The codes for fast computations of viscous transonic flow over wing/body/nacelle/tail configuration

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OBJECTIVE:

Development of the code for preliminary aerodynamic design of transonic transport configurations

REQUIREMENTS:

- Negligible computational time and resources. One computation 1~5min. (mean power PC computer)
- High reliability of results, capability to account properly for viscosity effects including moderate separation zones.
- Reliability, convenience for use by a designer. Possibility to be used as a “black box”.

COMPUTATIONAL METHOD:
VISCOUS-INVISCID INTERACTION

- External inviscid flow:
  solution of the conservative full potential equation;
  "Chimera" technique for complex configurations.

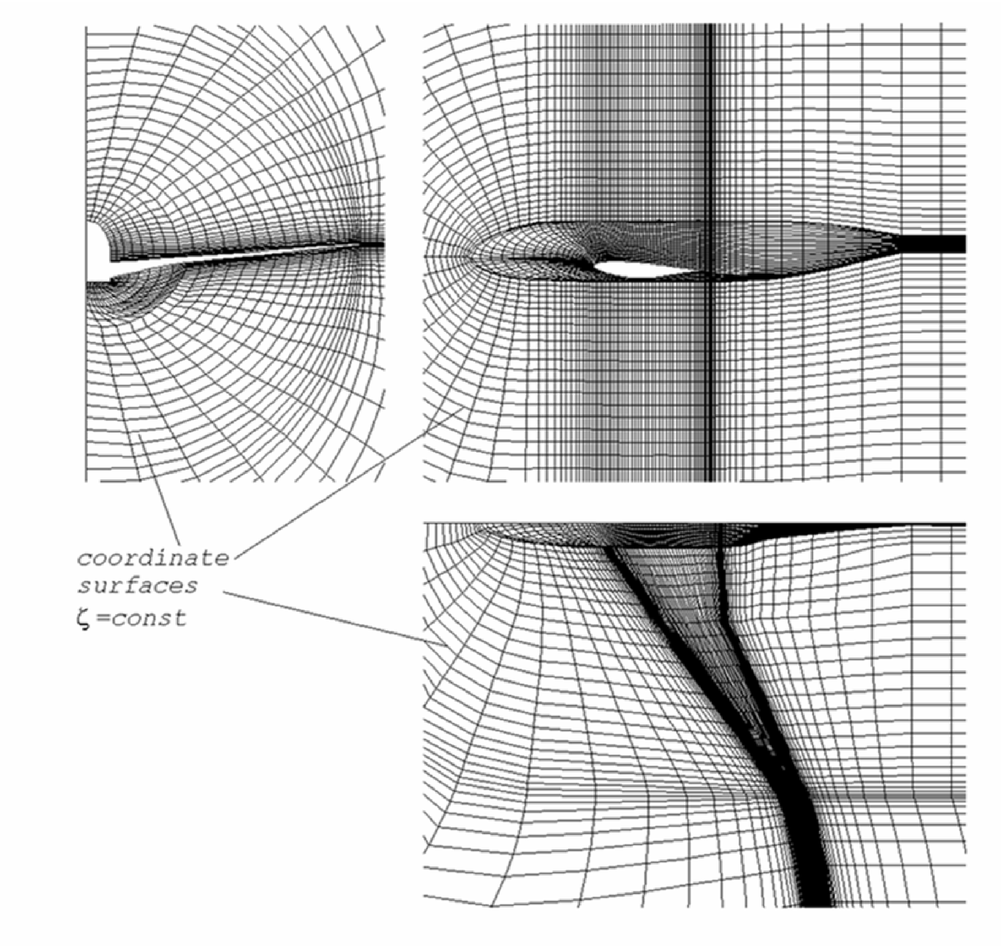
- Viscous region:
  finite-difference inverse method for calculation
  of 3-d compressible laminar and turbulent boundary layer;
  2-d integral or 3-d finite-difference method for viscous
  wake calculations.

- Viscous-inviscid coupling:
  quasi-simultaneous viscous-inviscid coupling scheme.
  (Rapid obtaining completely self-consistent solution: 6-8 viscous-inviscid iterations in case of moderate separation zones.)

EXTERNAL FLOW

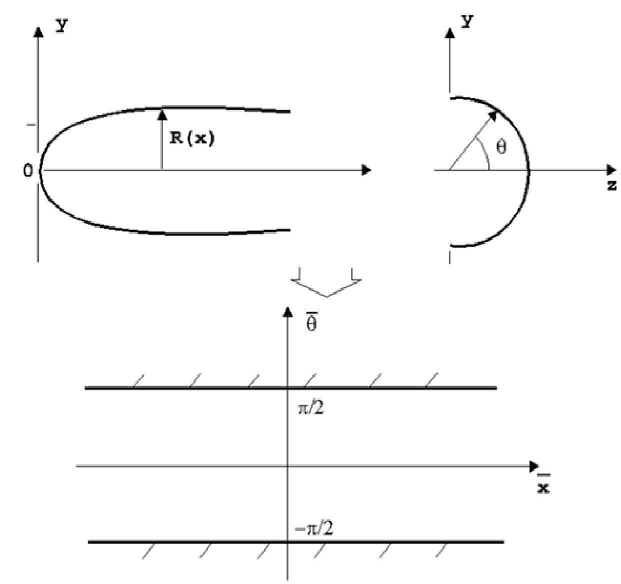
- Flexible algebraic 3-d grid generator.
- The solution of the conservative full potential equation by Approximate Factorization (AF) method (first or second order differentiable dissipation).
- "Chimera" algorithm for the calculation of the wing/body/nacelle/tail configuration.

Mesh generation. **Wing-body grid.**

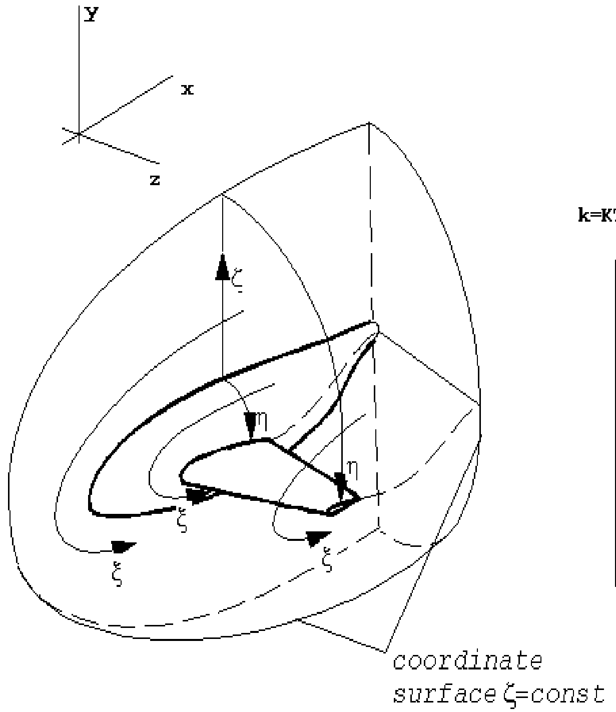


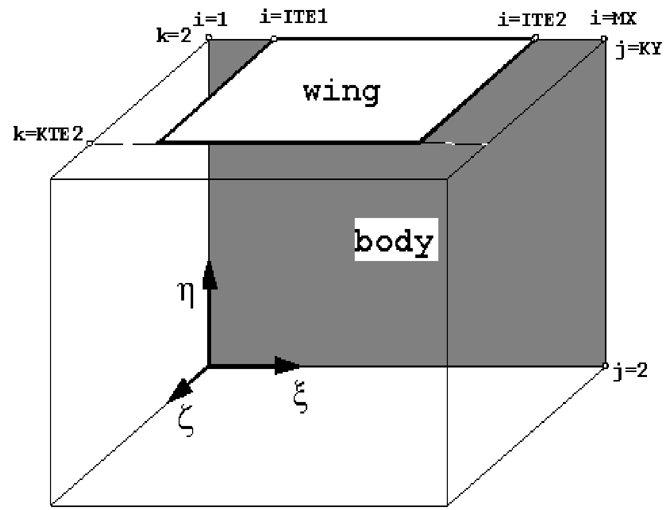
- Body of revolution angle-preserving mapping onto an infinite strip:

$$\bar{\theta} = \theta \qquad \bar{x} = \int_{x_* > 0}^{x} \left[\frac{1 + (dR/dx)^2}{R^2} \right]^{1/2} dx$$



Mesh generation. **Computational domain.**





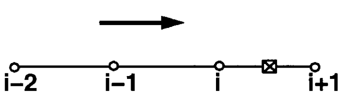
External flow. **Approximation.**

- CONSERVATIVE FULL POTENTIAL EQUATION

$$[\bar{\rho}U/J]_{\xi} + [\tilde{\rho}V/J]_{\eta} + [\rho W/J]_{\zeta} = 0.$$

- MODIFIED FINITE-VOLUME APPROXIMATION (**Too skewed grids are admissible**)
- NON-ISENTROPIC PROPERTIES OF THE FLOW ARE TAKEN INTO ACCOUNT

- FIRST OR SECOND ORDER ENQUIST-OSHER'S TYPE MULTIPLICATIVE DIFFERENTIABLE MONOTONIC ARTIFICIAL DISSIPATION SCHEME (**The lack of limiters promotes a high convergence speed**)



$$\tilde{\rho}_{i+1/2} = Q(q_{i+1/2}, \bar{q})/q_{i+1/2}$$

First order scheme : $\bar{q} = q_{i-1/2}$

Second order scheme : $\bar{q} = 2q_{i-1/2} - q_{i-3/2}$

Traditional Osher scheme : $Q(q_{i+1/2}, \bar{q}) = R(q_{i+1/2}) + L(\bar{q}) - \rho^* q^*$

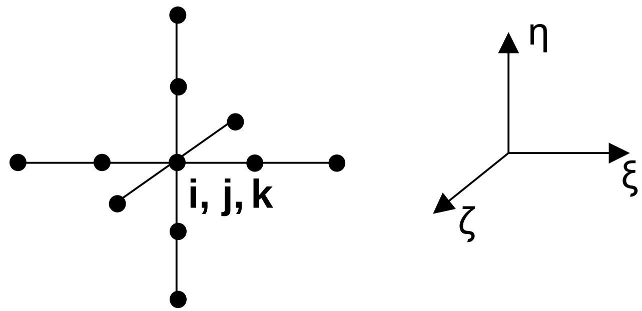
Multiplicative Osher scheme : $Q(q_{i+1/2}, \bar{q}) = \dfrac{R(q_{i+1/2}) * L(\bar{q})}{\rho^* q^*}$

$$R(q) = \begin{cases} \rho q, & q < q^* \\ \rho^* q^*, & q > q^* \end{cases} \qquad L(q) = \begin{cases} \rho^* q^*, & q < q^* \\ \rho q, & q > q^* \end{cases}$$

External flow. **Iterative solution.**

- The system of linear equation for the correction is constructed on the basis of the approximate Newton's fluxes linearization. **The artificial density is linearized.**

$$\left[d^{(3)}_{i,j,k}\overrightarrow{\delta}_{\xi} - d^{(2)}_{i,j,k}\overleftarrow{\delta}_{\xi} + d^{(5)}_{i,j,k}\overrightarrow{\delta}_{\eta} - d^{(4)}_{i,j,k}\overleftarrow{\delta}_{\eta} + \overleftarrow{\delta}_{\zeta} d^{(6)}_{i,j,k+1/2}\overrightarrow{\delta}_{\zeta} + d^{(8)}_{i,j,k}E^{+}_{\xi}\overrightarrow{\delta}_{\xi} - d^{(7)}_{i,j,k}E^{-}_{\xi}\overleftarrow{\delta}_{\xi} \right] C_{i,j,k} = -r_{i,j,k}$$



$$C = \Phi^{(n)} - \Phi^{(n-1)}$$

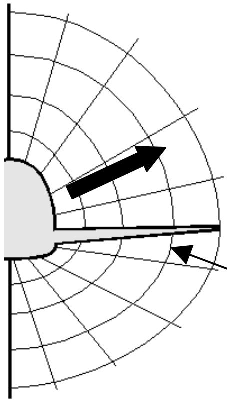
- The operator for the correction is constructed on the basis of approximate factorisation as a product of two operators:

$$\left[\sigma \overleftarrow{\delta}_{\zeta} d^{(6)}_{i,j,k+1/2} - d^{(3)}_{i,j,k}\overrightarrow{\delta}_{\xi} + d^{(2)}_{i,j,k}\overleftarrow{\delta}_{\xi} - d^{(5)}_{i,j,k}\overrightarrow{\delta}_{\eta} + d^{(4)}_{i,j,k}\overleftarrow{\delta}_{\eta} - \right.$$

$$\left. - d^{(8)}_{i,j,k}E^{+}_{\xi}\overrightarrow{\delta}_{\xi} + d^{(7)}_{i,j,k}E^{-}_{\xi}\overleftarrow{\delta}_{\xi} \right] \left[\sigma - \overrightarrow{\delta}_{\zeta} \right] C_{i,j,k} = \sigma \omega r_{i,j,k}$$

