Euler Equations from the birth of « CFD » to present codes for multiphysics and complex geometry in aerospace/ground transportation engineering

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Euler conference EE250

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summary

- Introduction : the time of pioneers in computing (the blunt body problem and 1-D problems) birth of CFD

1- The first tests in 2D with mixed BC : the problem of ireversibility and uniqueness

2- The problem of artificial viscosity/entropy vs mesh

3- The problem of acoustics waves and of absorbing BC

4- The problem of 3D vortical layer and of separated flows(unsteadiness and vortical instability)

5- The problem of multiphysics and of propagation

- Conclusion: the place of Euler solvers in multiphysics-multiscale computations in industrial applications

Introduction

- A long way driven by computational capabilities and by mathematics and numerical analysis and experimental evidences

- A non-linear process of iteration between:

-Pure mathematical problems(existence and unicity of the solutions of Euler equations)
-Numerical experiments through discrete solvers
-Experimental evidence of good/bad simulations

Historical inflexion (1970)

From the begining focus was put on specific Euler applications where inviscid and incompressible flow are out of the game (with all the associated simplifications); moreover the Navier-Stokes seemed complex so that the usual assumption was high Reynolds and no viscosity outside very thin boundary layers

Euler applications in transonic was coming in aerospace when the potential equation was mastered (from 1970 to 1975) and potential computations became progressively validated and daily used

Complex physics was not excluded and unsteady approach

was a challenge in 2D as soon as computers was sufficiently fast

Very large Reynolds number allowed in practice that the coupling with boundary layers was a reasonable choice for simulating supersonic and hypersonic flows

Focus was then put on shock-waves and their rebuilding

The progress was driven by computer speed and size of memory!

The algorithms was first tested in 1D

The number of points devoted to rebuid the shock-waves was at least 5 and so the complexity of real flow adressed first was poor and the numerical tests has to be validated also on simple analytic and experimental test cases

roughly the sixties and seventies saw the selection of basic algorithms and the first applications to 2D or axisymetric flows

An acceleration of research (as soon as appeared useful outputs of numerical computations) enables the 1980-1985 interval of time to be devoted to the building of new codes and the discovery of the first « Euler-specific » problems and of the first medecine

The building of real industrial codes occupied the next group of 5 years

After 1990 came the time of consolidation in 3D and the beginning of 3D unsteady applications among the leaders in CFD who addressed the complex configurations and physics

The men !

- Major leaders in the Euler Battle (1970-1980) for valuable computations and their major publications has to be named because, without their efforts, Euler codes would not appear at the level of present quality as evaluated by many workshops

The firsts

- 1928 **Courant-Friedrichs-Lewy**
- 1950 **von Neumann-Richtmyer**
- 1952 Courant-Isaacson-Rees
- 1954 **McCormack, Lax**
- 1956 **Godunov**
- 1957 Lax
- 1959 Godunov
- 1960 **Lax-Wendroff**
- 1962 **Richtmyer**
- 1963 Bielotserkovski-**Dorodnitsin, Oleinic** **the russian variant**
- 1964 Arucina, Harlov
- 1966 **Yanenko**-Yanshev, Conway-Smoller
- 1967 Ritchtmyer-Morton, Newman-Richtmyer-**Lapidus**-
- 1968 **Fromm, Gordon,**
- 1969 **Moretti**,Hopf, Rusanov the first in 2D+time
- Critical research addressed shock-waves,blunt bodies,

The first basic **algorithms**

The second ones

- 1970 **Kruzkoven counter of computer science and numerical analysis**
- 1971 Yanenko, Murmann-Cole
- 1972 Moretti,Lax, Courant-**Isaacson-Rees**
- 1973 Masson,Rizzi, **Lerat-Peyret**,
- 1974 **Turkel**,Viviand, LeRoux
- 1975 Tannehill,Moretti**,Rizzi**, Peyret-Viviand,
- 1976 Voroshtsov-Yanenko, **Warming-Beam**, Rubbert-Weber-Brune-Johnson, **Harten**-Hyman-Lax
- 1977 **Van Leer**, Chattot,Holt, , **Lerat-Sides**,Briley-McDonald, **Hemker, P**andolfi**-Zanetti**
- 1978 Foester-Vieweg**, Steger**-Warming, Beam-Warming, Baker, **Balhaus-Holst-**Steger, Wanbecq, Viviand-Veuillot
- **Désidéri-Steger**, Tannehill
- 1979 **Sod**, VanLeer, Roe, Moretti,**Jameson-Turkel**, Périaux

First computations, conservative and second order,splitting…

at the period where transonic potential flows was finally in daily use

The third rank

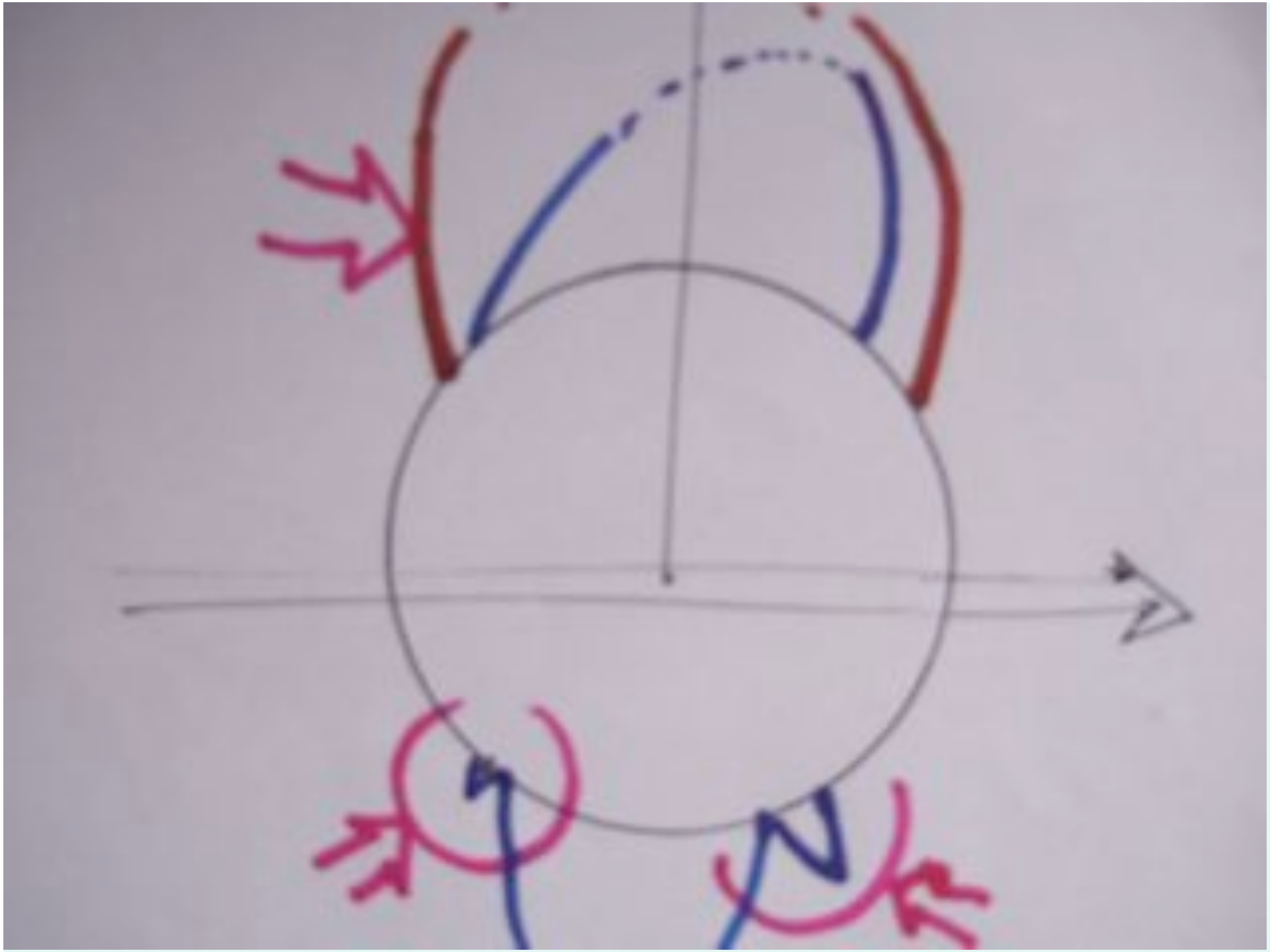
- 1980 Moretti, Boppe-Stern, Caughey-Jameson, Murcer-Murman,**Engquist-Osher**, Sells, VanLeer, Chattot, **Crandall-Majda**
- 1981 Fromm, **Roe**, Steger-Warming,Moretti,Mc Cormack, Osher,Schmidt-Jameson-Whitfield, Lerat, Rizzi-Viviand, **Hussaini-Orszag**, **Brooks-Hugues**, **Peyret-Taylor**, Baba-Tabata, Borel-Morice,
- 1982 Moretti-, Osher, Brooks-Hughes, Yee-Warming-Harten, Vijayasundaram,Rizzi
- Ni, Lerat-Sides-Laru
- 1983 Osher-Chakravarthy, Thomas-Holst,Moretti, Thomson-Warsi, Lerat, Harten, Hughes, Harten-Lax-VanLeer, Zanetti, **Osher-Salomon**, Bruneau-Chattot-Launais, **Collela-Woodward**, McCormack, **Satofuka**, **Glowinski-Périaux-Perrier-Pironneau** Glowinski-Périaux-Perrier-Pironneau-Poirier-Bristeau, Satofuka, **Dervieux-Périaux**, **Casier-Deconink-Hirsch**, Jameson-Schmidt-Turkel,
- 1984 Whitfield-Janus, Woodward-Coletta,Roe ,Morice, Jameson, Stoufflet, **Yee-Warming-Harten**, **Dervieux-Vijayasundaram**, Leveque, Brénier, **Hughes-Mallet**
- 1985 Holst,
- 1986 Moretti,Lijewski,
- 1987 Moretti, Roach,**Peyret-Taylor**
- **Operational codes: from Roe 1981 on simple Geometry to wing section FDM with Jameson, Yee-warming, Woodward,…**
- **and on complex geometry FEM since 1983/1989 in FDM**

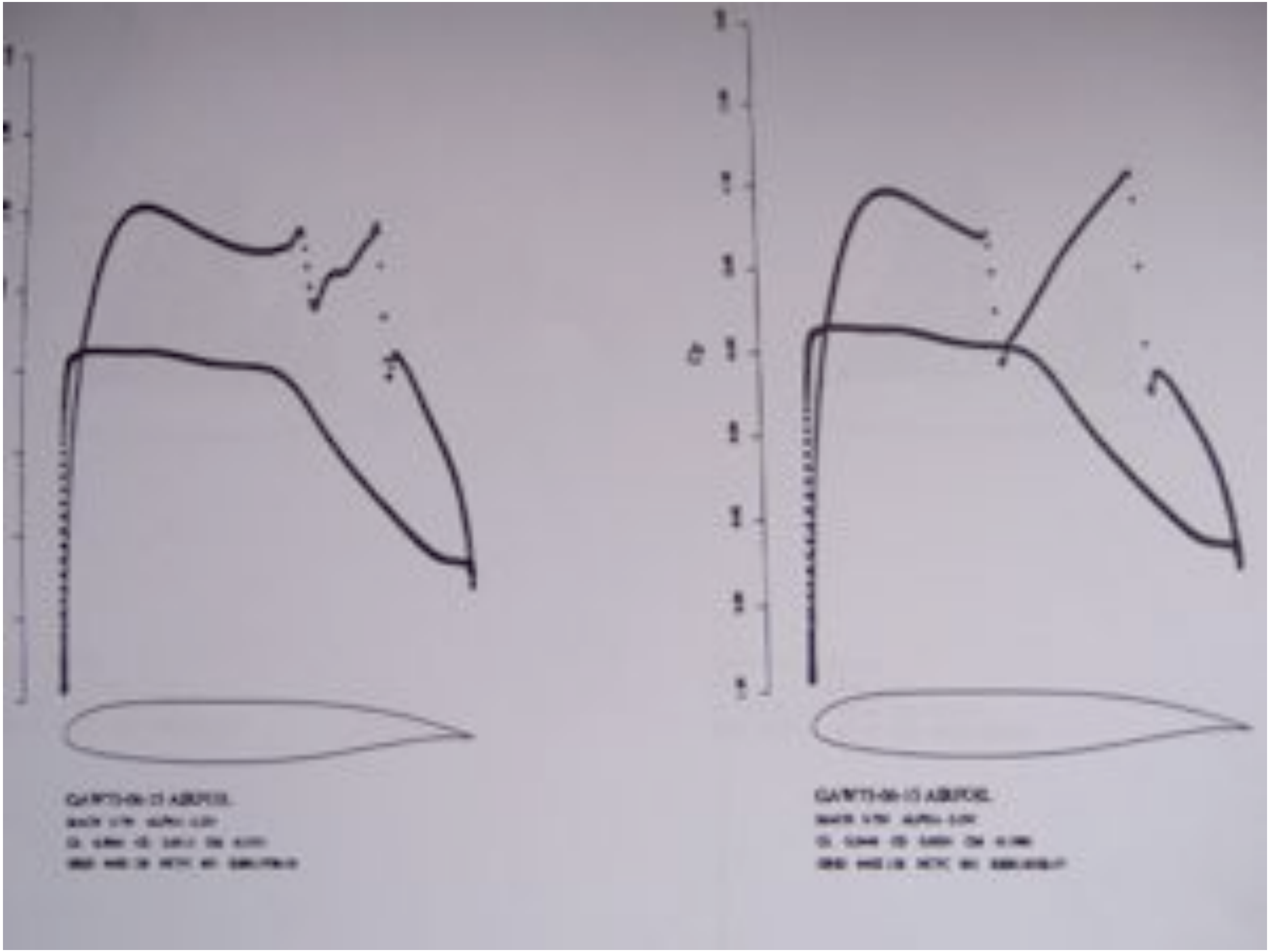
Some years after these glorious times went the consolidation !

