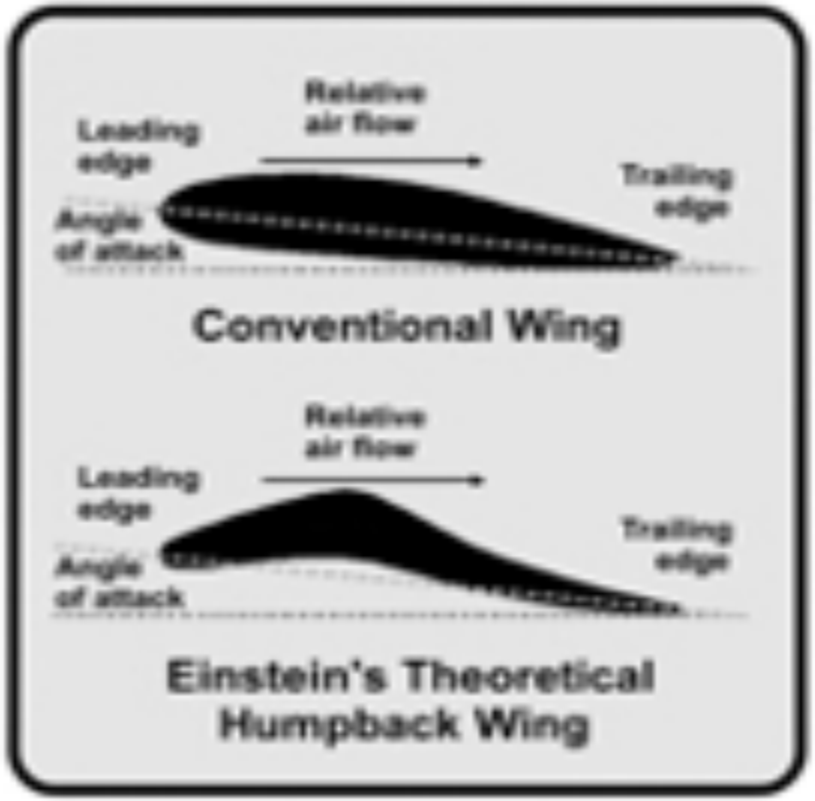
[J.Jansson/J.Hoffman/N.Jansson, 2011]

FORCES ON AIRPLANE COMPUTABLE FOR ALL ANGLES OF ATTACK



SECRET = NS/SLIP: FOR EVERYONE!!

EINSTEIN'S HUMPBACK WING:
NOT ELEGANT: DID NOT WORK:
TOO COMPLICATED



NEW THEORY OF FLIGHT

- REAL FLOW = POTENTIAL FLOW + 3D ROTATIONAL SLIP SEPARATION

- REAL FLOW = POT FLOW + ELEGANT SEP

- REAL FLOW = POT FLOW + KUTTA CONDITION

OLD THEORY OF FLIGHT

- REAL FLOW = POT FLOW + CIRCULATION TO SATISFY KUTTA CONDITION
- UNPHYSICAL: CIRCULATION
- PHYSICAL: 3D ROTATIONAL SLIP SEP

CTL ON LINE

- http://ctl.csc.kth.se
- http://fenicsproject.org
- https://launchpad.net/unicorn

SOME REFERENCES 2013

- J.Hoffman, J.Jansson, R.Vilela de Abreu, C.Degirmenci, N.Jansson, K.Müller, M.Nazarov and J.Hiromi Spühler, Unicorn: parallel adaptive finite element simulation of turbulent flow and fluid-structure interaction for deforming domains and complex geometry, Computer and Fluids, Vol.80, pp.310-319, 2013.
- R.Vilela de Abreu, J.Hoffman and N.Jansson, Towards the development of adaptive finite element methods for aeroacoustics, submitted
- J.Jansson, J.Hoffman and N.Jansson, Simulation of 3d unsteady incompressible flow past a NACA 0012 wing section, submitted
- J.Hoffman, J.Jansson and C.Johnson, New Theory of Flight, submitted
- J.Jansson, N.C.Degirmenci and J.Hoffman, Framework for adaptive fluid-structure interaction with industrial applications, Int. J. Materials Engineering Innovation, in press.
- M.Nazarov and J.Hoffman, Residual based artificial viscosity for simulation of turbulent compressible flow using adaptive finite element methods, Int. J. Num. Methods Fluids, Vol.71(3), pp.339-357, 2013.

CJ ON LINE

- http://claesjohnson.blogspot.se

- MATHEMATICAL SIMULATION TECHNOLOGY
- WORLD AS COMPUTATION
- SECRET OF FLIGHT
- COMPUTATIONAL BLACKBODY RADIATION
- BOOKS