External flow. **Iterative solution.**

- Direct sweep (intermidiate values $\overline{C}_{ijk}$ definition)

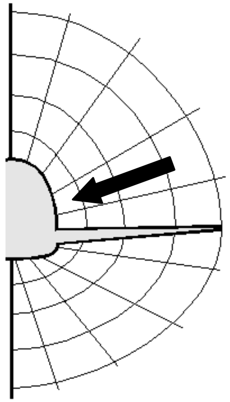


$$d^{(1)}_{ijk}\overline{C}_{ijk} - d^{(2)}_{ijk}\overline{C}_{i-1jk} - d^{(3)}_{ijk}\overline{C}_{i+1jk} - d^{(4)}_{ijk}\overline{C}_{ij-1k} - d^{(5)}_{ijk}\overline{C}_{ij+1k} -$$

$$- d^{(8)}_{ijk}\vec{\delta}_{\xi}\,\overline{C}_{i+1jk} + d^{(7)}_{ijk}\overleftarrow{\delta}_{\xi}\,\overline{C}_{i-1jk} = \overline{r}_{ijk} \qquad \overline{r}_{ijk} = \sigma\omega r_{ijk} - \sigma d^{(6)}_{ijk\text{-}1/2}\overline{C}_{ijk\text{-}1}$$

In plane ζ=const an approximate solution for intermediate values $\overline{C}_{ijk}$ is carried out on the base of **LU** approximate decomposition + **GMRES** algorithm. (**L** and **U** are four-diagonal matrixes)

- Inverse sweep (correction C_{ijk} definition)



$$\left[\sigma - \vec{\delta}_{\zeta}\right] C_{i,j,k} = \overline{C}_{i,j,k}$$

CALCULATION OF THE 3-D COMPRESSIBLE BOUNDARY LAYER

- Finite-difference method for calculation of 3-d compressible laminar and turbulent boundary layer:
  Predictor-corrector or upwind approximation scheme

- Separation regions:
  Raihner and Flugge-Lotz approximation + *inverse mode*

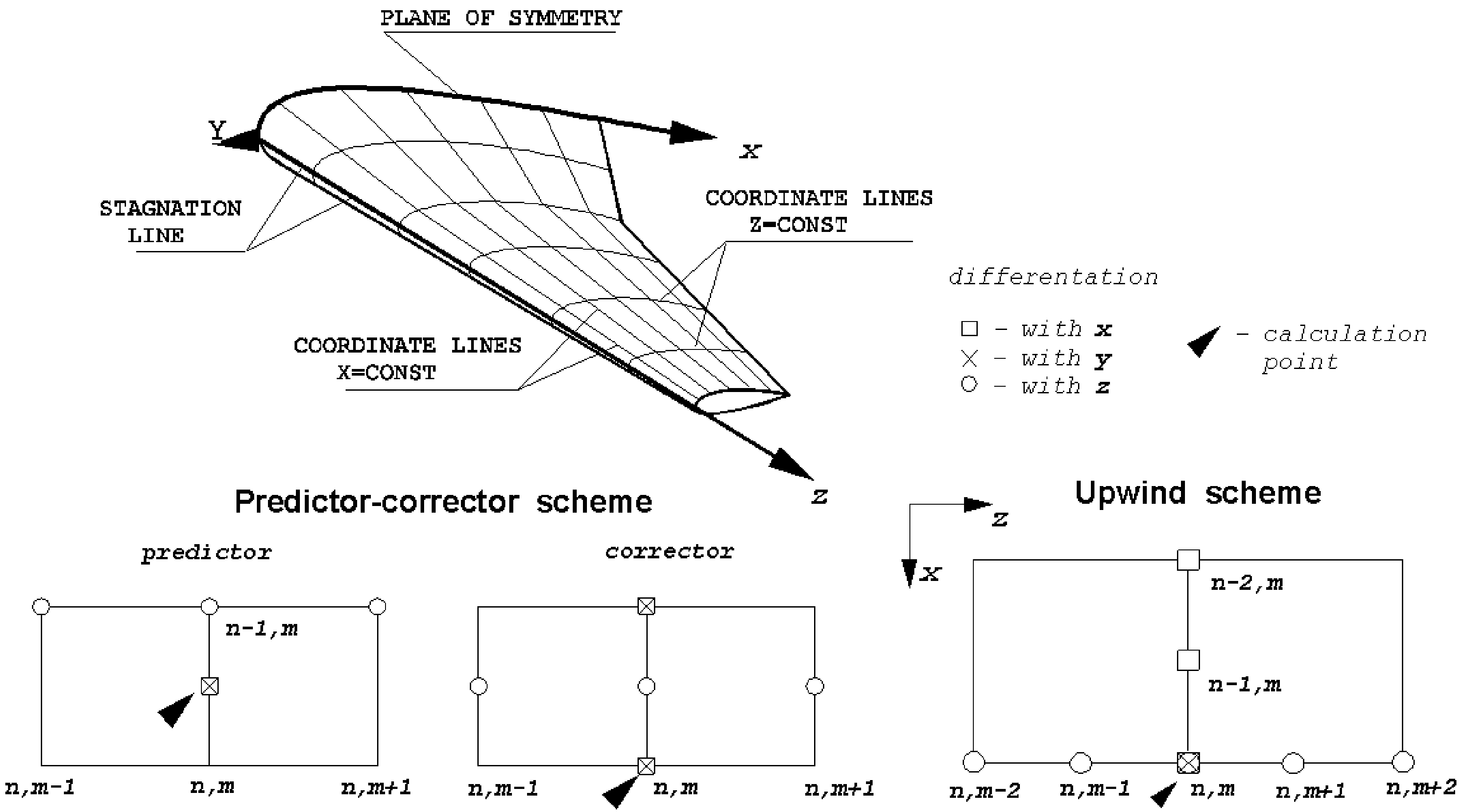
- Viscous wake:
  2-d integral method (Green) at wake sections
  3-d finite-difference method

- Algebraic or not equilibrium (Spalart-Almaras) eddy viscosity models.

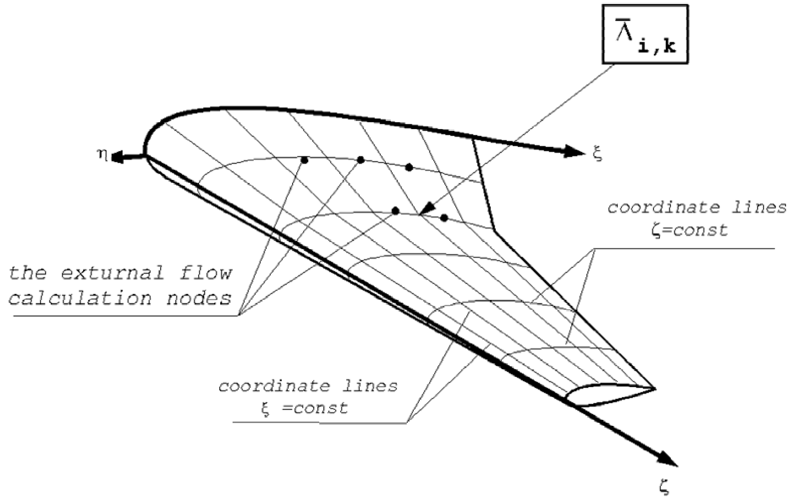
SYSTEM OF EQUATIONS OF 3-D COMPRESSIBLE BOUNDARY LAYER

$$\left.\begin{aligned}
&\frac{\partial}{\partial \boldsymbol{x}}(\rho \boldsymbol{u} \boldsymbol{h}_2 \sin\theta) + \frac{\partial}{\partial \boldsymbol{z}}(\rho \boldsymbol{w} \boldsymbol{h}_1 \sin\theta) + \boldsymbol{h}_1 \boldsymbol{h}_2 \sin\theta \frac{\partial}{\partial \boldsymbol{y}}(\rho \boldsymbol{v}) = 0 \\
&\rho \frac{\boldsymbol{u}}{\boldsymbol{h}_1}\frac{\partial \boldsymbol{u}}{\partial \boldsymbol{x}} + \rho \frac{\boldsymbol{w}}{\boldsymbol{h}_2}\frac{\partial \boldsymbol{u}}{\partial \boldsymbol{z}} + \overline{\rho \boldsymbol{v}}\frac{\partial \boldsymbol{u}}{\partial \boldsymbol{y}} - \rho \boldsymbol{k}_1 \boldsymbol{u}^2 \cot\theta + \rho \boldsymbol{k}_2 \boldsymbol{w}^2 \csc\theta + \rho \boldsymbol{k}_{12} \boldsymbol{u}\boldsymbol{w} = \\
&\qquad = -\frac{\csc^2\theta}{\boldsymbol{h}_1}\frac{\partial \boldsymbol{p}}{\partial \boldsymbol{x}} + \frac{\cot\theta \csc\theta}{\boldsymbol{h}_2}\frac{\partial \boldsymbol{p}}{\partial \boldsymbol{z}} + \frac{\partial}{\partial \boldsymbol{y}}\left(\mu \frac{\partial \boldsymbol{u}}{\partial \boldsymbol{y}} - \overline{\rho \boldsymbol{u}'\boldsymbol{v}'}\right) \\
&\rho \frac{\boldsymbol{u}}{\boldsymbol{h}_1}\frac{\partial \boldsymbol{w}}{\partial \boldsymbol{x}} + \rho \frac{\boldsymbol{w}}{\boldsymbol{h}_2}\frac{\partial \boldsymbol{w}}{\partial \boldsymbol{z}} + \overline{\rho \boldsymbol{v}}\frac{\partial \boldsymbol{w}}{\partial \boldsymbol{y}} - \rho \boldsymbol{k}_2 \boldsymbol{w}^2 \cot\theta + \rho \boldsymbol{k}_1 \boldsymbol{u}^2 \csc\theta + \rho \boldsymbol{k}_{21} \boldsymbol{u}\boldsymbol{w} = \\
&\qquad = \frac{\cot\theta \csc\theta}{\boldsymbol{h}_1}\frac{\partial \boldsymbol{p}}{\partial \boldsymbol{x}} - \frac{\csc^2\theta}{\boldsymbol{h}_2}\frac{\partial \boldsymbol{p}}{\partial \boldsymbol{z}} + \frac{\partial}{\partial \boldsymbol{y}}\left(\mu \frac{\partial \boldsymbol{w}}{\partial \boldsymbol{y}} - \overline{\rho \boldsymbol{w}'\boldsymbol{v}'}\right)
\end{aligned}\right\}$$

FINITE-DIFFERENCE STENCILS FOR BOUNDARY LAYER CALCULATION



BOUNDARY LAYER. CALCULATION PROCEDURE



- algebraic system for the vector of the boundary layer parameters $\vec{\Delta}_{i,k}$

$$[D]\vec{\Delta}_{i,k} = \vec{R} + \vec{R}_{\xi}\left(p_{\xi}\right)_{i,k} + \vec{R}_{\zeta}\left(p_{\zeta}\right)_{i,k}$$

p_{ξ}, p_{ζ} - **partial pressure derivatives**

$\vec{R}, \vec{R}_{\xi}, \vec{R}_{\zeta}$ - **known vectors**

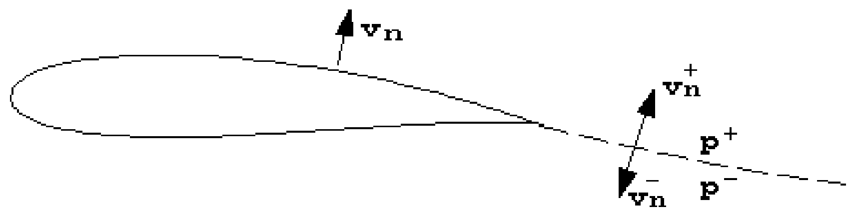
$[D]$ - **known matrix**

- representation of the solution as a linear combination of partial solutions (pressure derivatives are considered as parameters):

$$\vec{\Delta}_{i,k} = \vec{Y} + \vec{X}\left(p_{\xi}\right)_{i,k} + \vec{Z}\left(p_{\zeta}\right)_{i,k}$$

$$[D]\vec{Y} = \vec{R}, \quad [D]\vec{X} = \vec{R}_{\xi}, \quad [D]\vec{Z} = \vec{R}_{\zeta}$$

QUASI-SIMULTANEOUS COUPLING SCHEME:



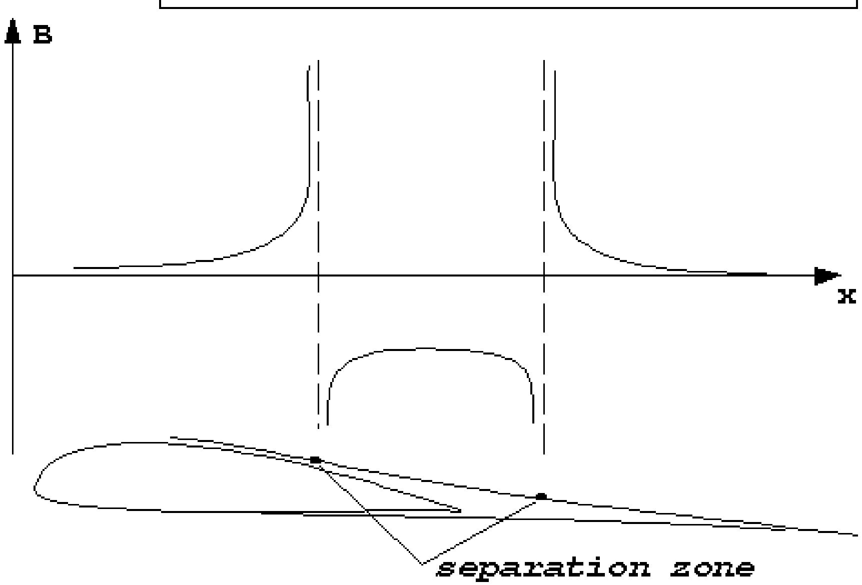
surface: $$v_n^b = \frac{1}{\rho_e} \frac{d(\rho_e u_e^b \delta^*)}{ds}$$

wake: $$\Delta v_n^b = \frac{1}{\rho_e} \frac{d(\rho_e u_e^b \delta^*)}{ds}$$

Coupling condition:

$$v_n^b = v_n^i \,, \quad \Delta v_n^b = \Delta v_n^i$$

$$u_e^b = u_e^i$$



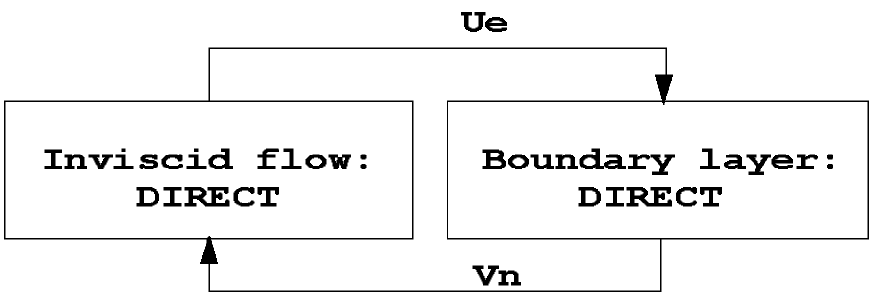
$$v_n^b = B * (du_e^b/ds) + C$$

$$\Downarrow$$

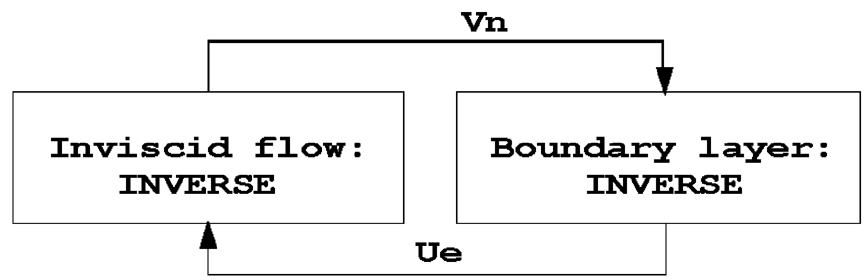
$$v_n^i - v_n^b = B * (du_e^i/ds - du_e^b/ds)$$

ALGORITHMS OF VISCOUS-INVISCID INTERACTION:

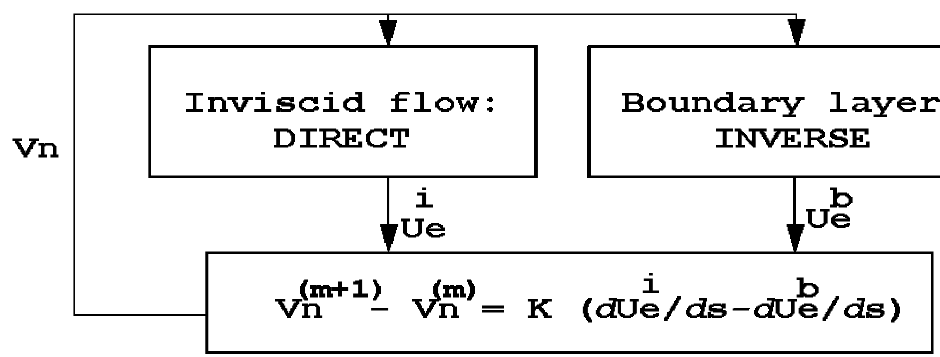
Direct coupling:



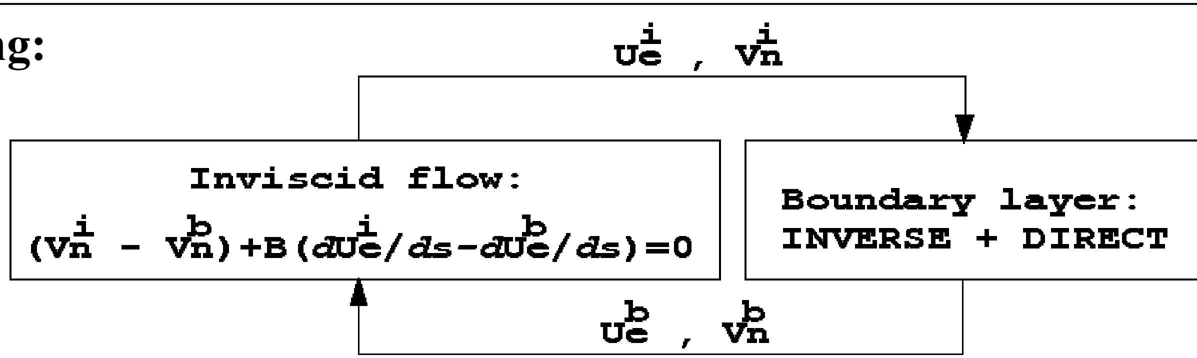
Inverse coupling:



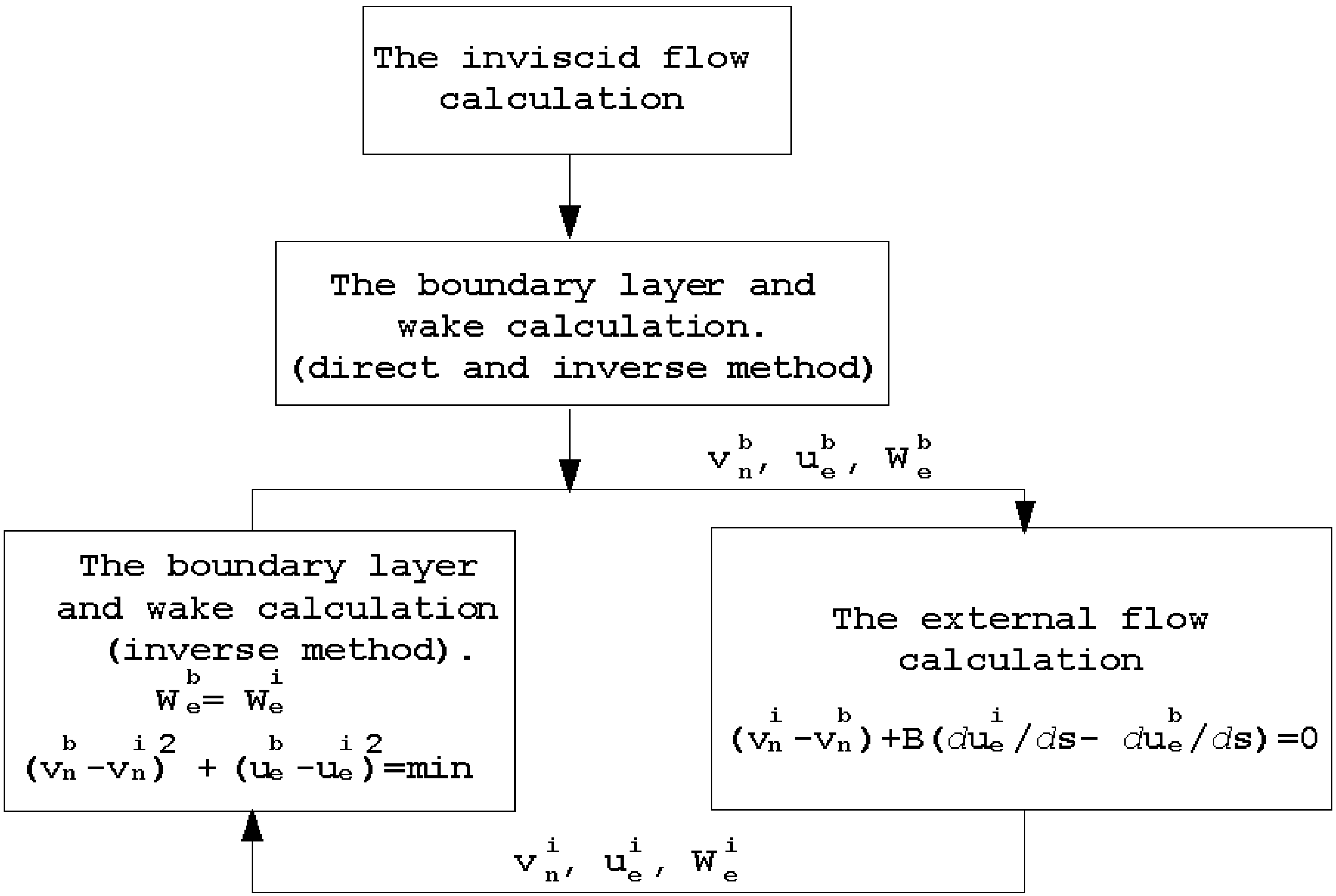
Semi-inverse coupling:



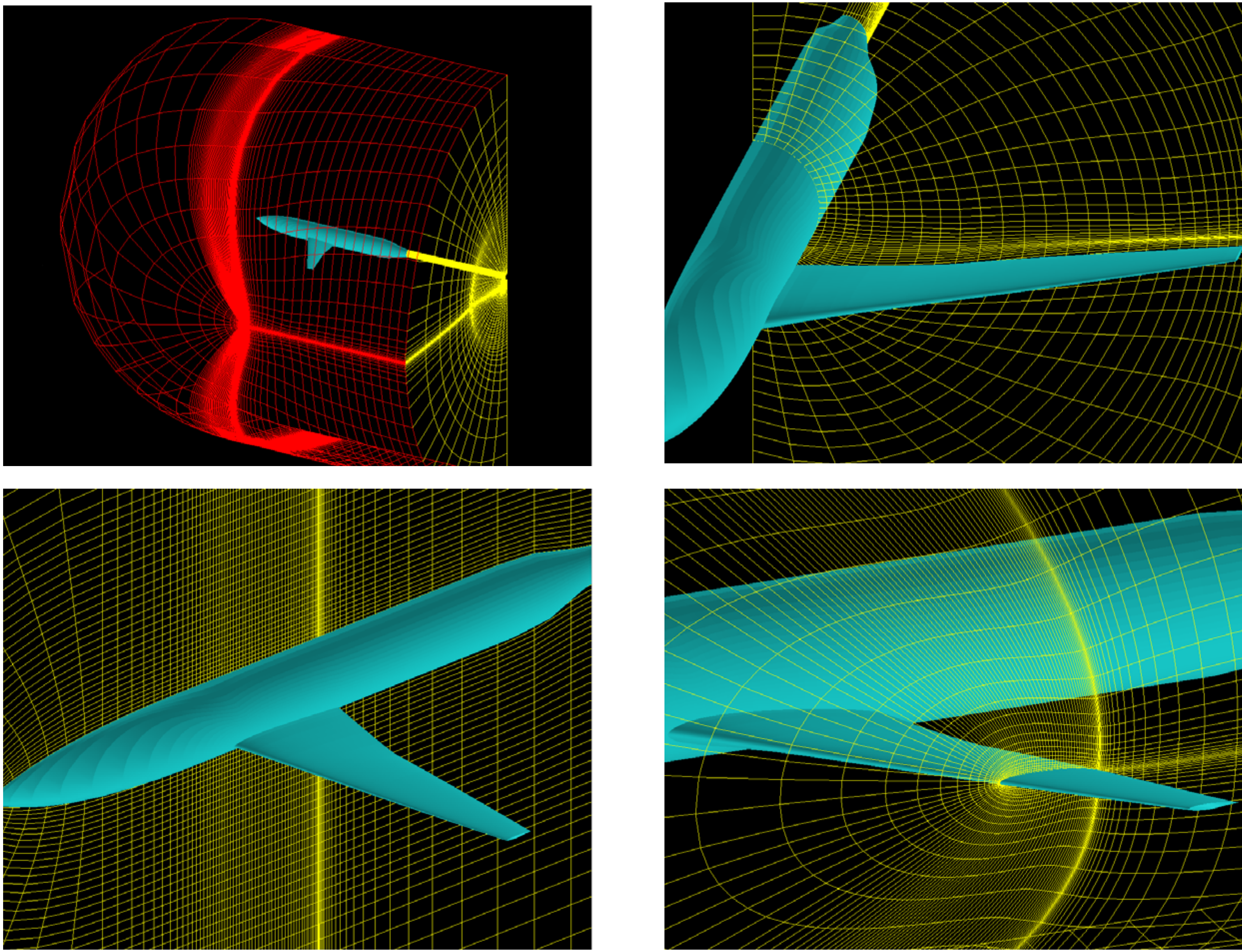
Quasi-simultaneous coupling:



QUASI-SIMULTANEOUS COUPLING SCHEME:

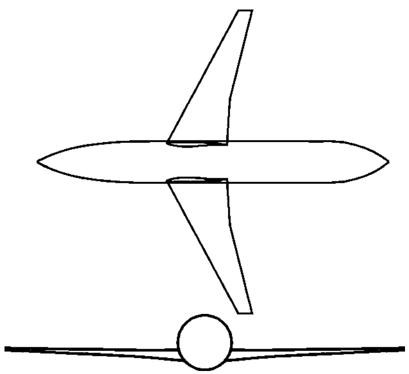


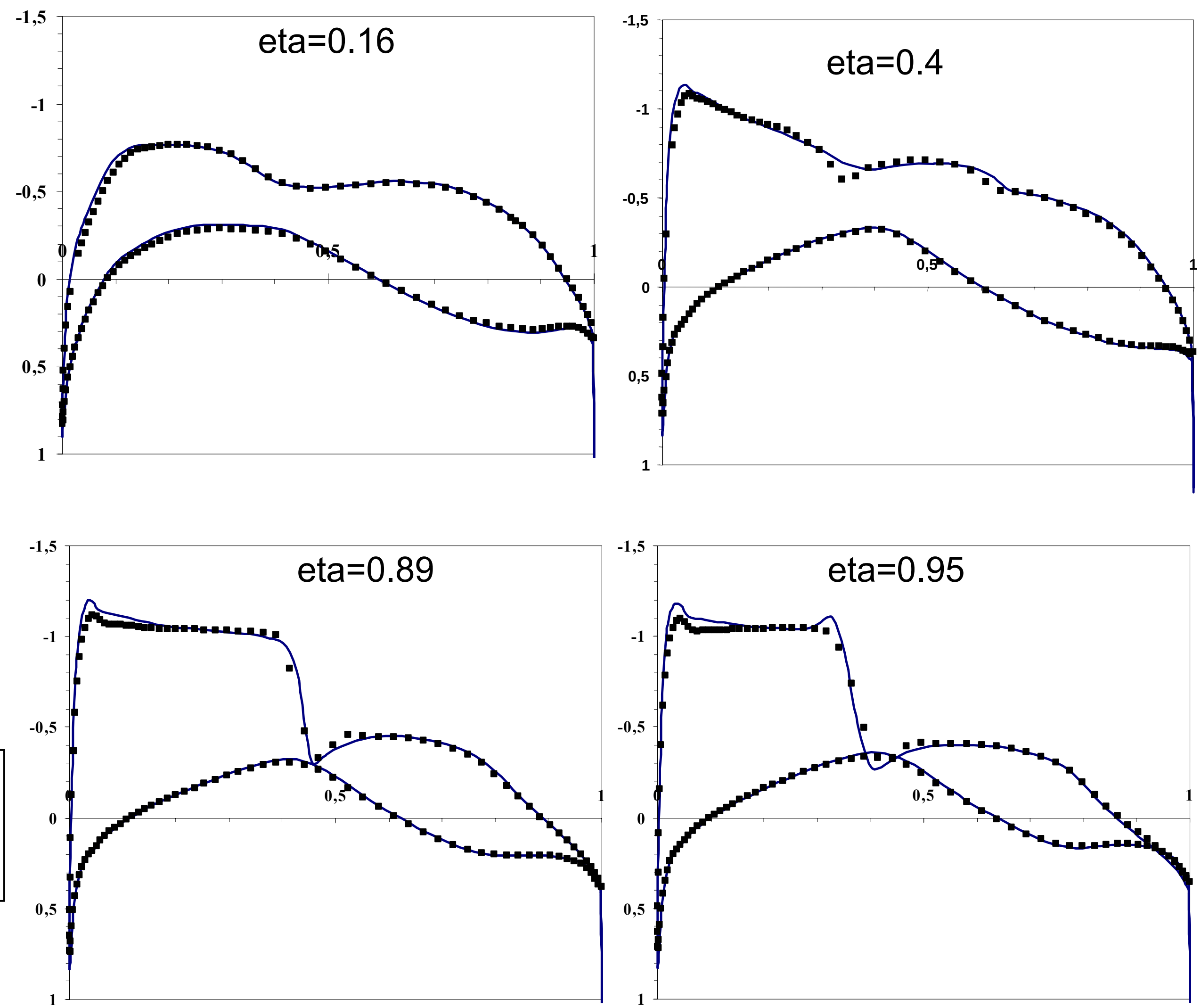
Wing-body W4: **computational mesh**



Wing/body W4: **Comparison with Euler computation (inviscid flow)**

M=0.78, alpha=0
beta=0, inviscid

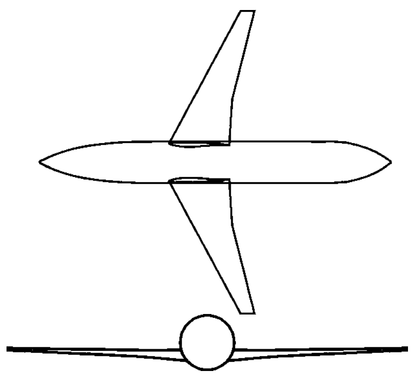




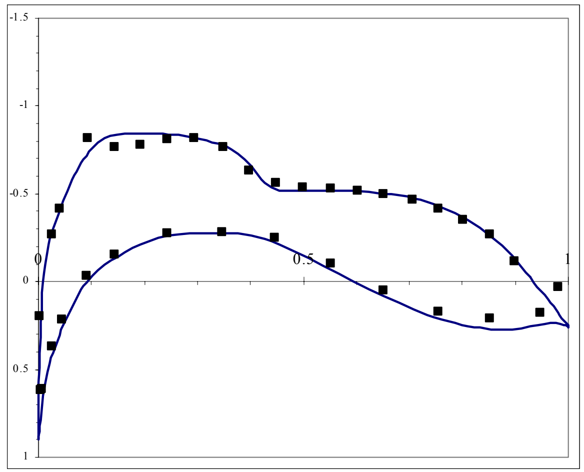
— **BLWF**
■ ■ ■ **Euler calculation**

Wing/body W4 configuration

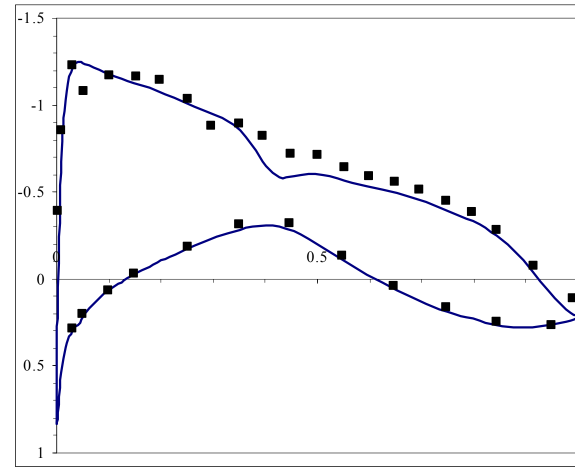
M=0,78 Alpha=0.84 Re =12 mill



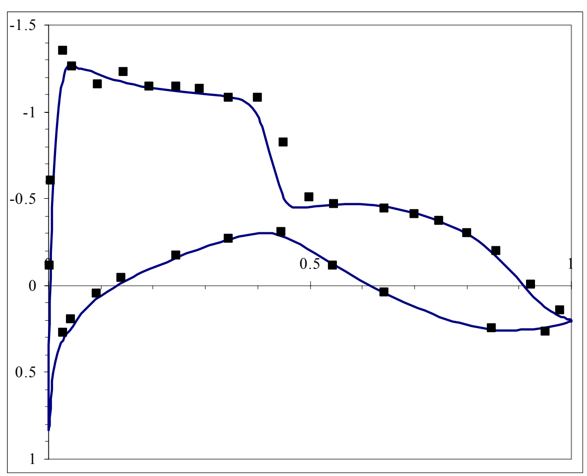
eta=0.16



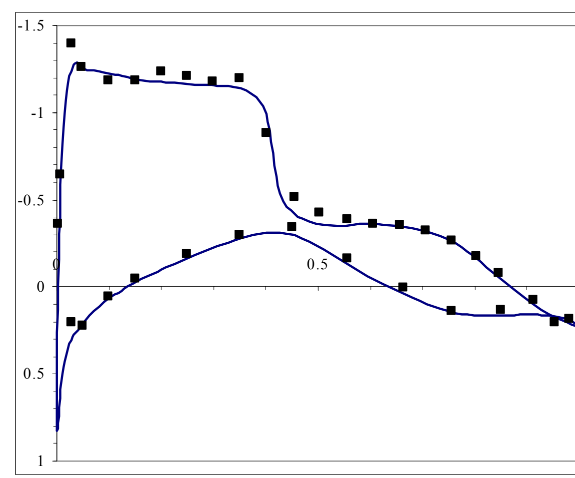