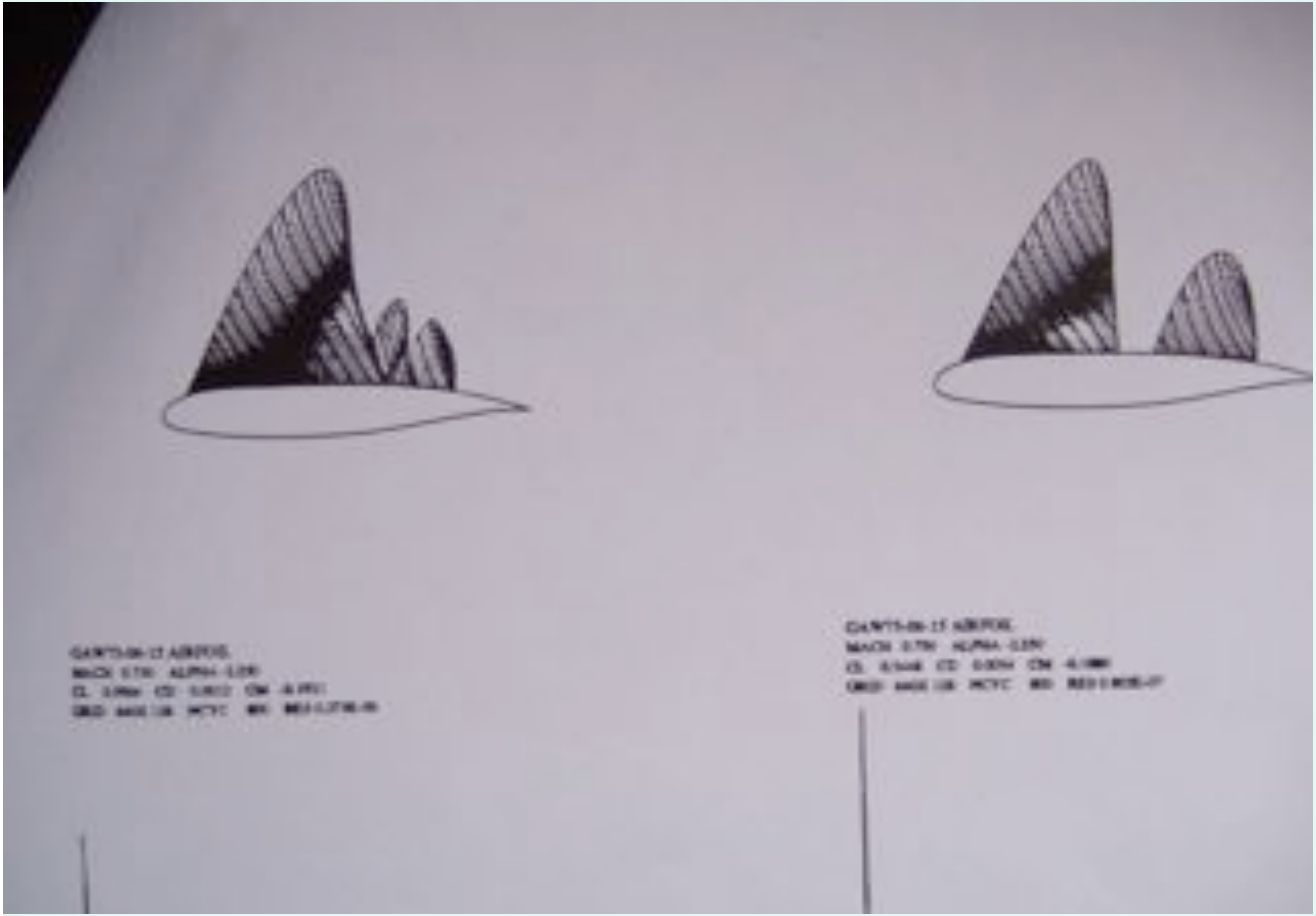
Covering now the problems one after the others

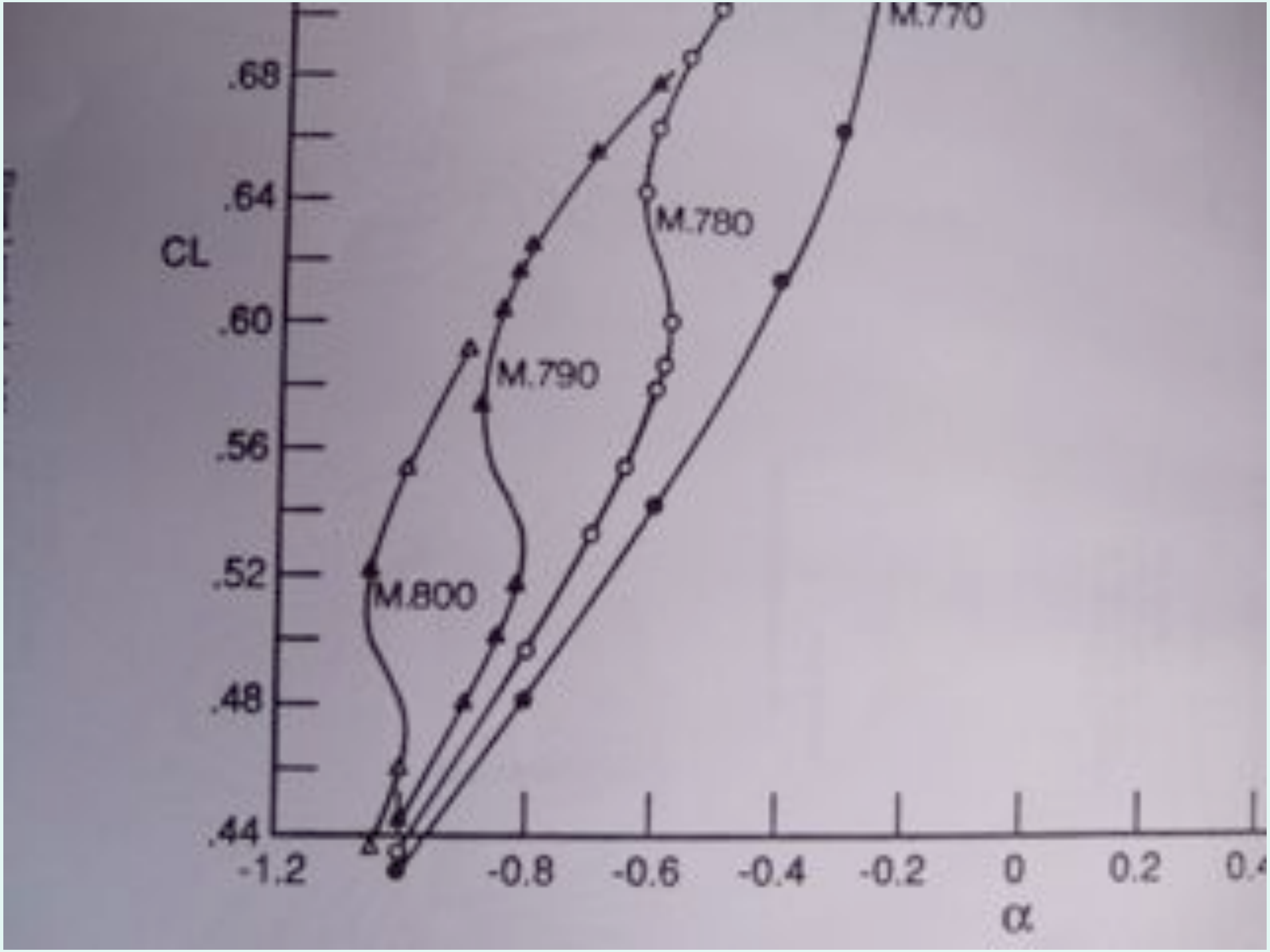
1- The first tests in 2D with mixed BC : the problem of irreversibility and uniqueness

- The examples of 2D nozzle/ cylinder
- Entropy condition and inverse shock-wave
- At least three solutions to equation?









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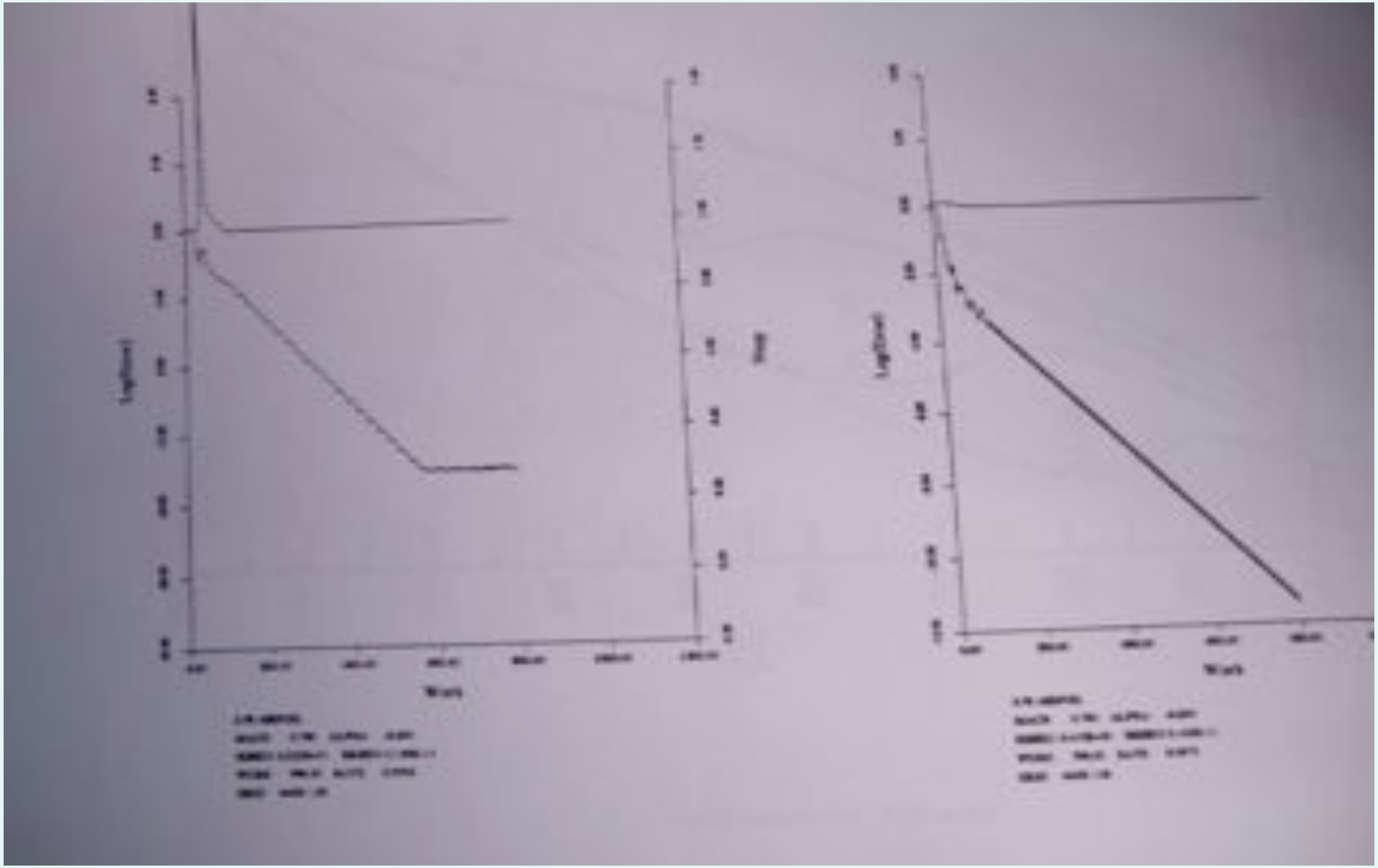


2- The problem of artificial viscosity/entropy vs mesh

- The problem of shock wave capture/mesh

A reference test for spreading of S-W

- The oscillating wing section of a rotor:

A reference test with low to high Mach number and high to low angle of attack

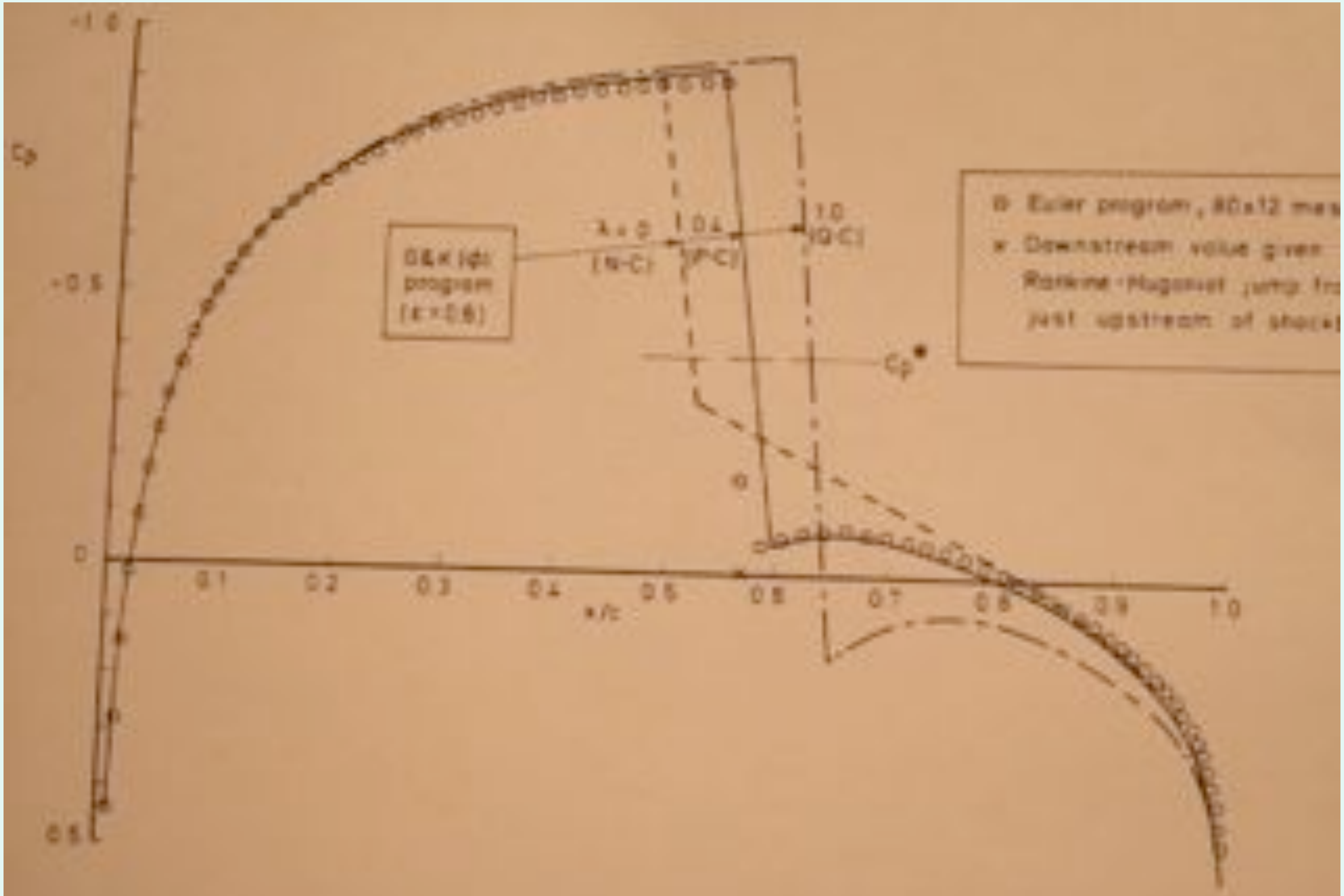


Fig 11 Comparison of solutions of Euler and potential flow equations for NACA 0012: $M_\infty = 0.816$, $\alpha = 0°$

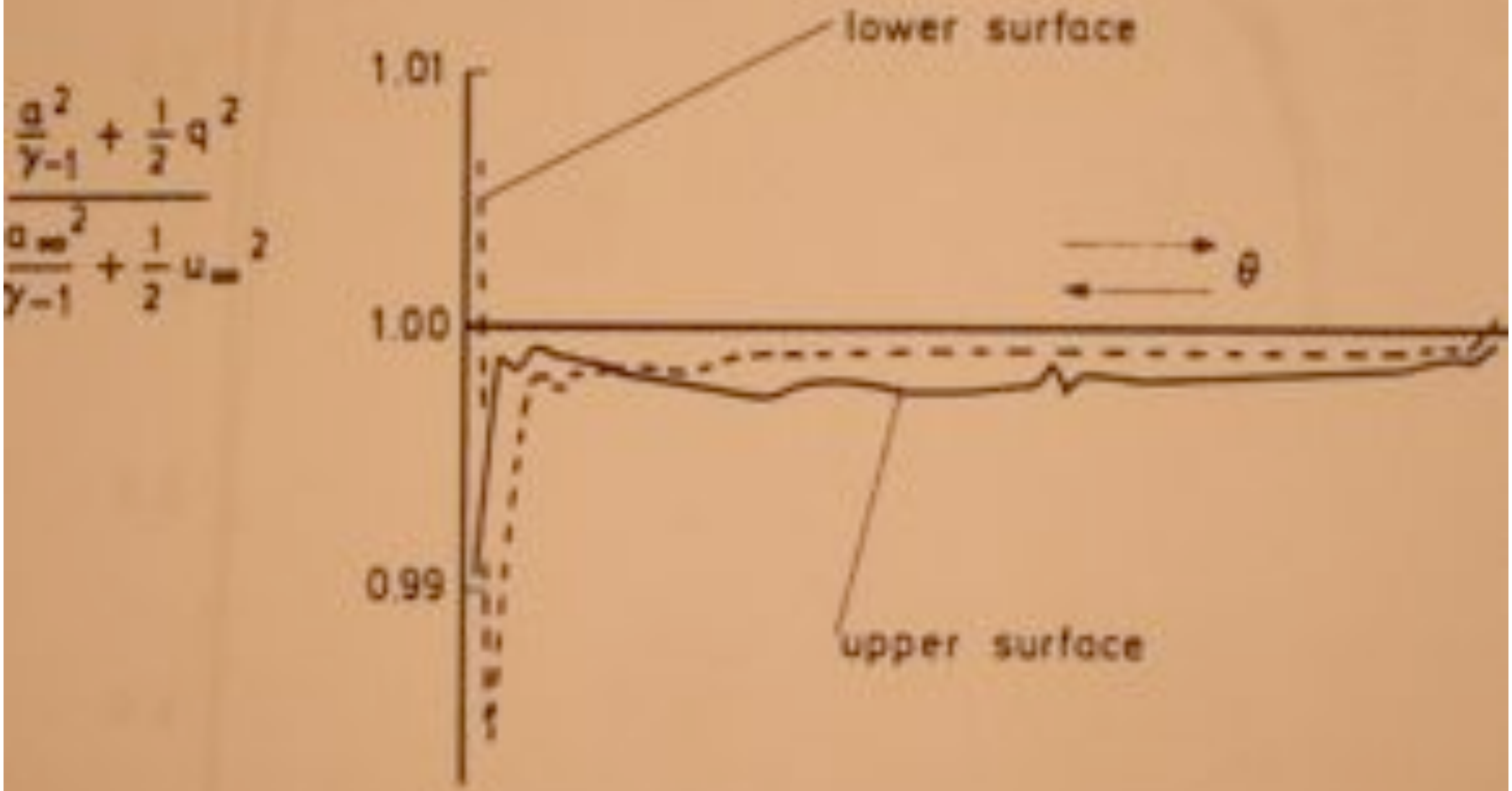


Fig 13 Error distribution in entropy function and total unthalpy from present program. NACA 0012; $M_\infty = 0.8$, $\alpha = 1.25°$

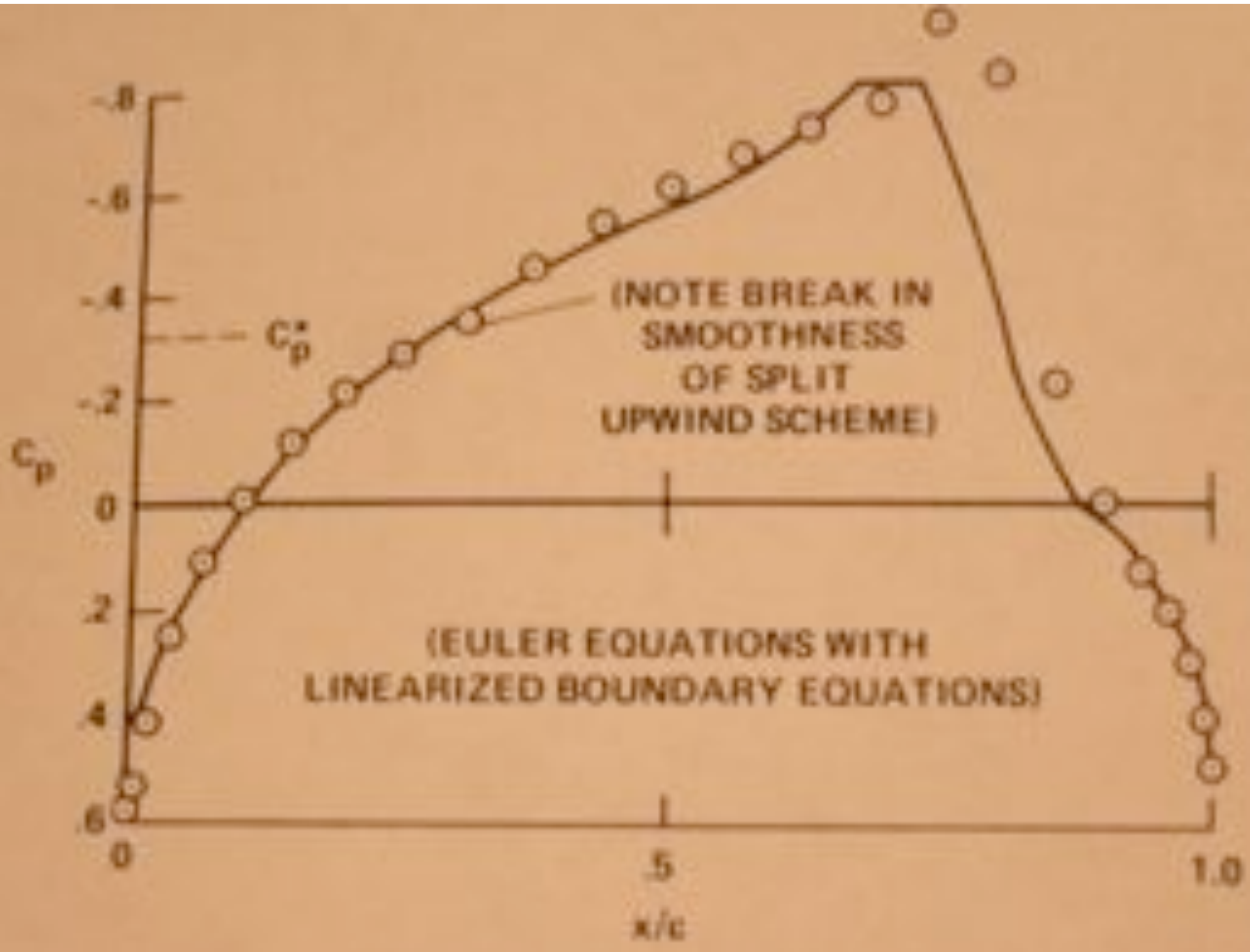
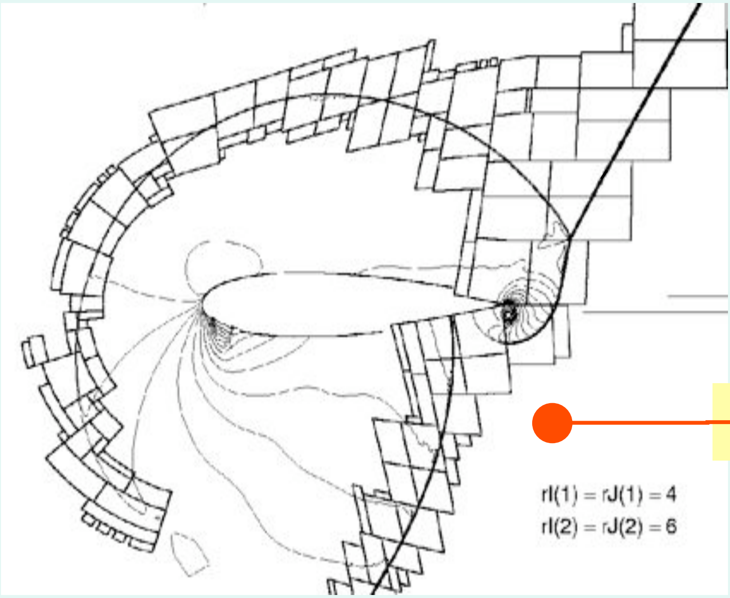


FIG. 7. Steady state solution for 11.4% thick parabolic arc airfoil, M_∞

Adaptive Mesh Refinement (AMR) - 2D shock interactions



← Density contours
Planar shock reflection off the NACA0018
Unsteady inviscid flow