eta=0.4



eta=0.65

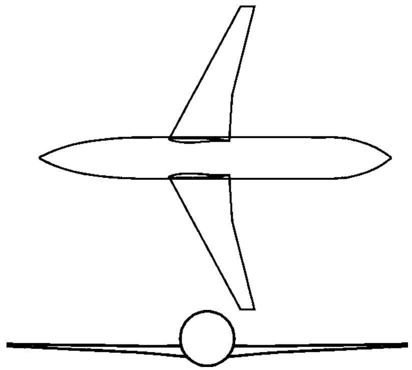


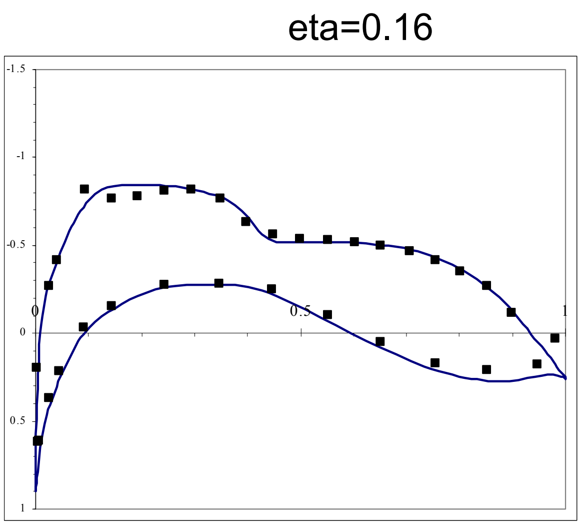
eta=0.89

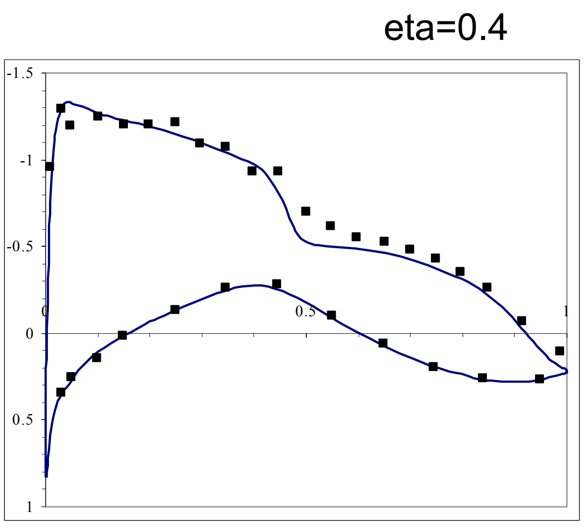


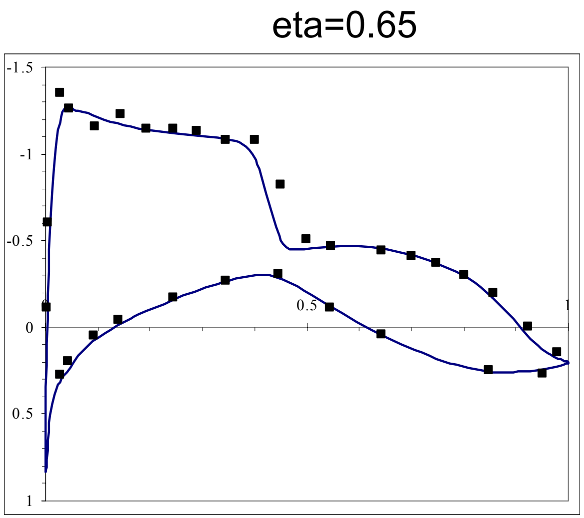
Wing/body W4 configuration

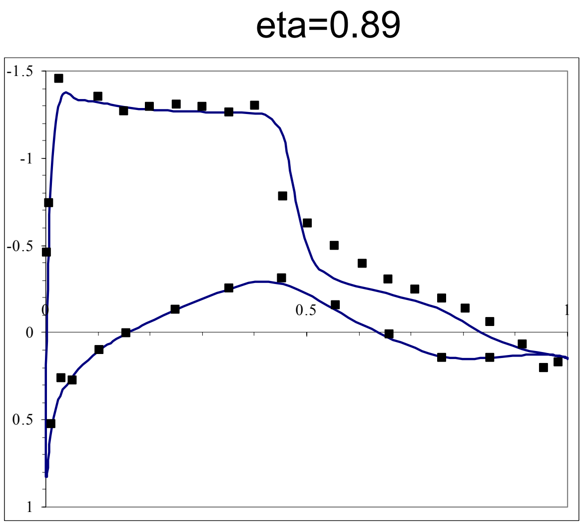
M=0,78 Alpha=1.39 Re =12 mill





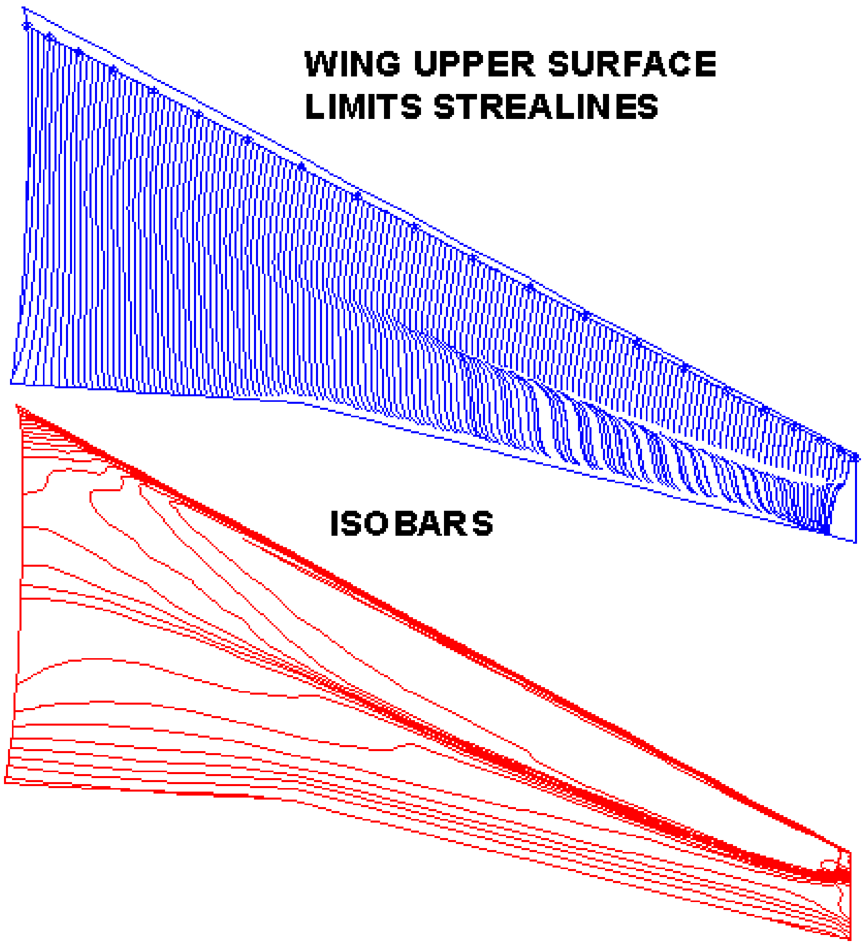


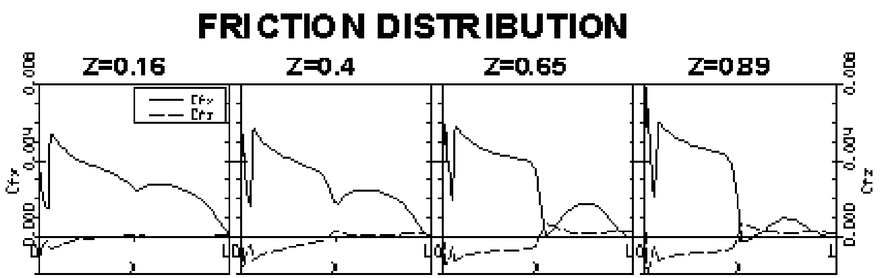


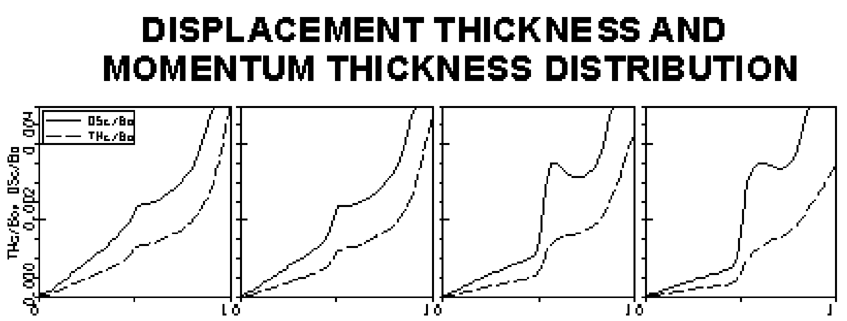


Wing/body W4 test: **boundary layer parameters.**

Wing-body W4. M =.75, CL=0.48, BETA=0º, Re=3.0*10⁶

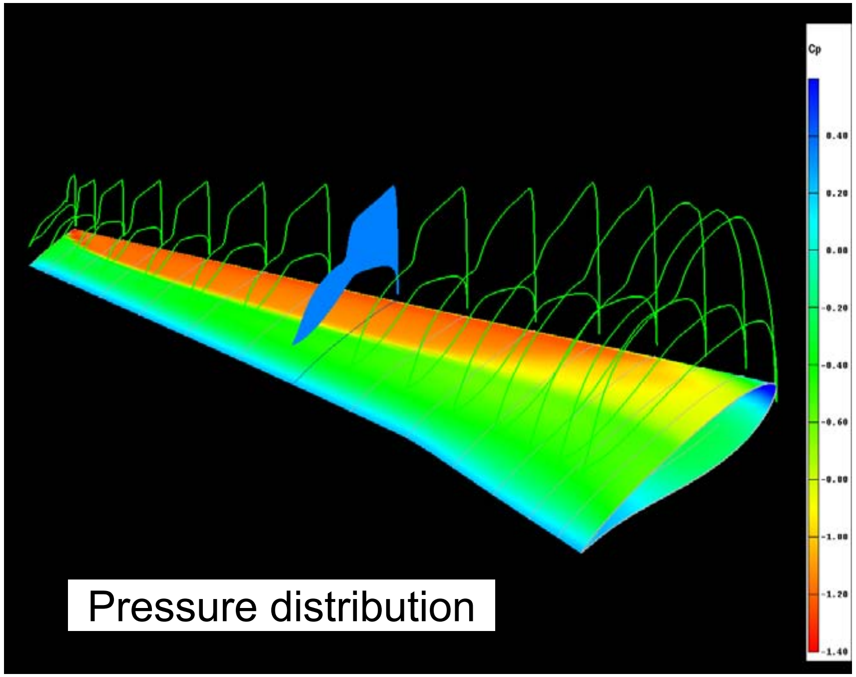


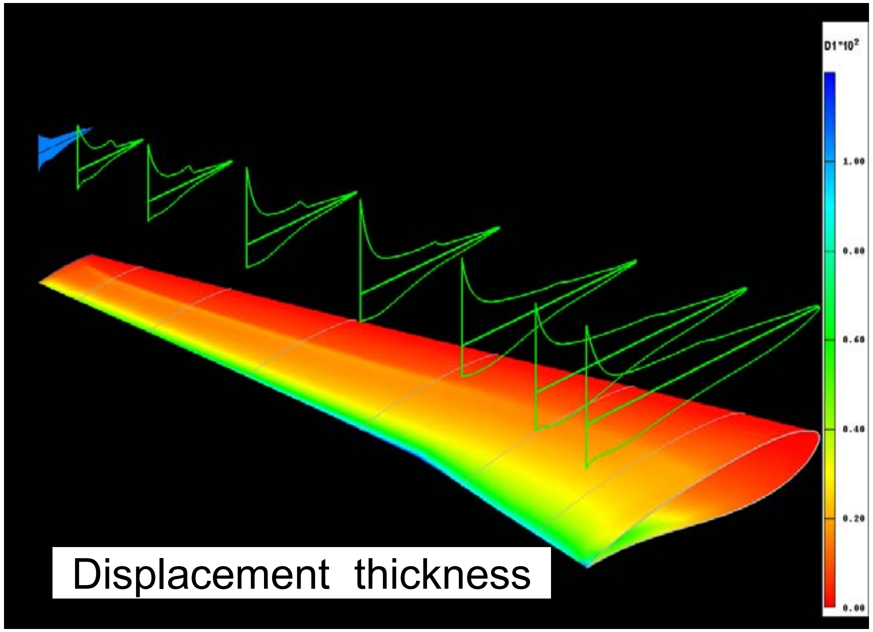


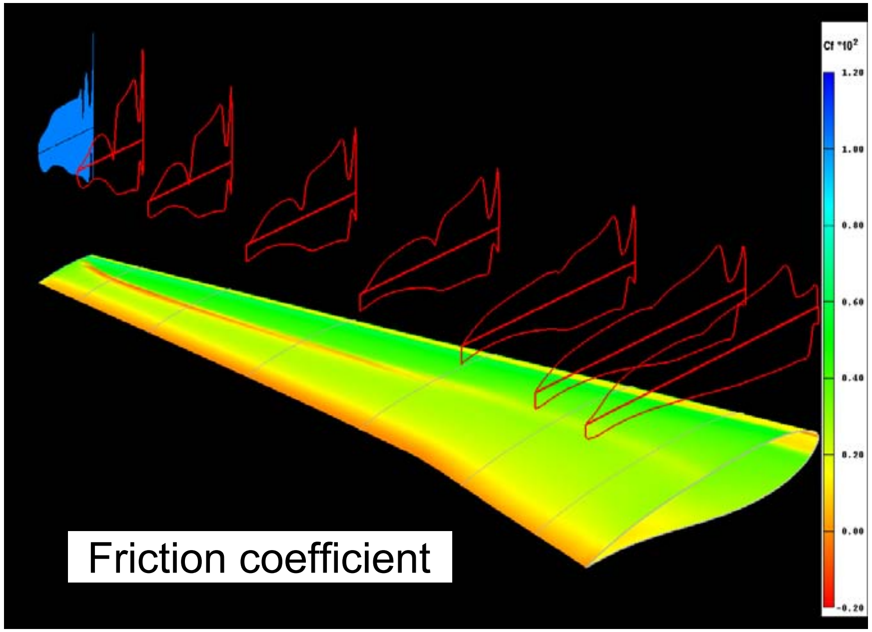


Wing/body W4 configuration

M=0.78 Alpha=0.84
Re=12 mill

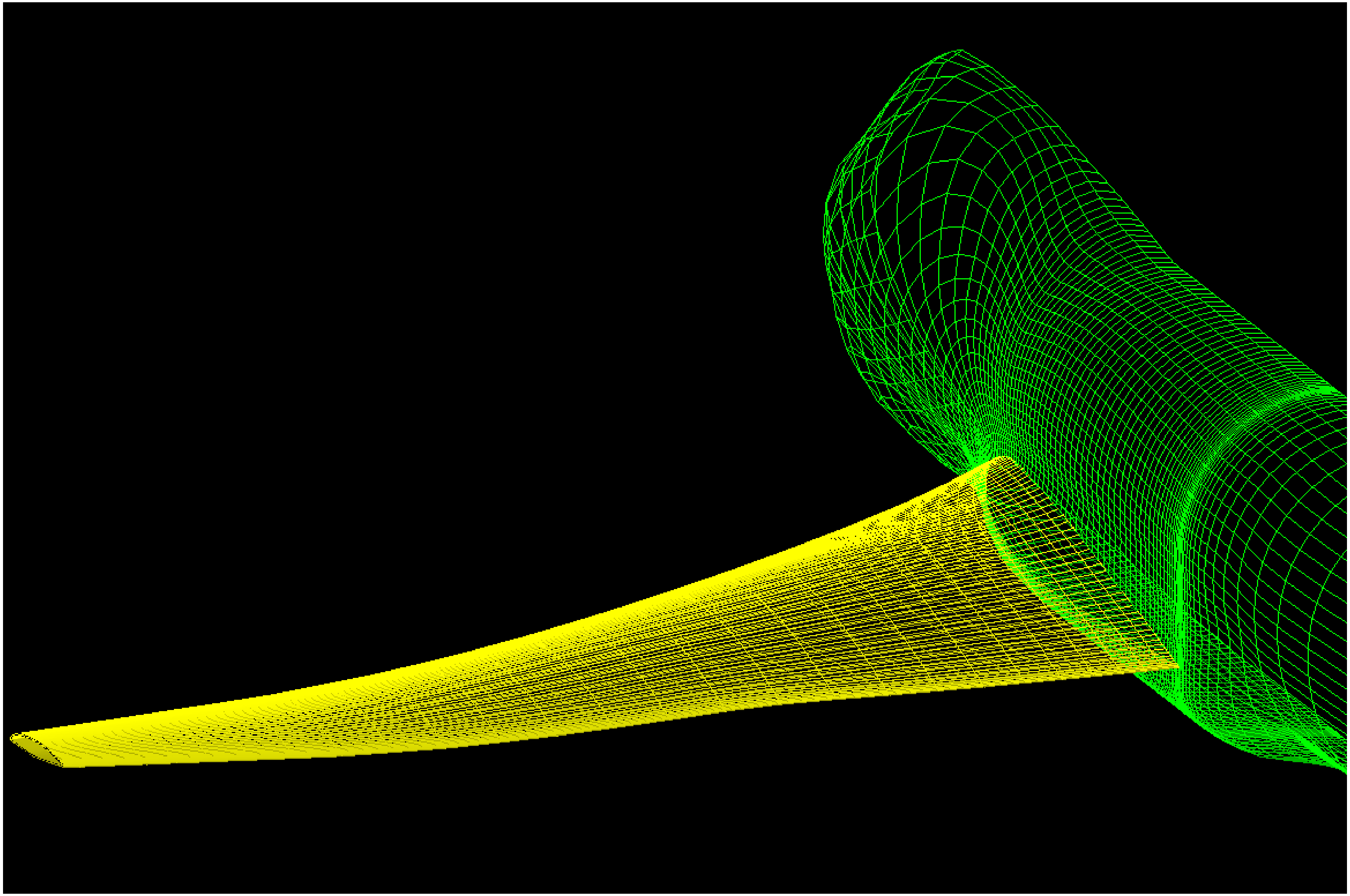






WING/BODY B-747

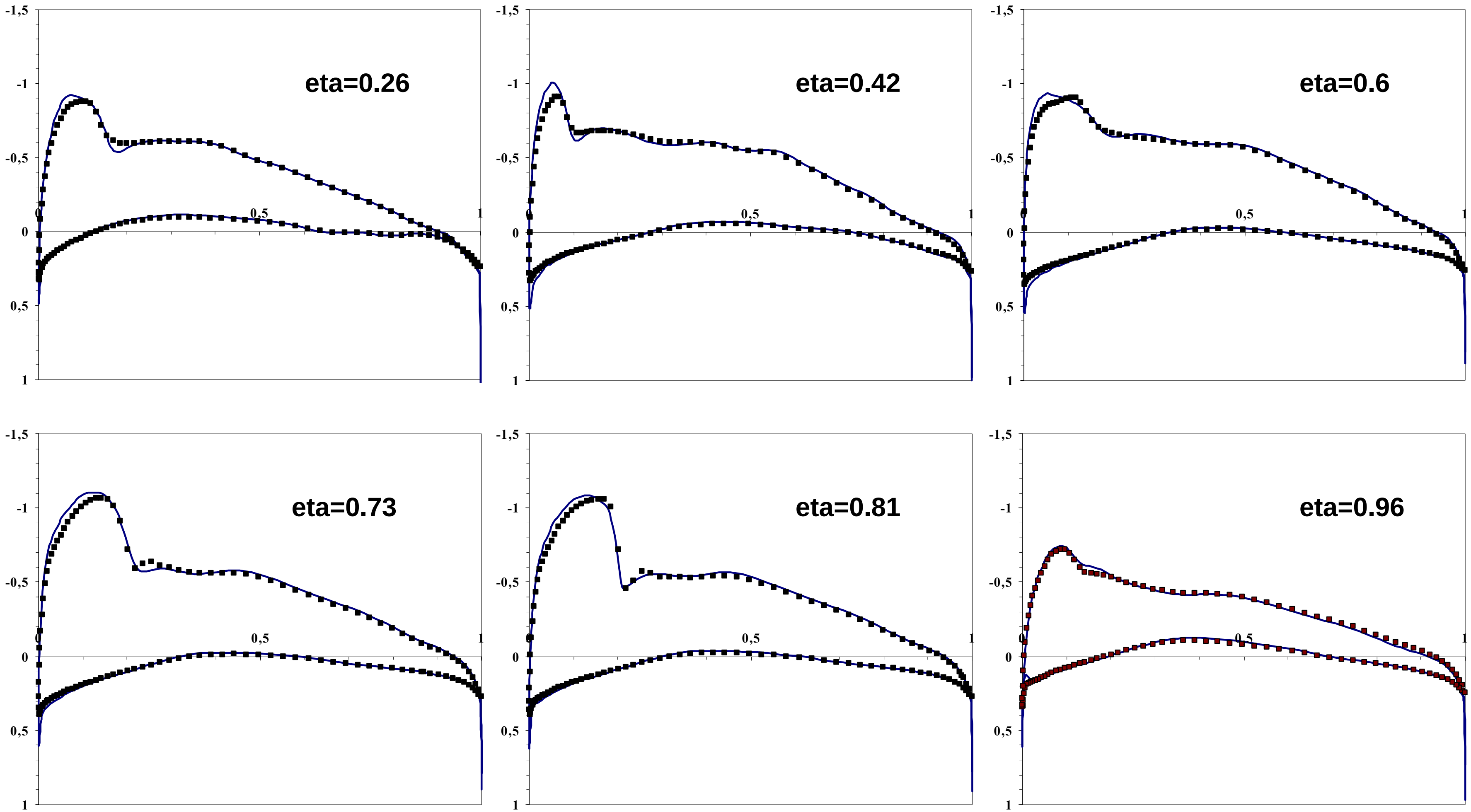
Surface grid: wing 3741 nodes (129*29), body 4175 nodes (167*25)



WING/BODY B747. **Comparison with Euler computation (inviscid flow)**

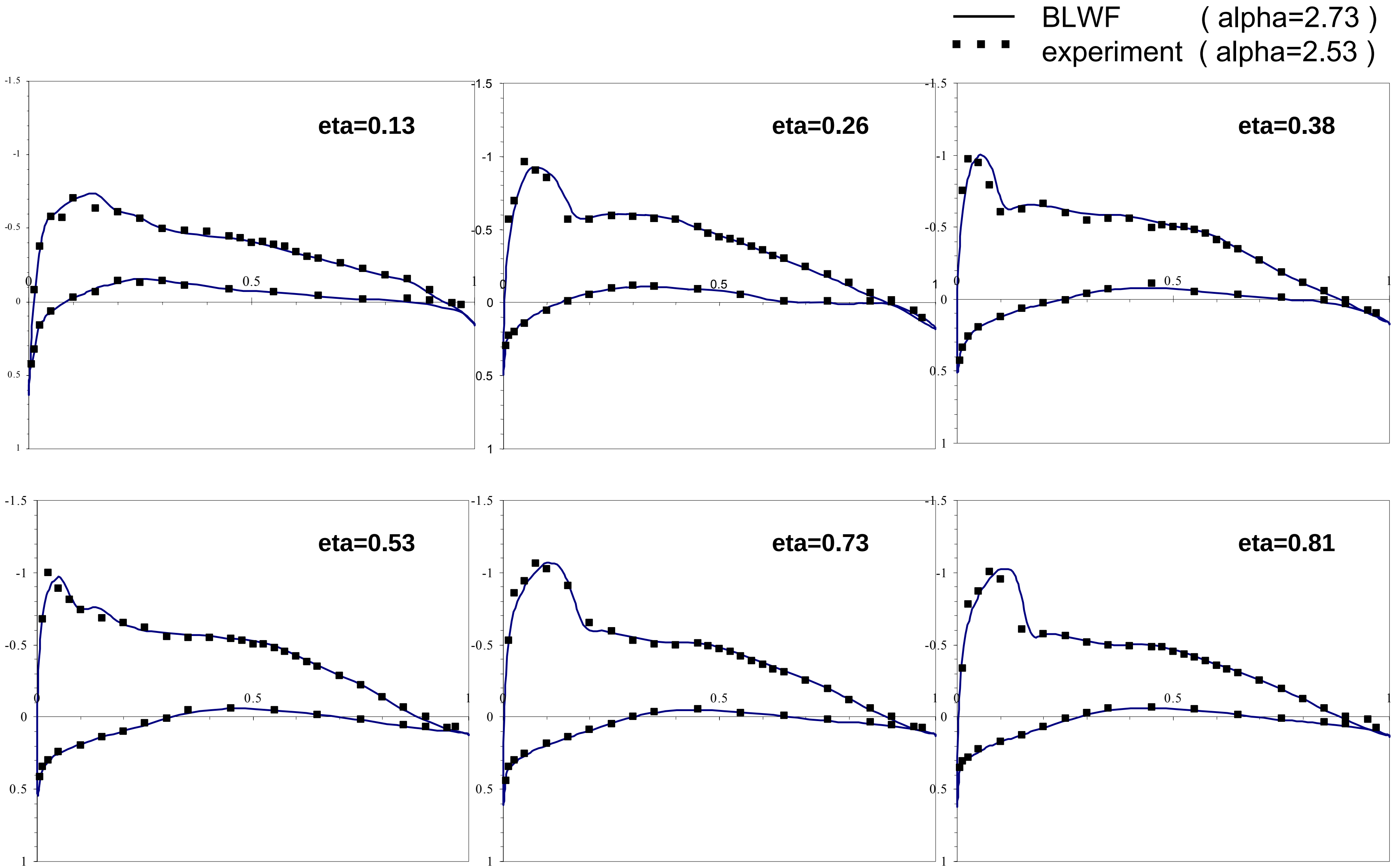
M=0.8 Clift=0.383

BLWF calculation, alpha=2.5
Euler calculation, alpha=2.3



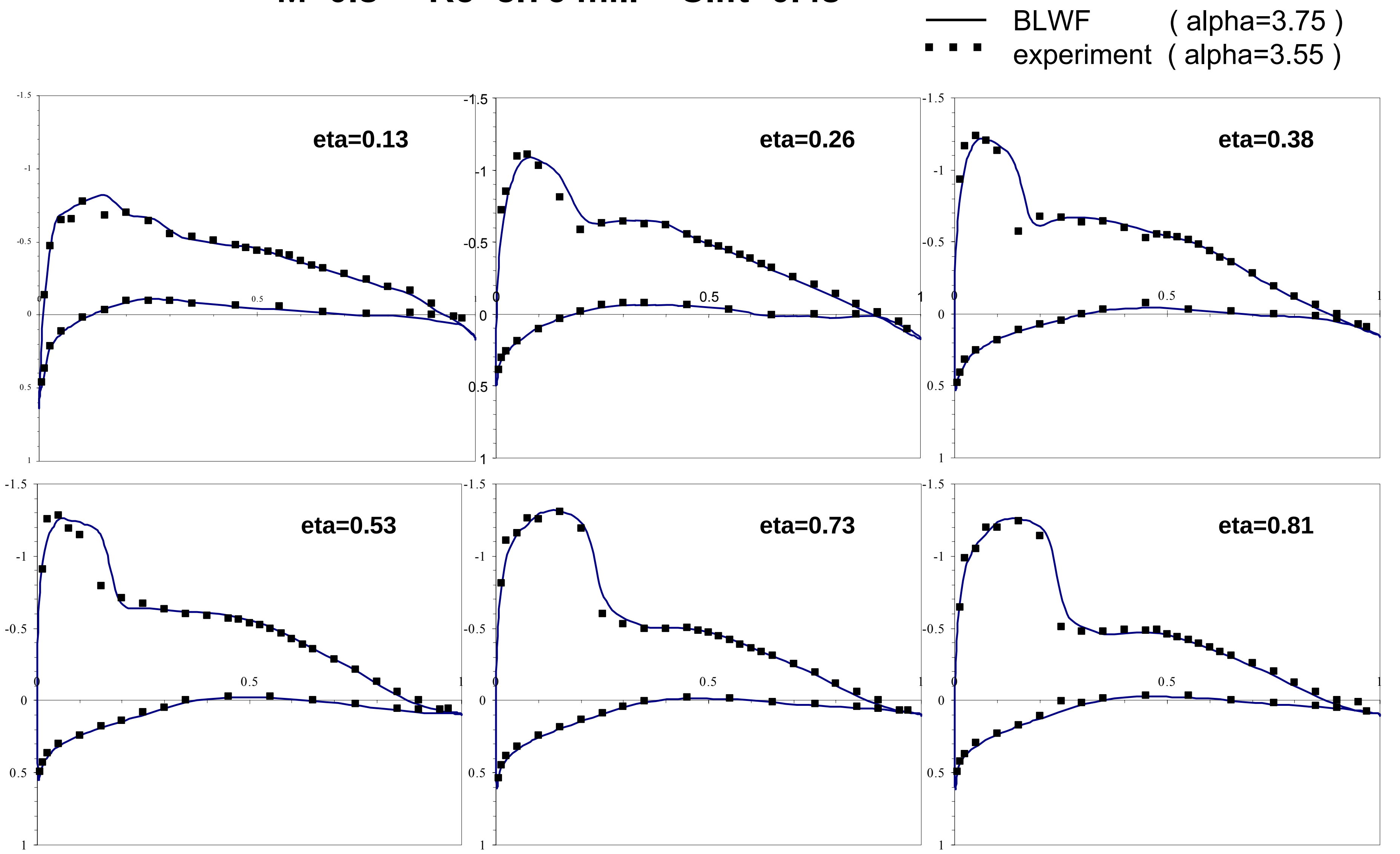
WING/BODY B747.