Incident shock
M_{shock}=1.5

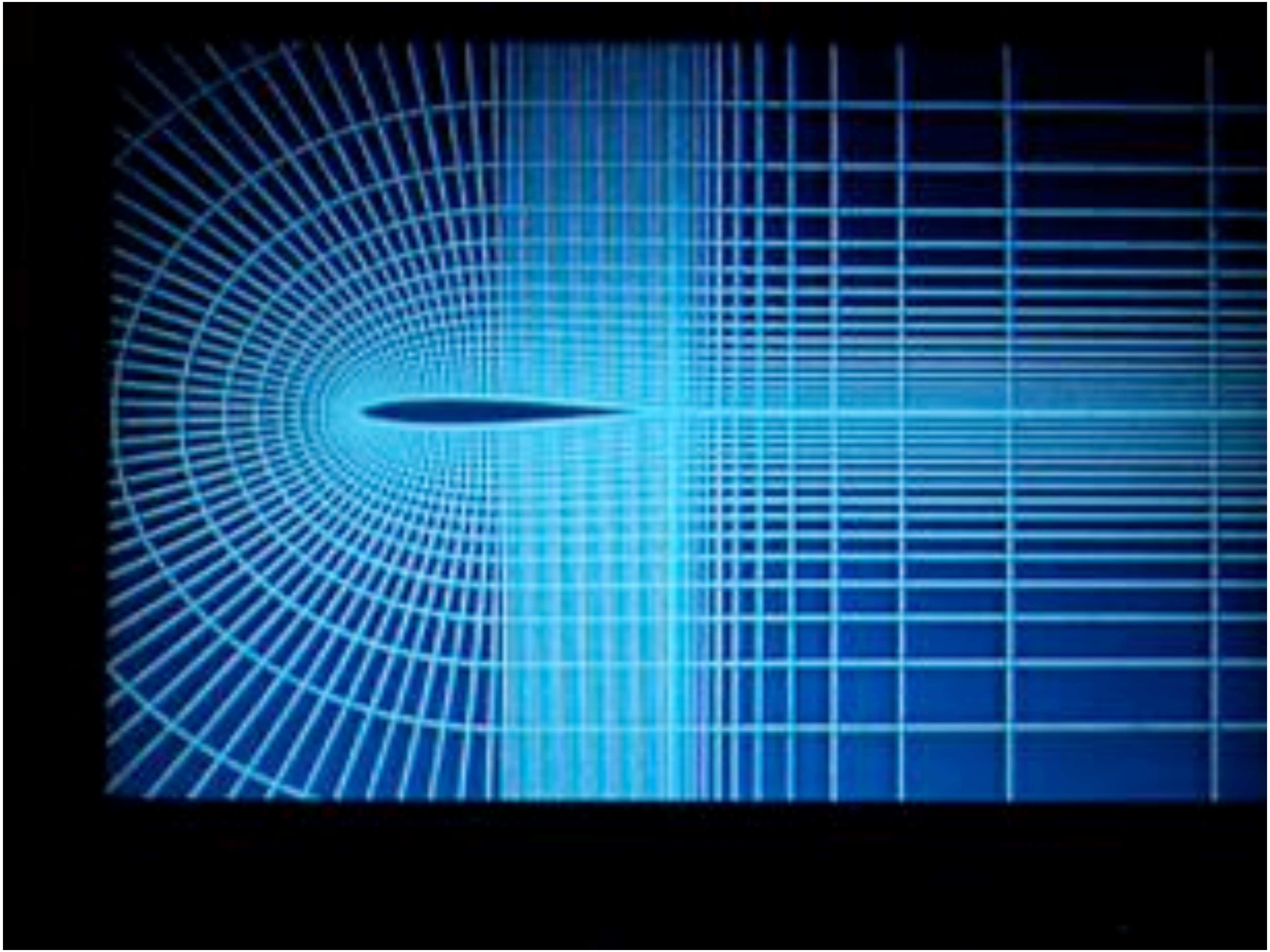
Incident shock

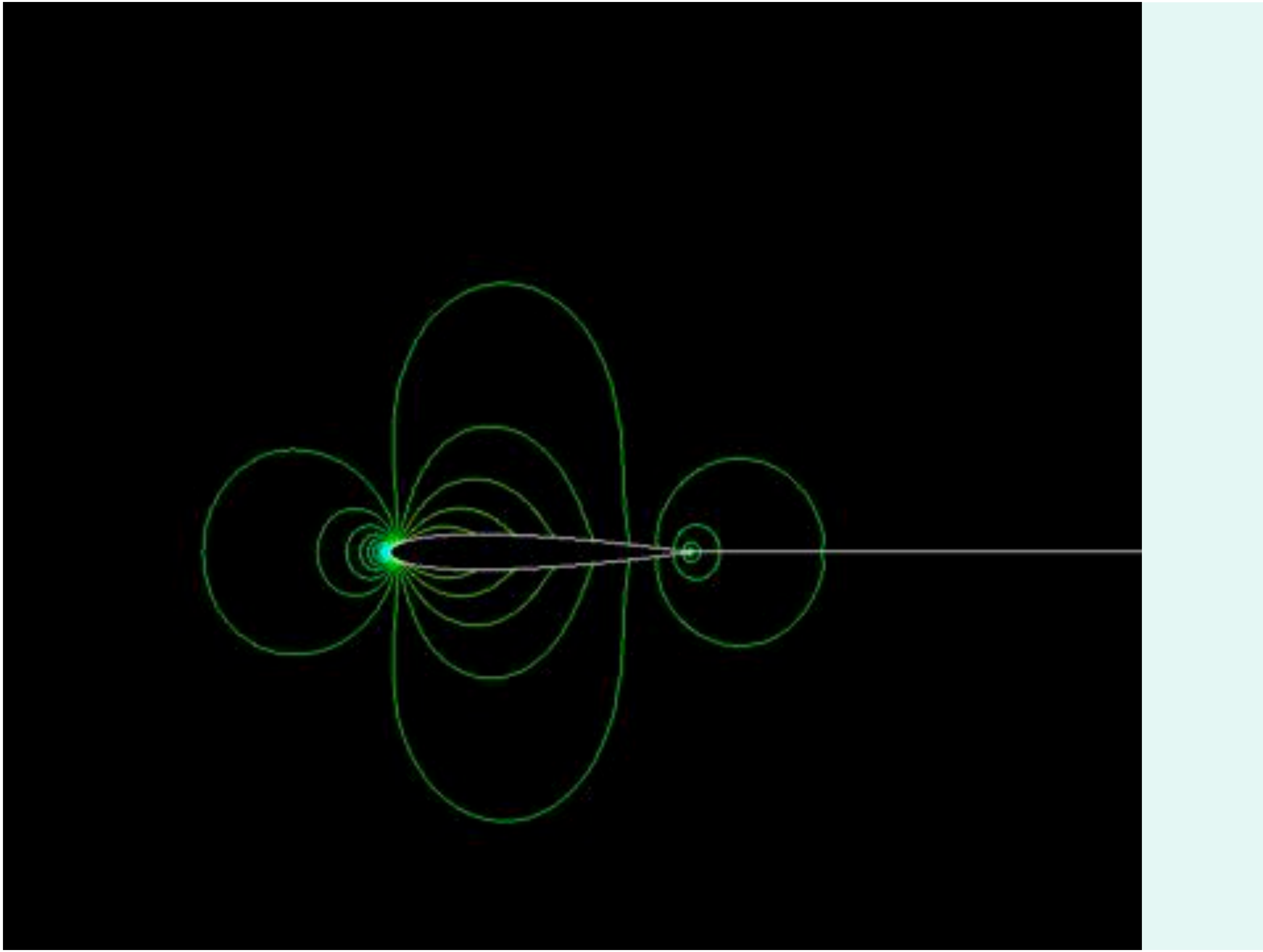
Density contours →
Shock / Boundary layer interaction (laminar)
Re - 296.000
Steady viscous flow

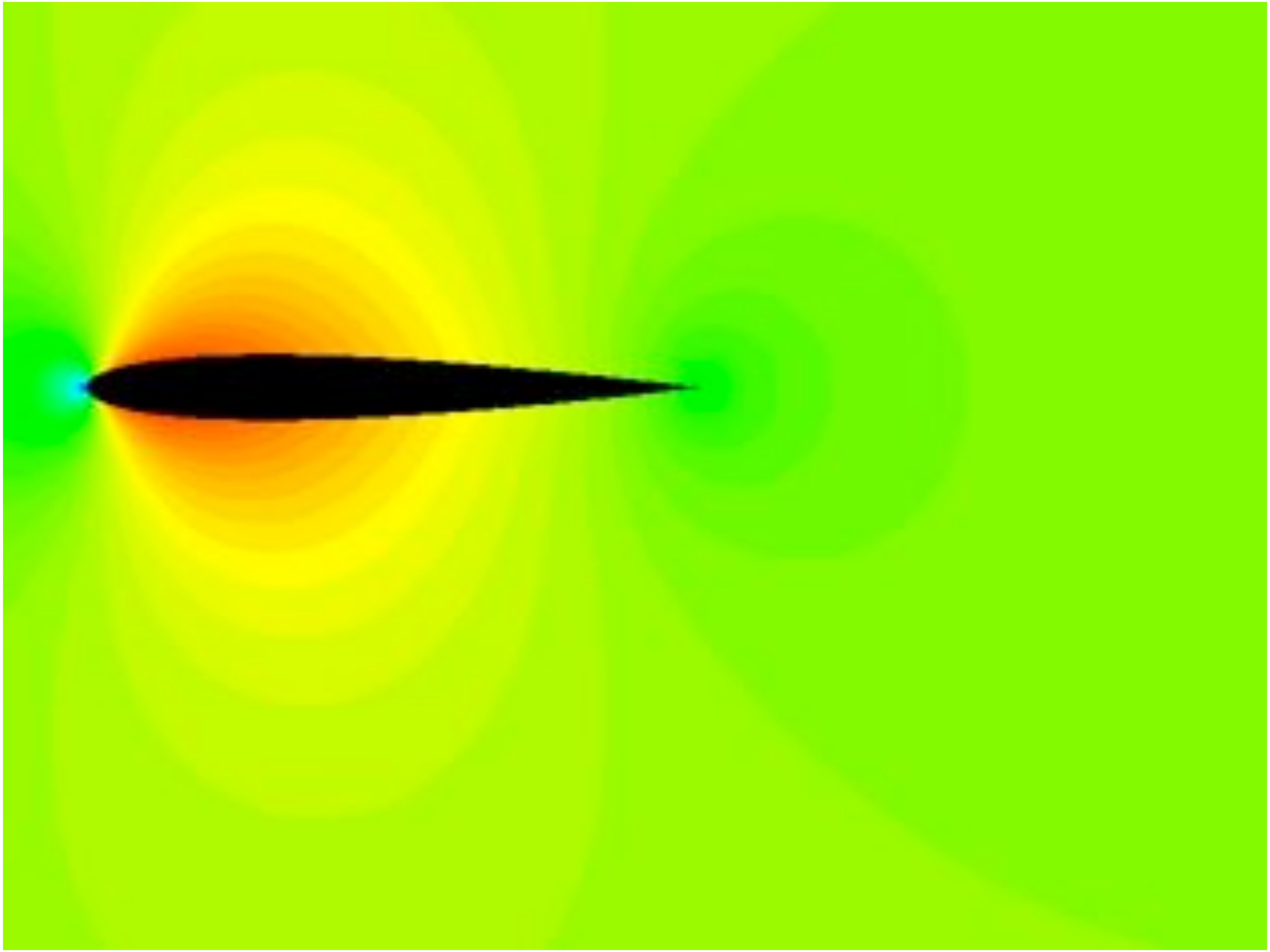
Leading edge

Wall boundary layer

Onera - DSNA







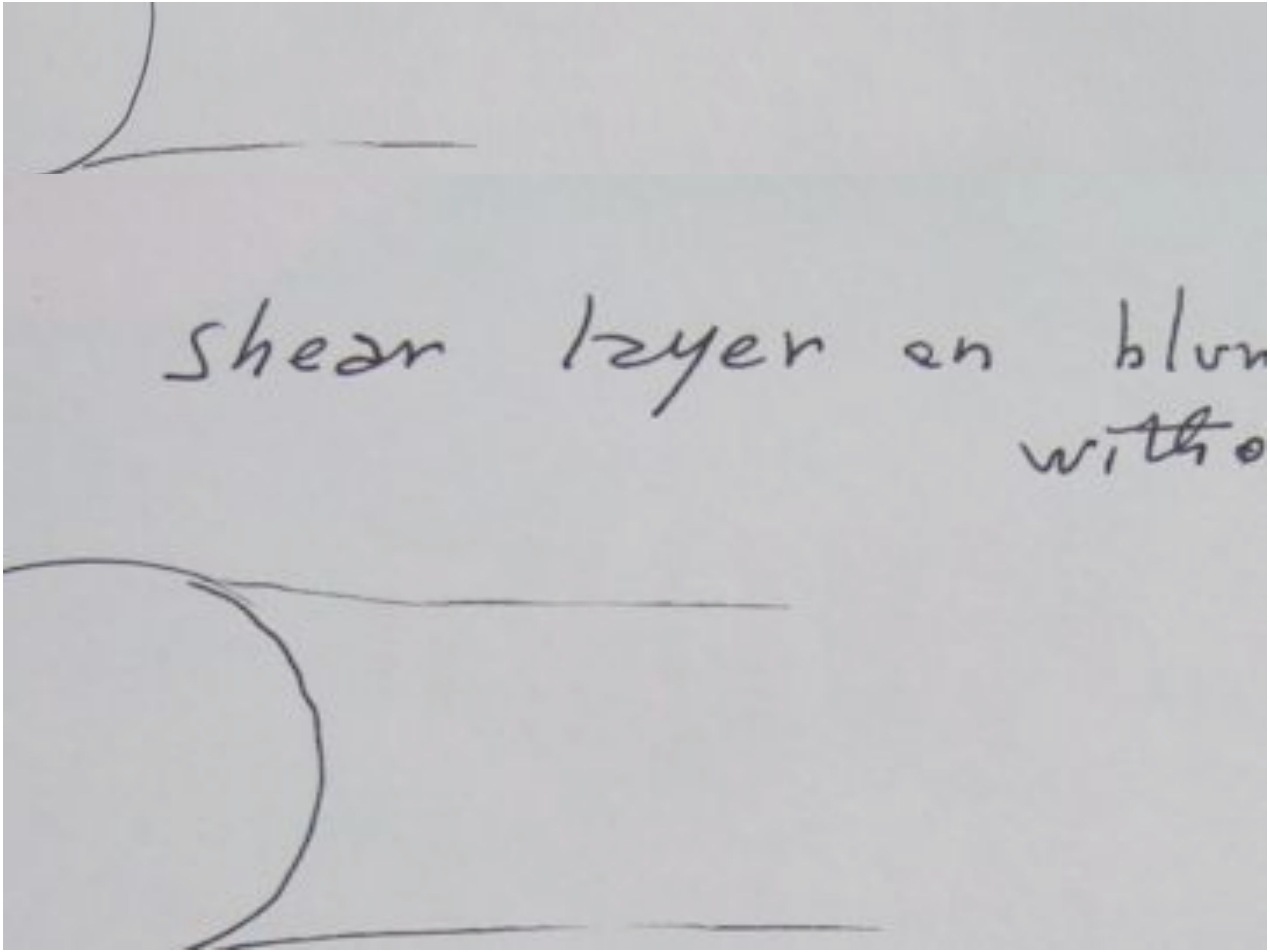
3- The problem of acoustic waves and of absorbing BC