M=0.8 Re=5.76 mill Clift=0.35



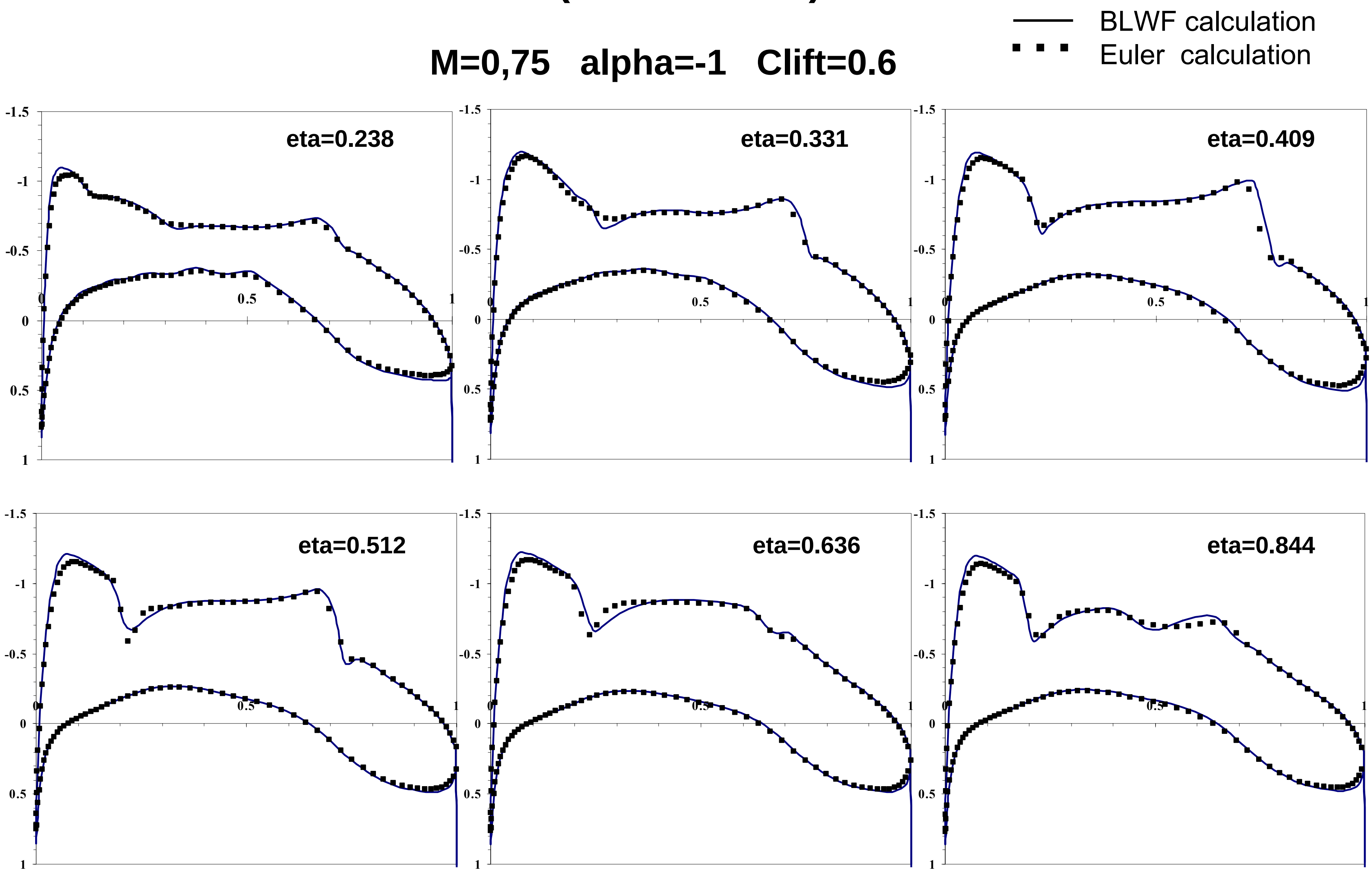
WING/BODY B747

M=0.8 Re=5.76 mill Clift=0.43



WING/BODY DLR-F4. **Comparison with Euler computation (inviscid flow)**

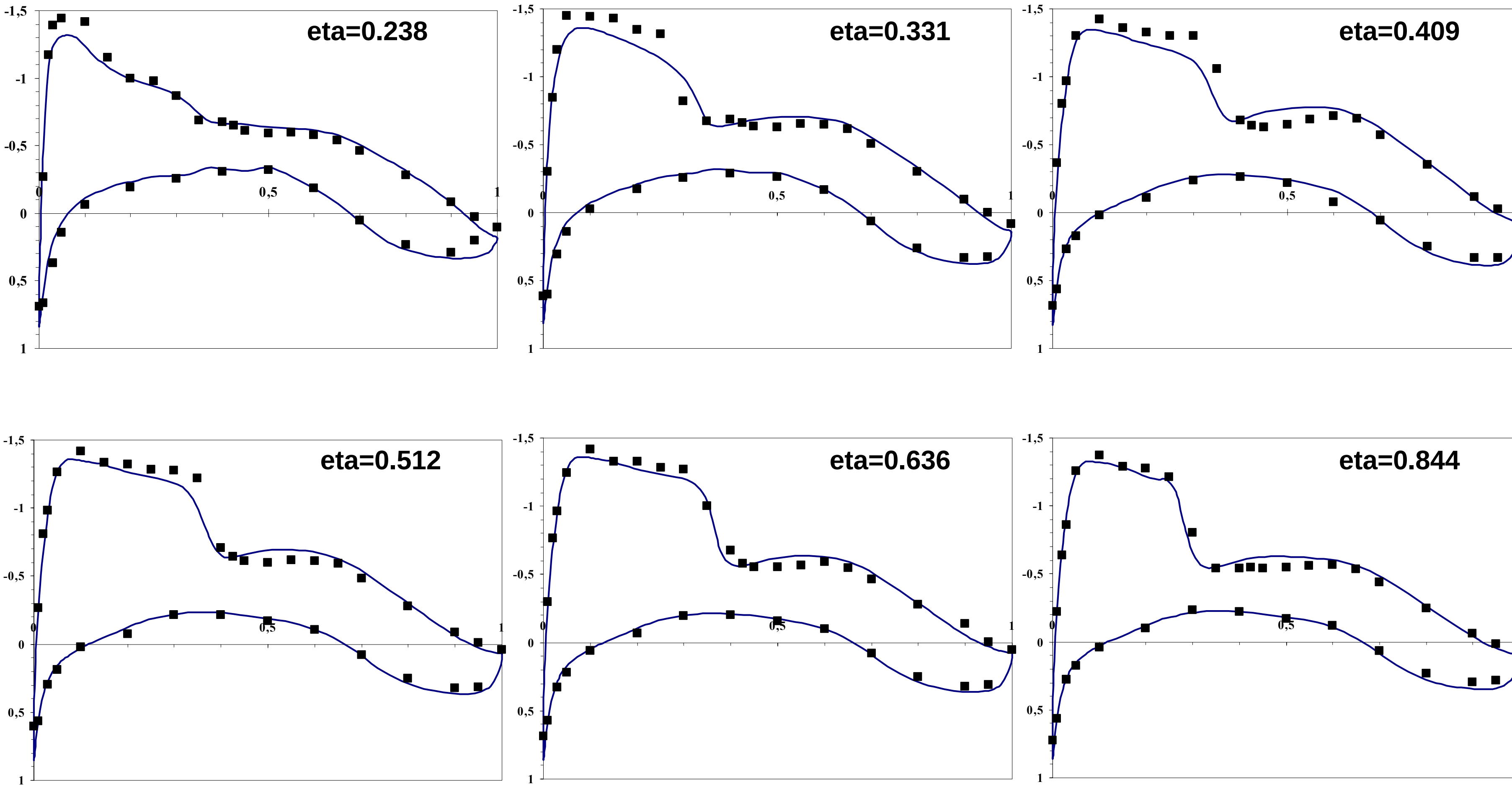
M=0,75 alpha=-1 Clift=0.6



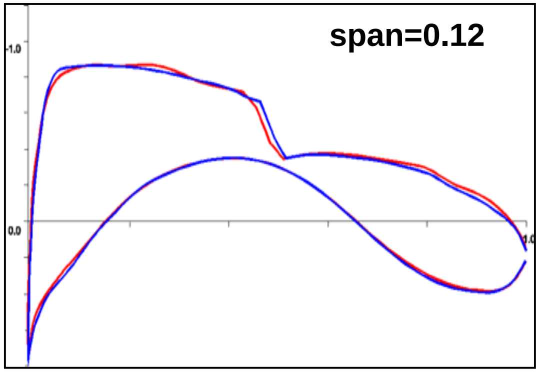
Wing/Body DLR-F4

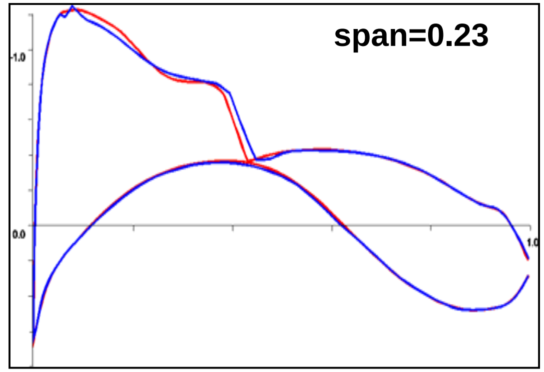
M=0.75 Re=3.0 mill Clift=0.6

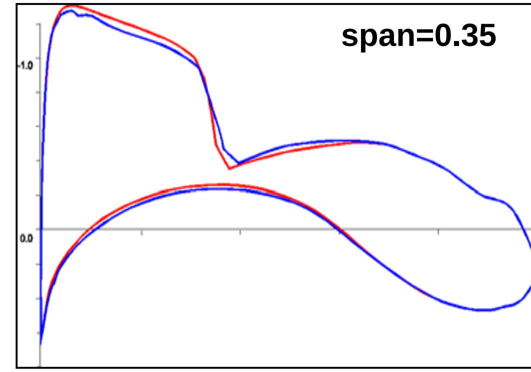
——— BLWF calculation
■ ■ ■ experiment



Wing/body configuration: **comparison with BAE Euler multiblock code. inviscid**



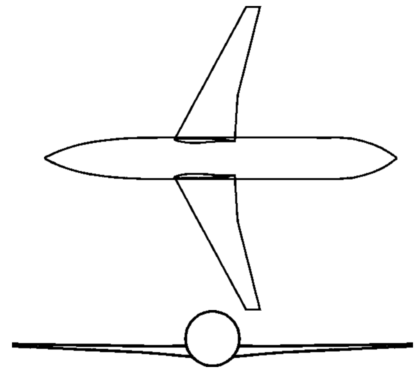




Wing/body

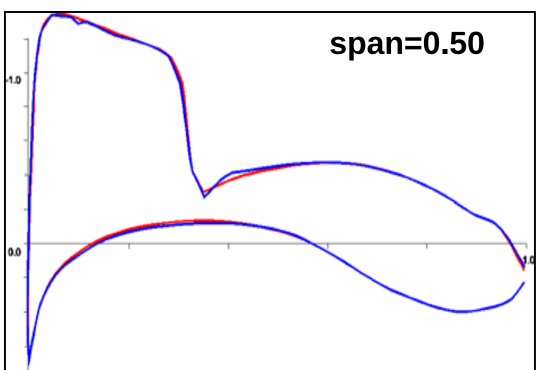
M =.80, ALPHA=2.885º,

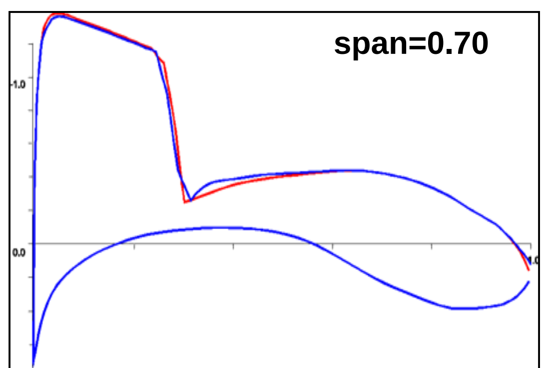
BETA=0º, inviscid

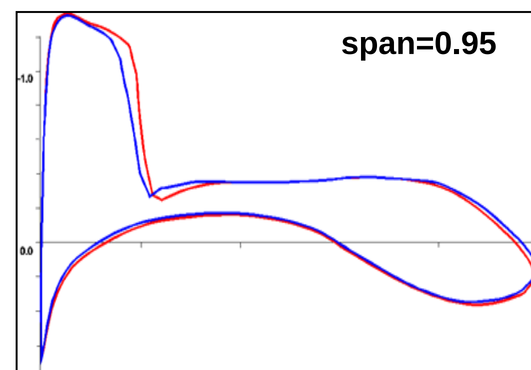


Euler, multiblock. (BAE code.)