- Does transient acoustic waves generated at the start of the computation may return from boundaries of the domain of computation and disturb the field?
- Analogy with a train entering a tunnel

4- The problem of 3D vortical layer and of separated flows(unsteadiness and vortical instability)

- ***First:*** new problem of non-unique « dead flow » parts with separation and wakes

Second: open separation and 3D vortical flow generation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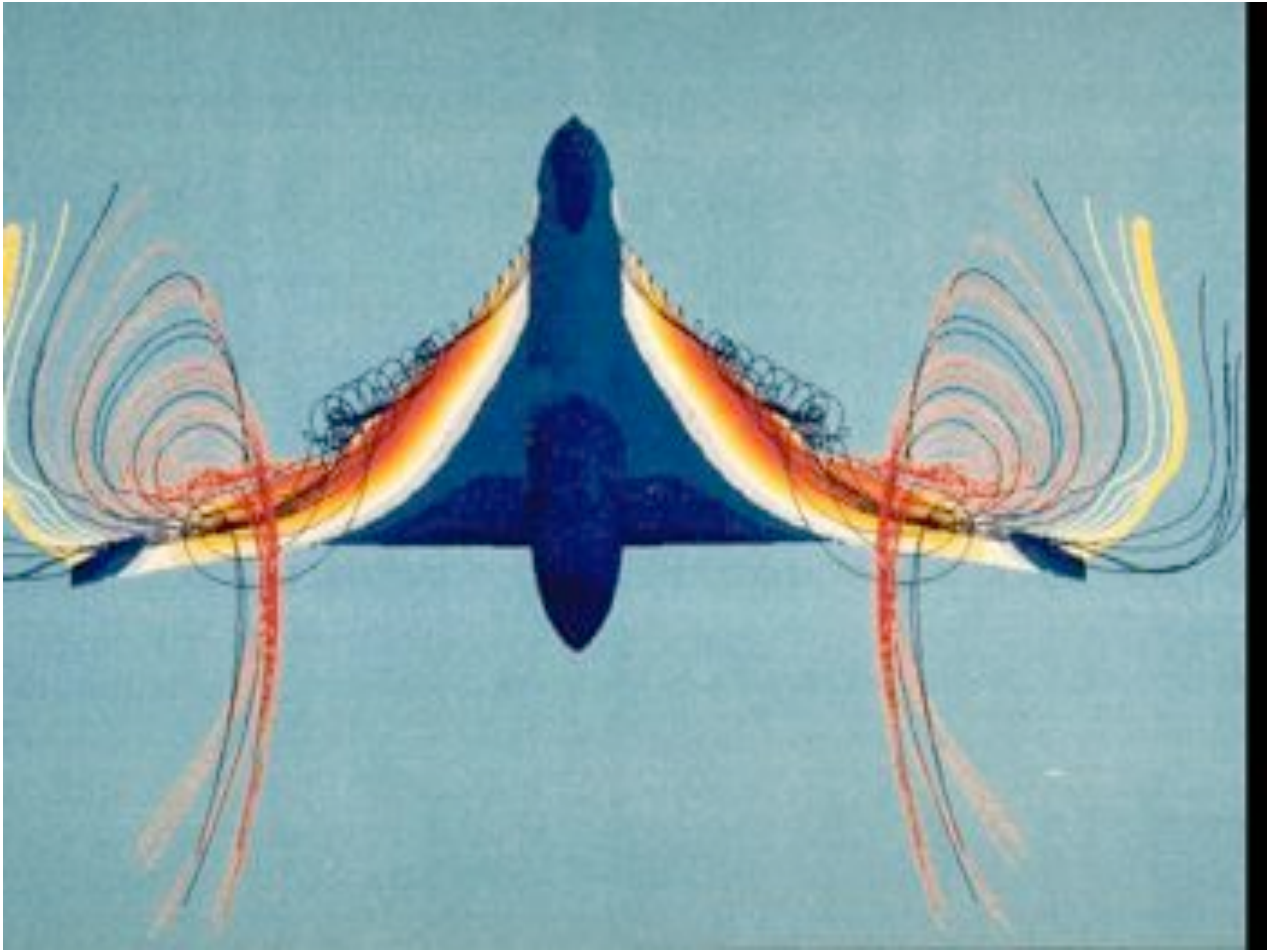

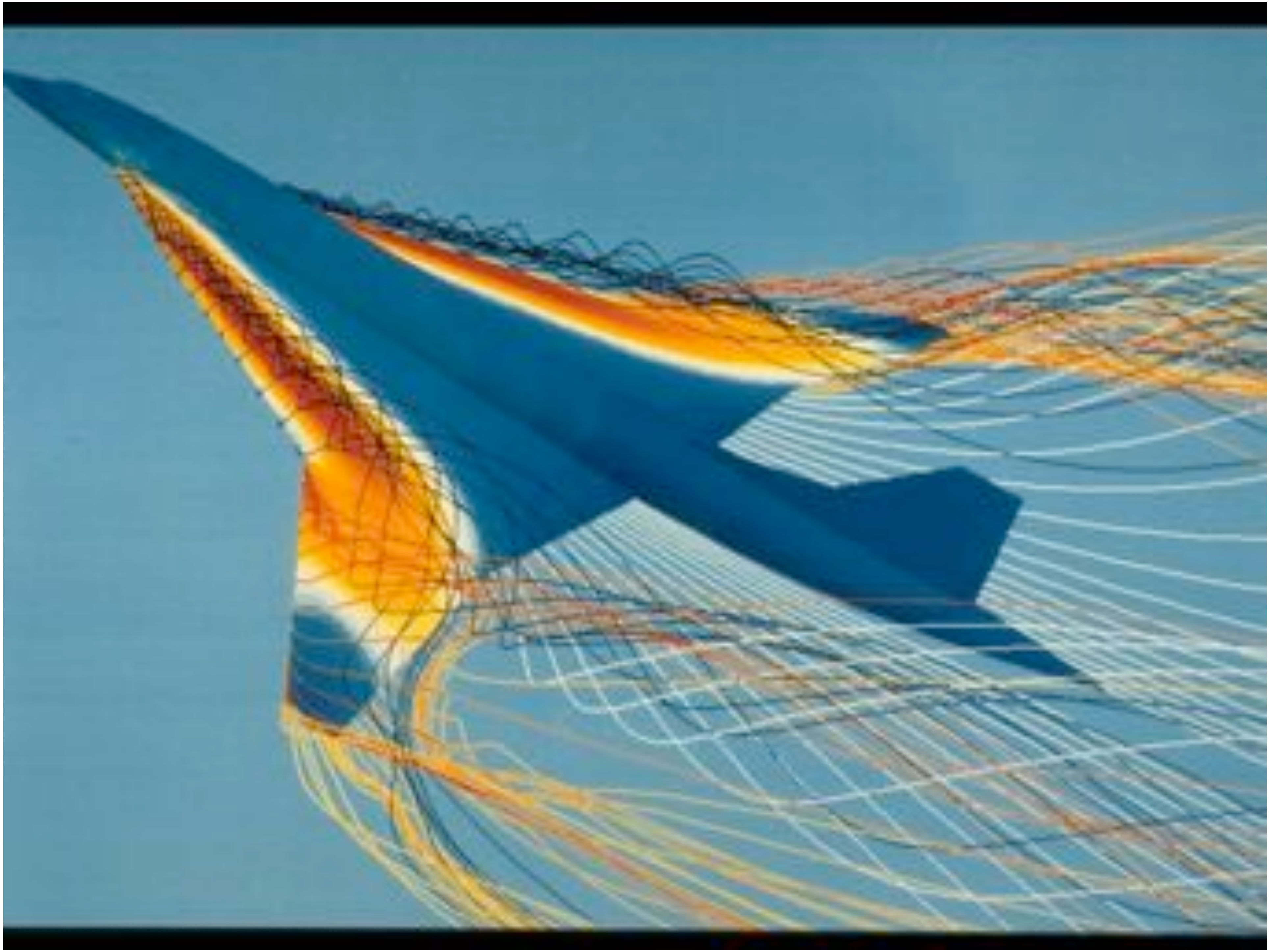

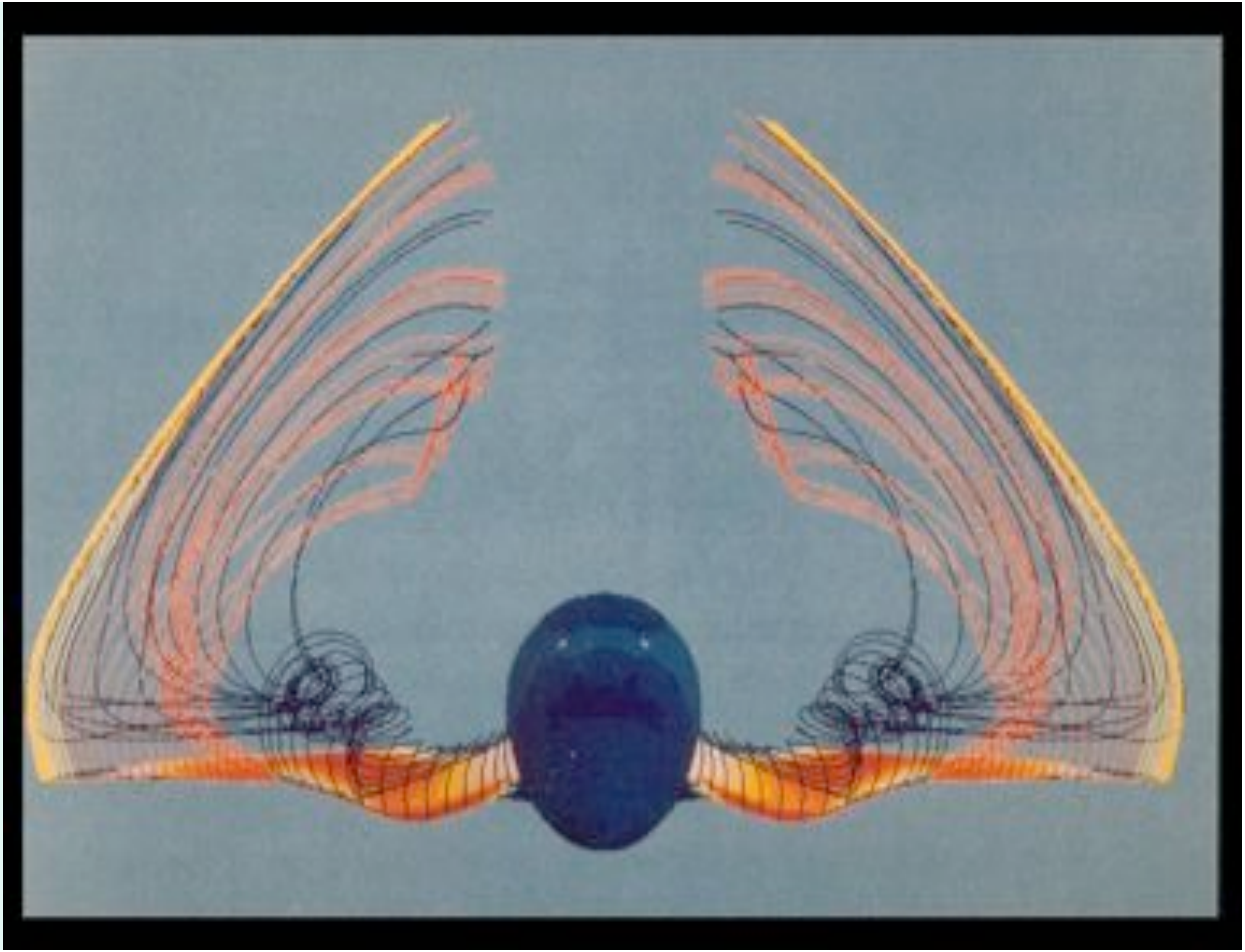

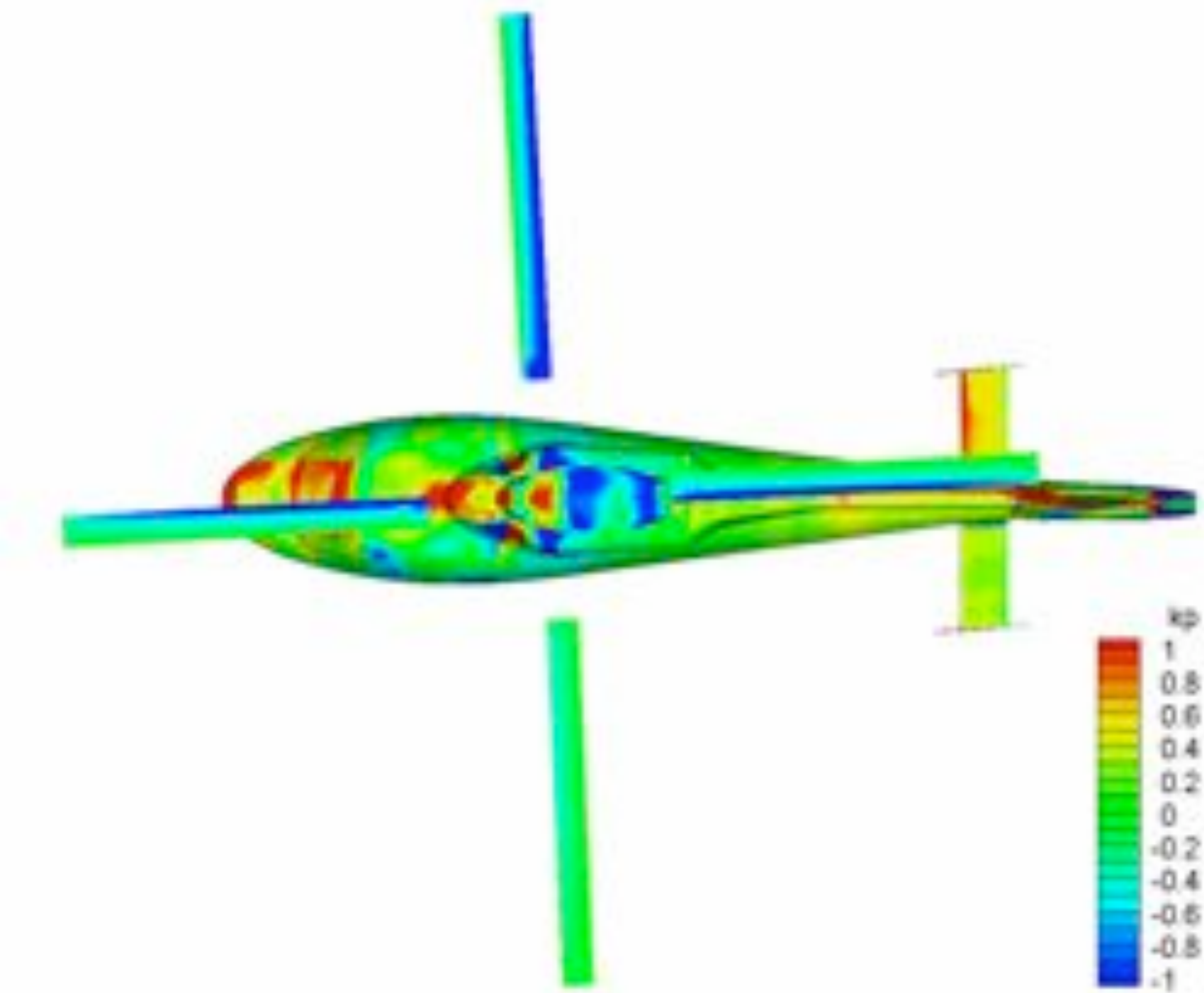
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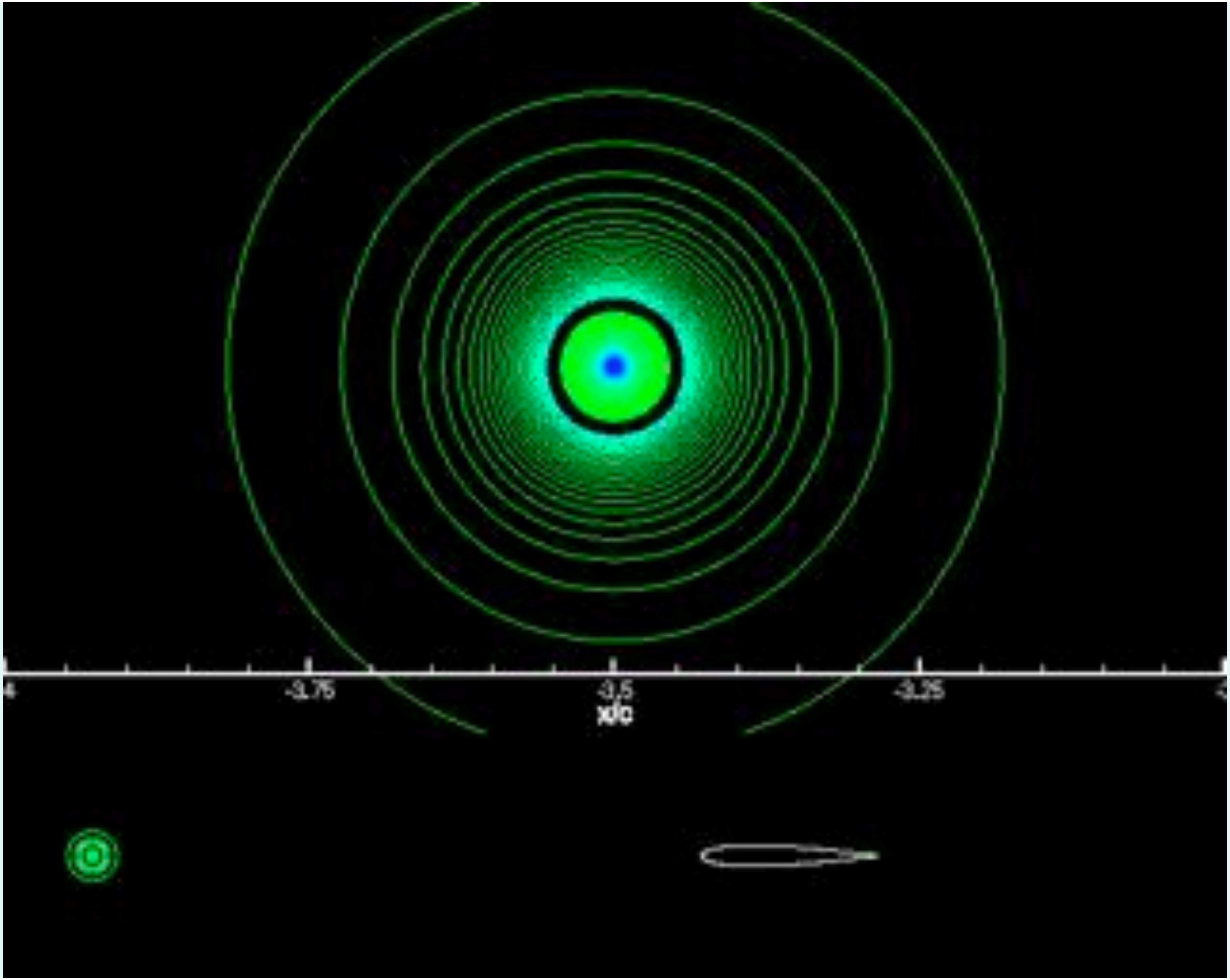
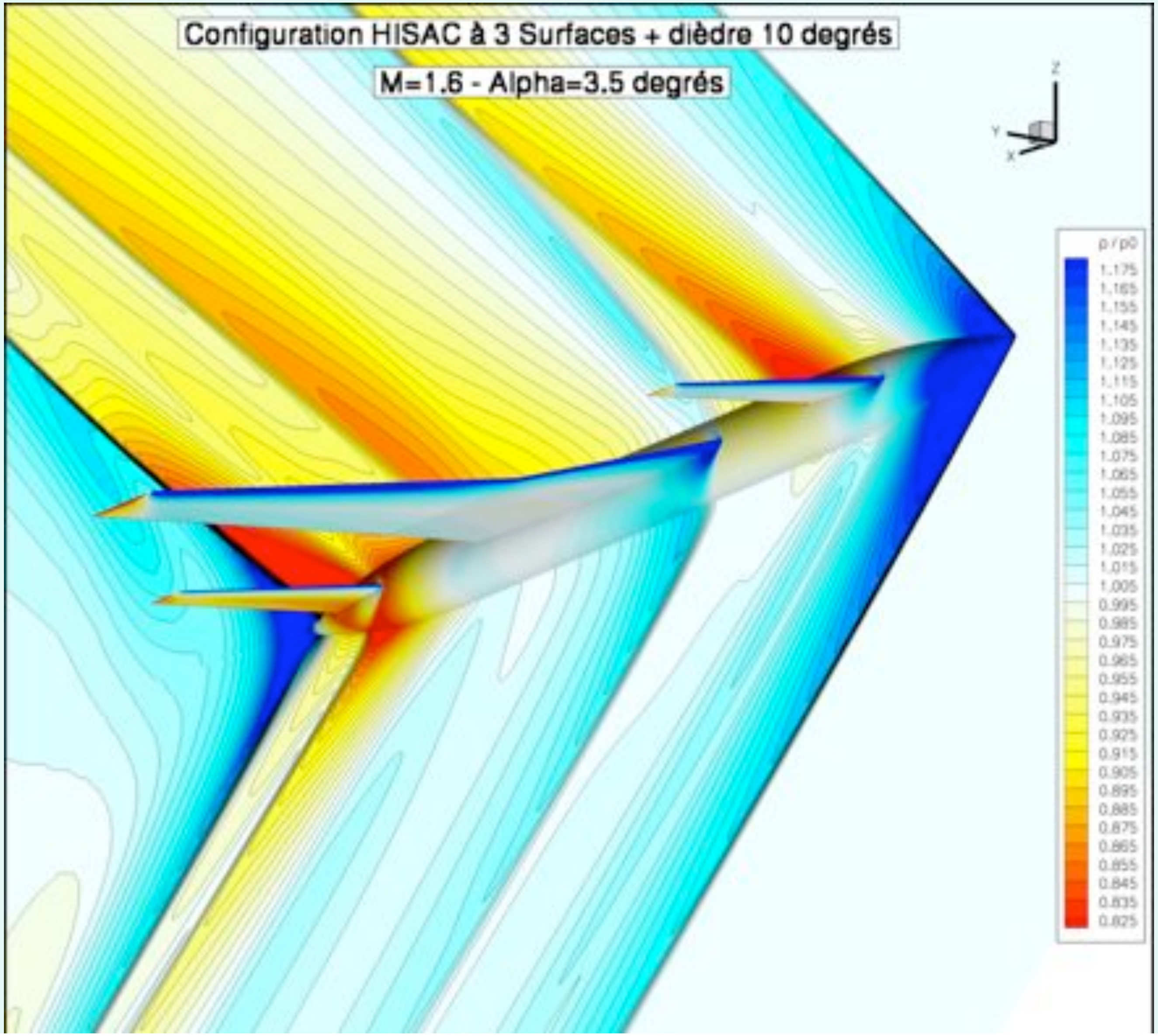


-3.75
-3.5
-3.25
x/c

5- The problem of multiphysics and of propagation

- Coupling on the boundaries
- -heat and masse transfert
- -elastic fluid-structure
- -catalyse, radiation, rarefaction
- Coupling in the field
- -chemistry/combustion
- -magneto
- -di/tri..hydrodynamicsphasic
- The current form of 4D equation seems easy to be complemented by similar modeling? But… what different caracteristic lenghs are present?

Programme HISAC
Étude paramétrique de configurations aérodynamiques pour la réduction du Bang sonique



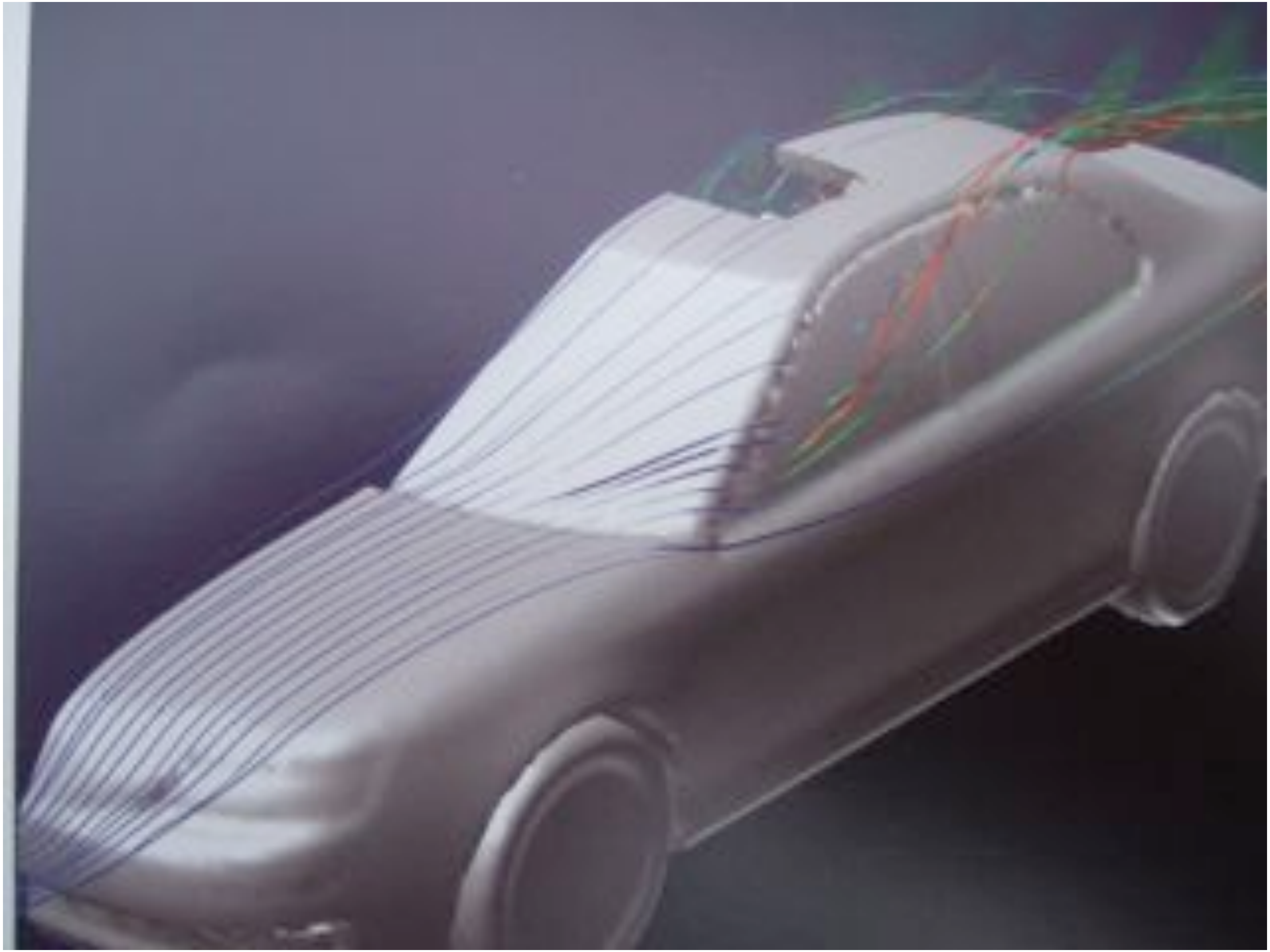
Workshops

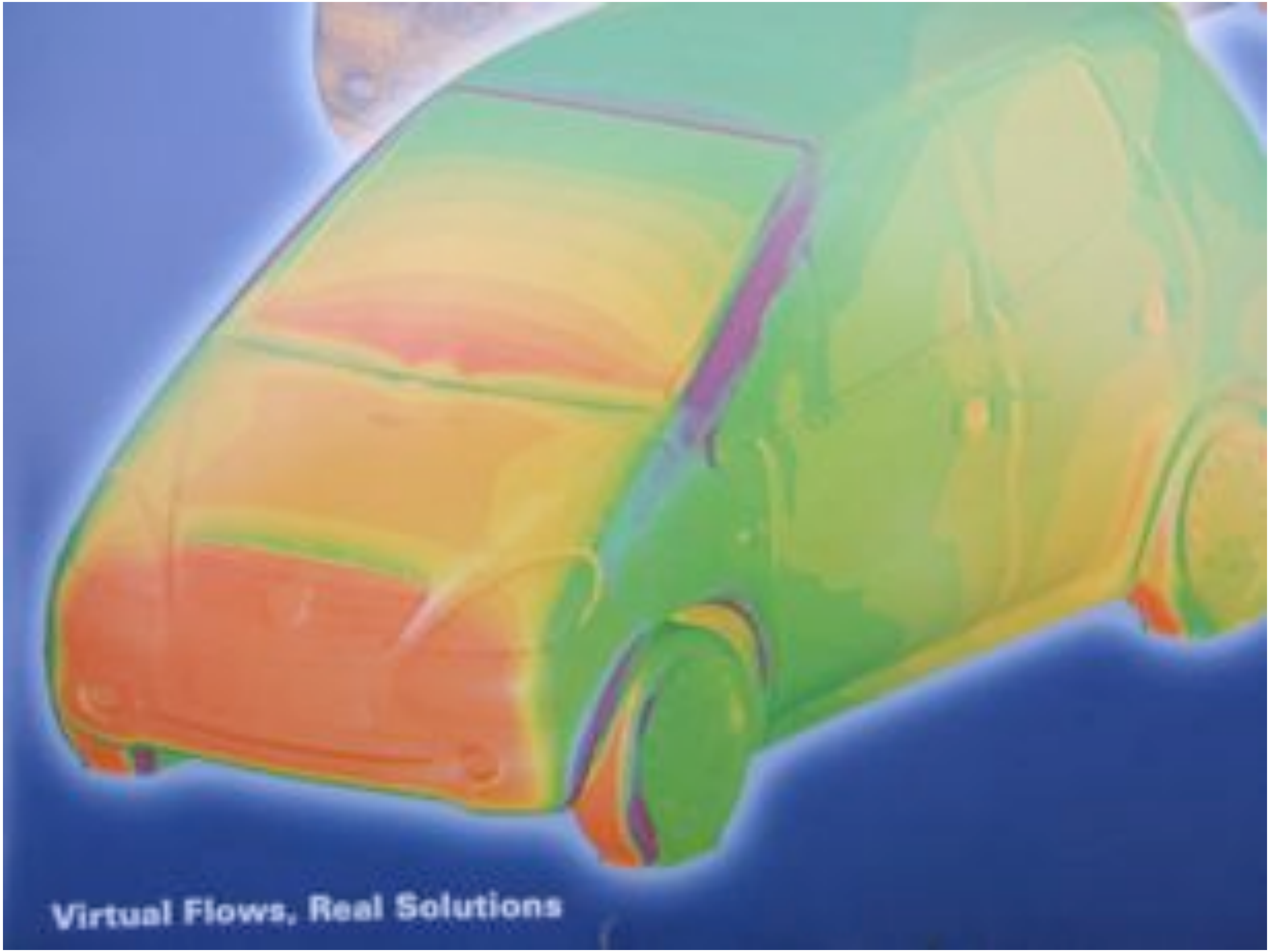
- As surprising as it will appear now, the first **systematic** workshops on Euler appeared with the Hermès european spacecraft program: the constrained budget and the technological challenge required the use of a large number of european industrial and scientific research and development teams; there cooperation in numerical analysis,computer science and experimental validation was exemplary **thanks to frequent workshops where numerical and experimental data were compared systematically**; they so contributed greatly to Euler validated codes appearance in eighties

Wokshops will be always mandatory for Euler codes !

as for other equations but experiments are not here!

Conclusion: today the place of Euler solvers are in multiphysics-multiscale computations in industrial applications




Virtual Flows, Real Solutions

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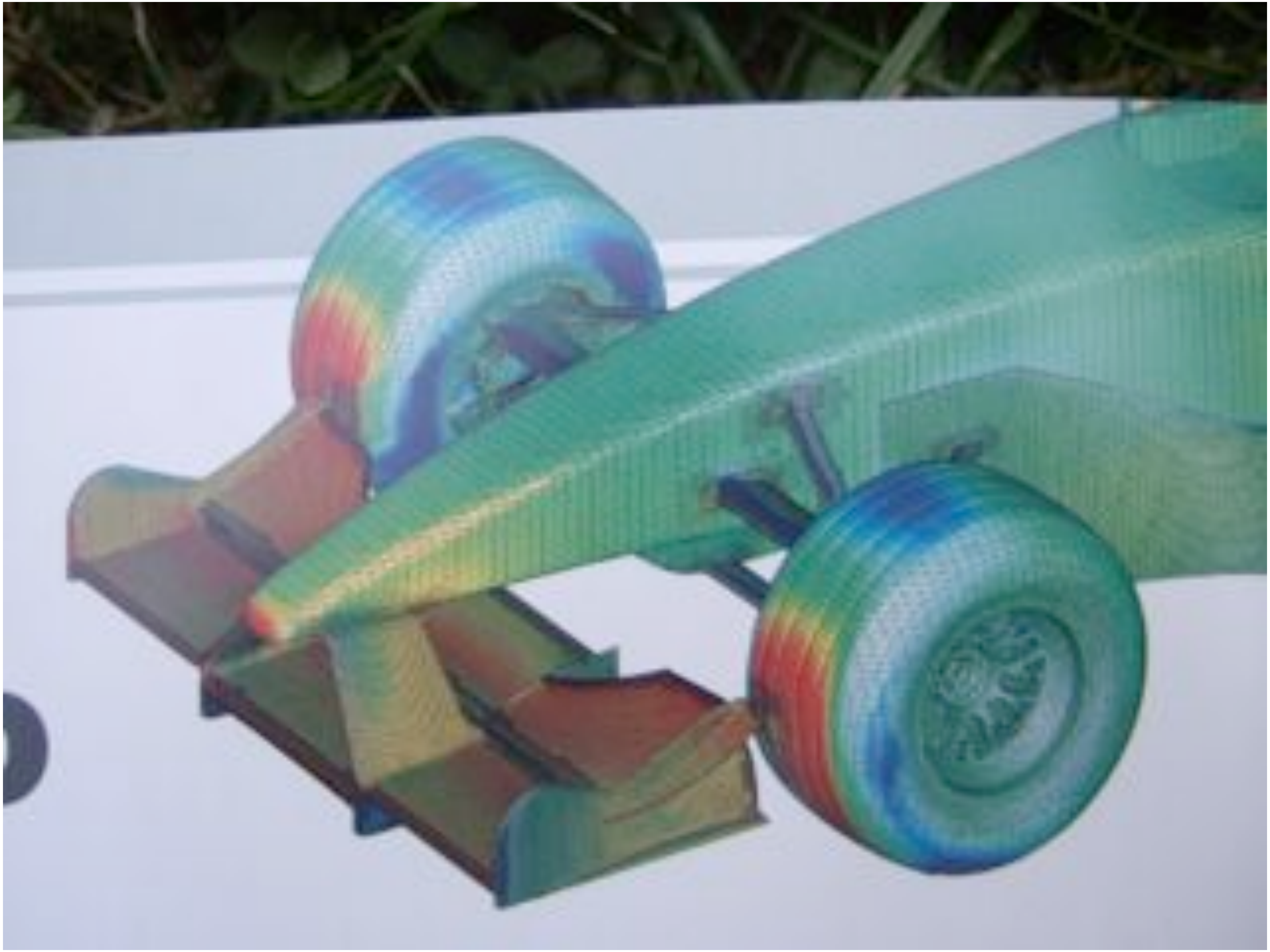

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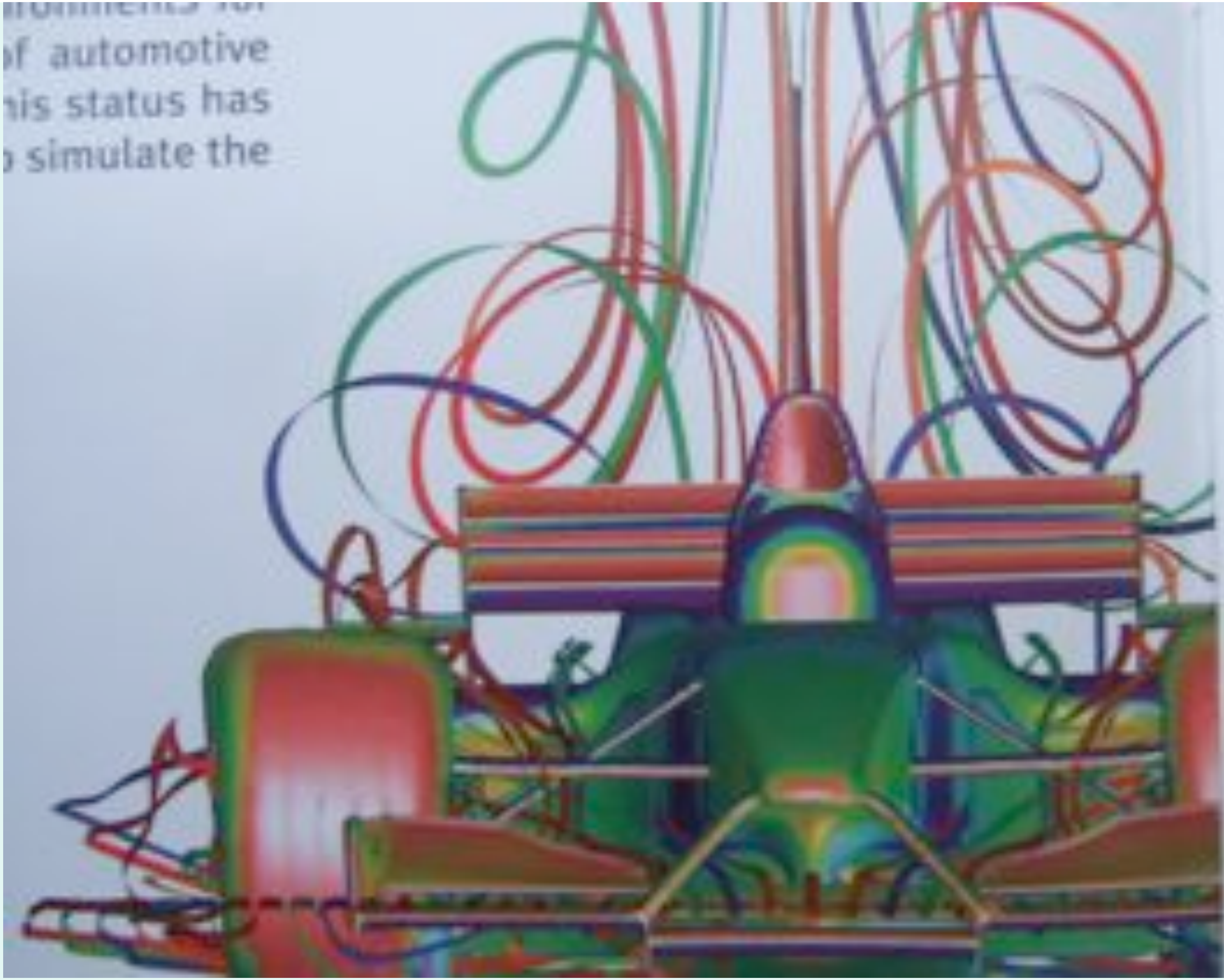
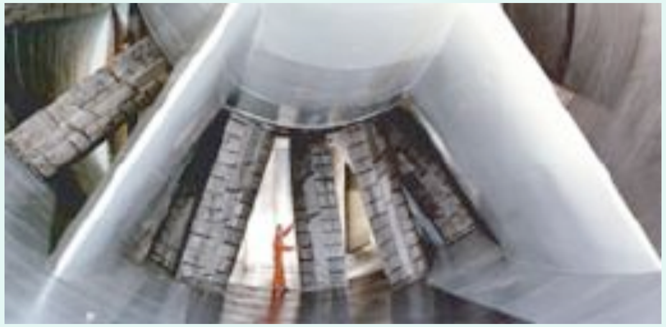


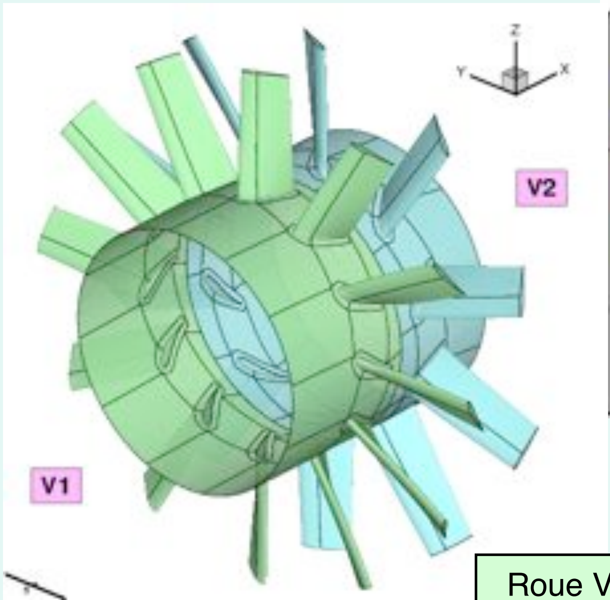
Etude de la stabilité aéroélastique des nouveaux ventilateurs de la soufflerie transsonique S1MA (1/2)

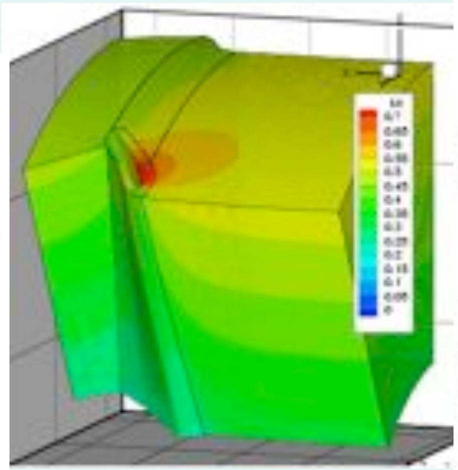
Domaine de fonctionnement stationnaire

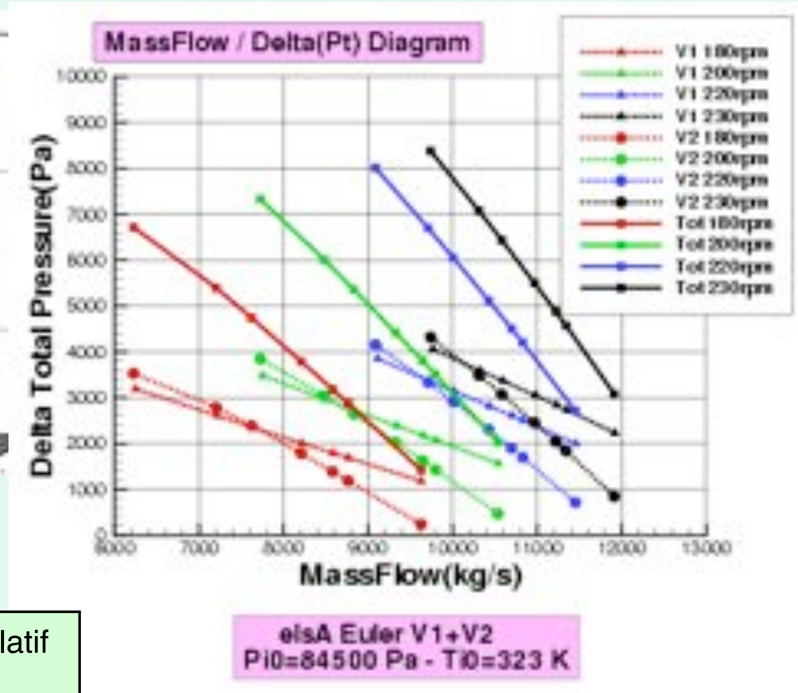
- 2 roues de 12 (V1) et 10 aubes (V2)
- 15 m de diamètre, moyeu de 7.5m de diamètre
- Chiffres caractéristiques:
  - Debit : ~9000kg/s
  - Compression : ~ 6000Pa
  - Vitesse de rotation : ~200 rpm



Champ compresseur (elsA Euler)





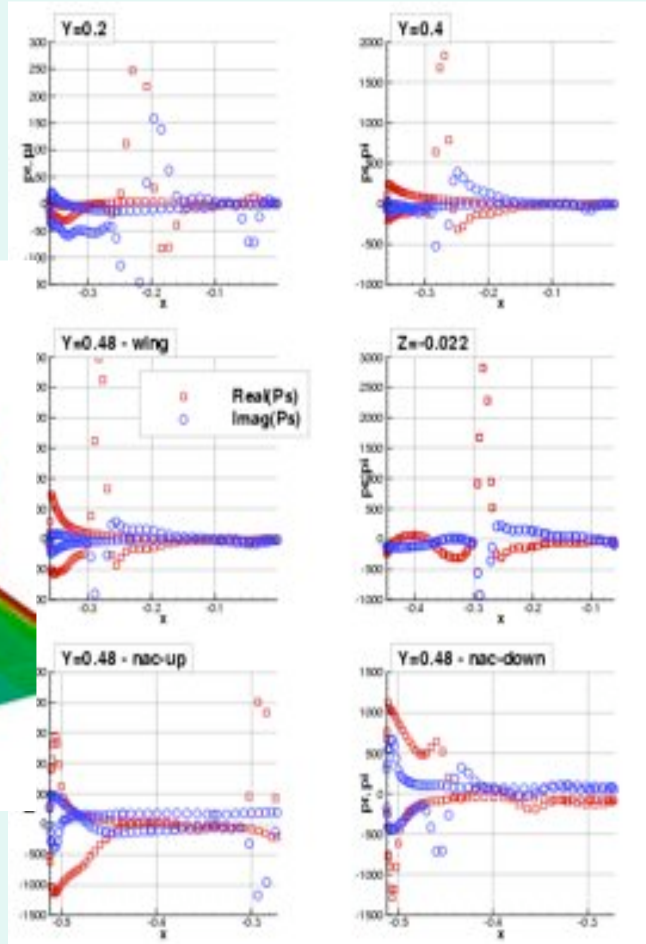


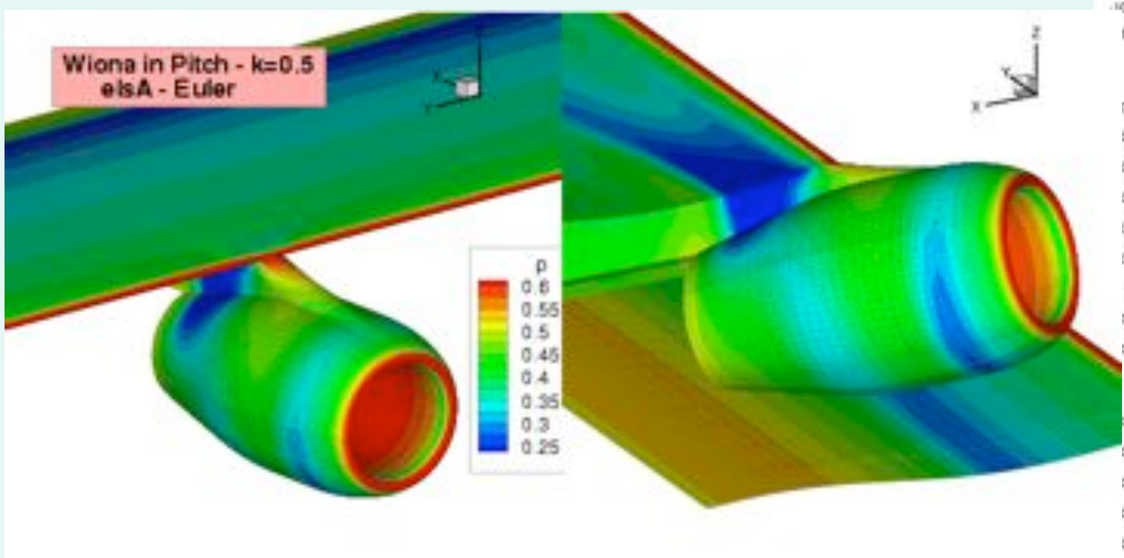
Roue V1 - Euler – Champ de Mach relatif
220 rpm – 9590 kg/s

Coopération ONERA / DLR NLAS: Wiona
Interaction aile/nacelle oscillante aéroélastique (2/2)

- elsA : Calcul Euler de tangage nacelle
- Mach=0.82 - i = -.6 deg - Pi0 = 60KPa - Ti0 =304 K
- Fréquence réduite K=0.5 – Amplitude 1 degré
- Maillage déformable

Analyse harmonique de pression





Pression réduite instationnaire

Billions of operations and billions of data : Actual top CFD computations for airplane design on the BULL Tera 10 (10 teraflops crest and number 5 in Top 500)

Complete drag of an aircraft in transonic regime requires:

- ***Navier-Stokes+turb.modelling. 800 procs and 250 hours allowing***

10exp18 flotting operations for giving precise drag/lift results

the computation requires also data on 110.000.000 tetraedra = 10exp10 octets

For historical comparison

-1984 first 3D inviscid transonic potential flow on a complete aircraft in my group (the first)

(10exp13 flops on 10exp 6 tetraedras)

-1989 first 3D transonic Euler+B.L. on a complete aircraft (10exp14flops on 10exp7 tet.)

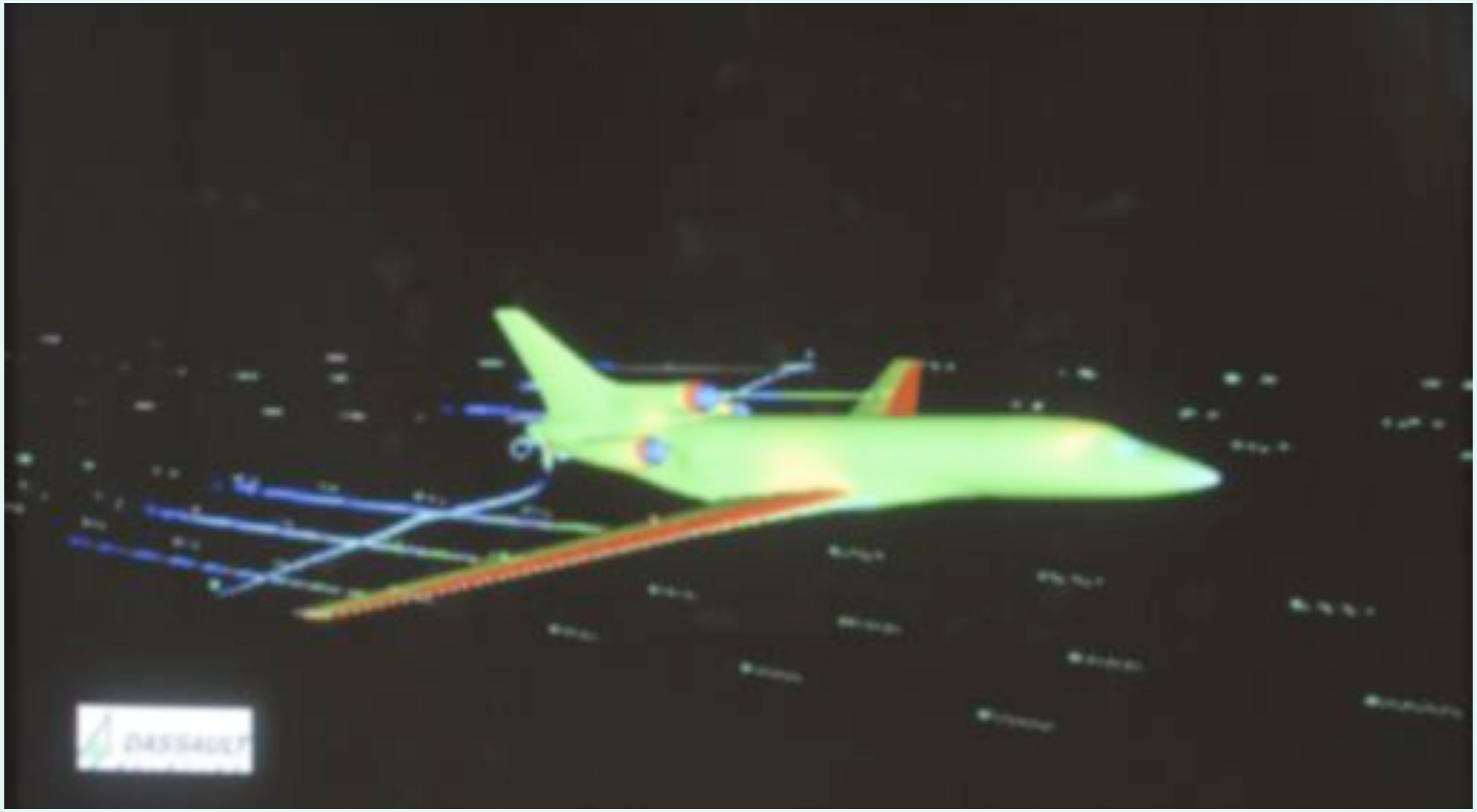
-1997 first 3D equivalent coupled Euler for transonic flutter virtual flight test and hypersonic(10exp16)

-2002 first 3D Car drag Euler analysis(10exp15)

-2007 First 3D Reynolds Averaged Navier-Stockes complete aircraft virtual flight for drag analysis

(10exp18 flops on 10exp 8 tetraedras)

B-- Falcon 7X transonic drag in cruise conditions as predicted by a RANS solver




DASSAULT

The Euler Step ?

- ***YES*** with or without boundary layer coupling ***real flight enveloppe*** (high incidence,Mach, far field acoustic; near field LES coupling ***and*** multiphysics)
- ***BUT remaining problems are still here***

--spurious entropy production coupled with mesh size/ singular curvature kinks/ dicontinuities / traling edges

--shear layer instability

--shock-waves spreading and distorsion-absorbing boundary conditions and far field vanishing sound and S—W propagation damping

--mass flow precise conservation (ducts) and facing non uniqueness in shocks and separations