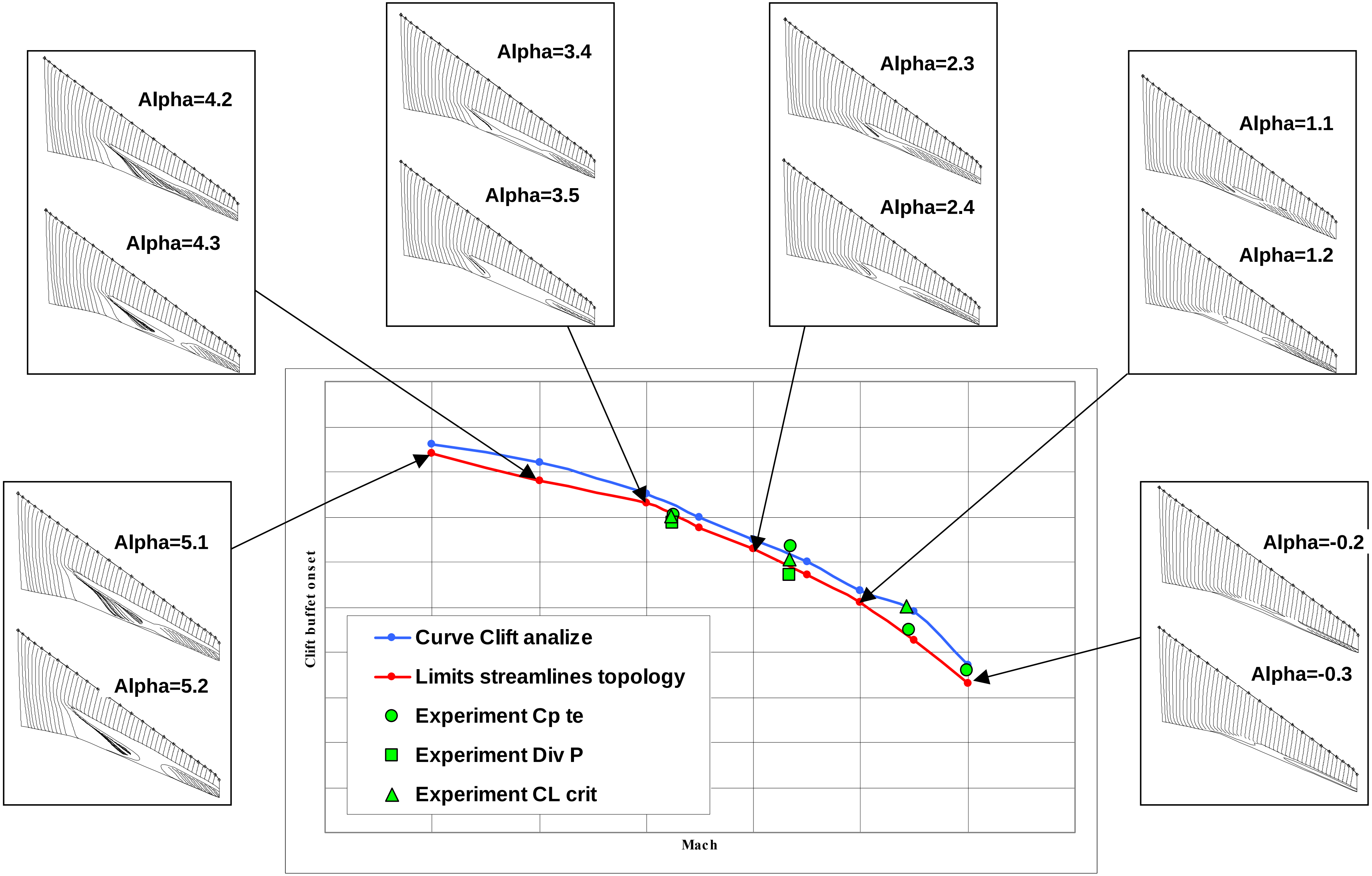
BLWF - inviscid



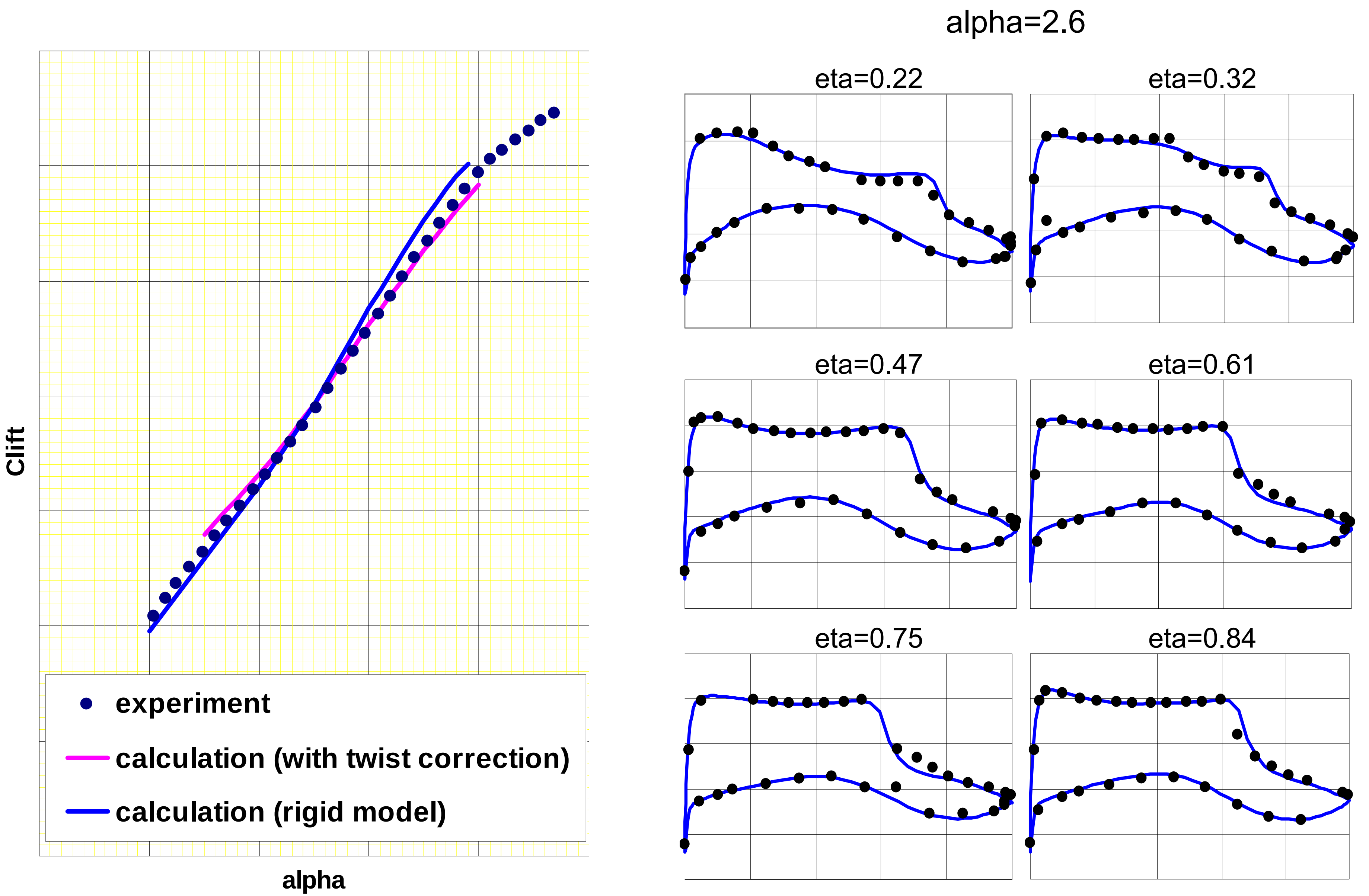




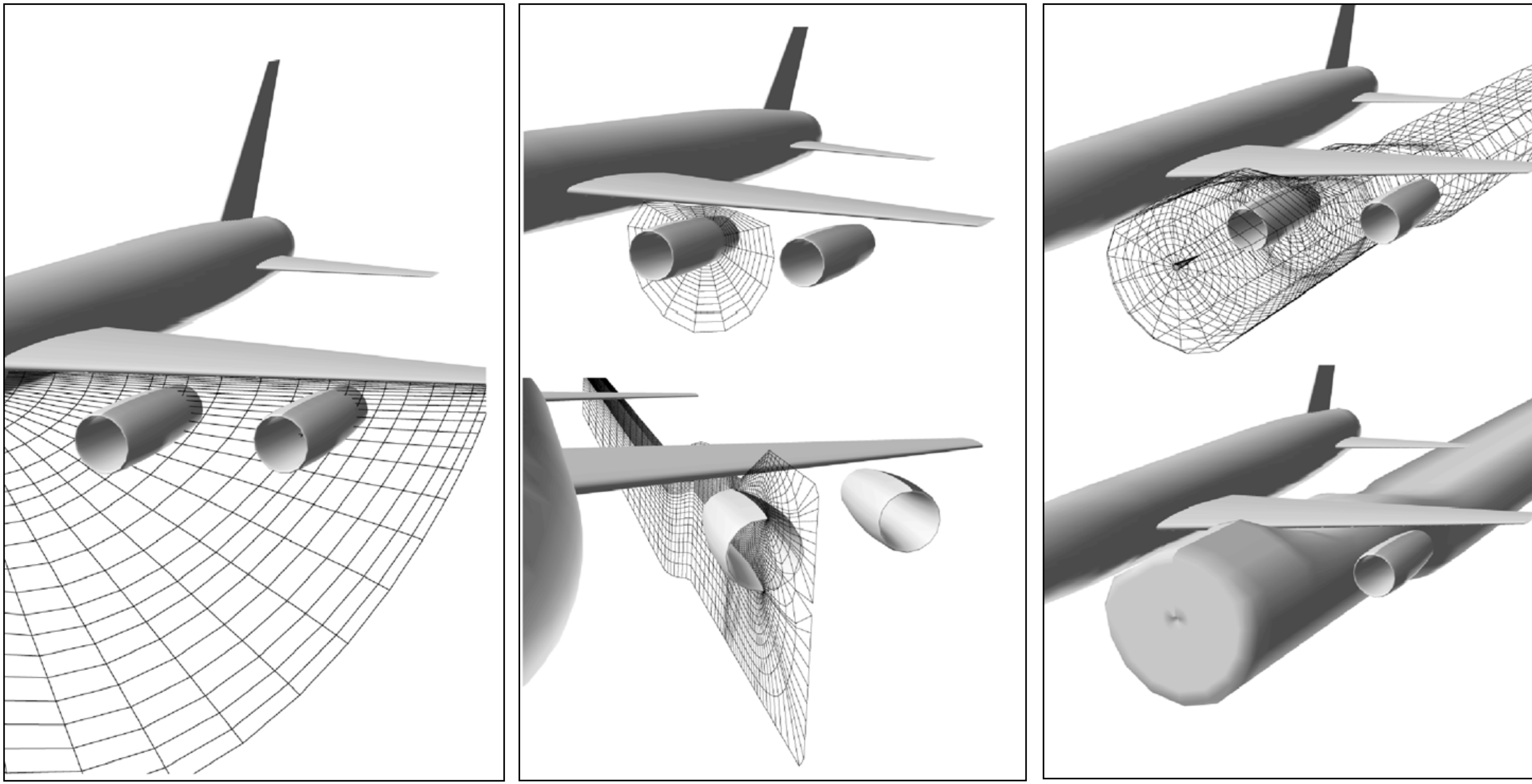
Buffet onset prediction. Wing-body   Re=50 mill.



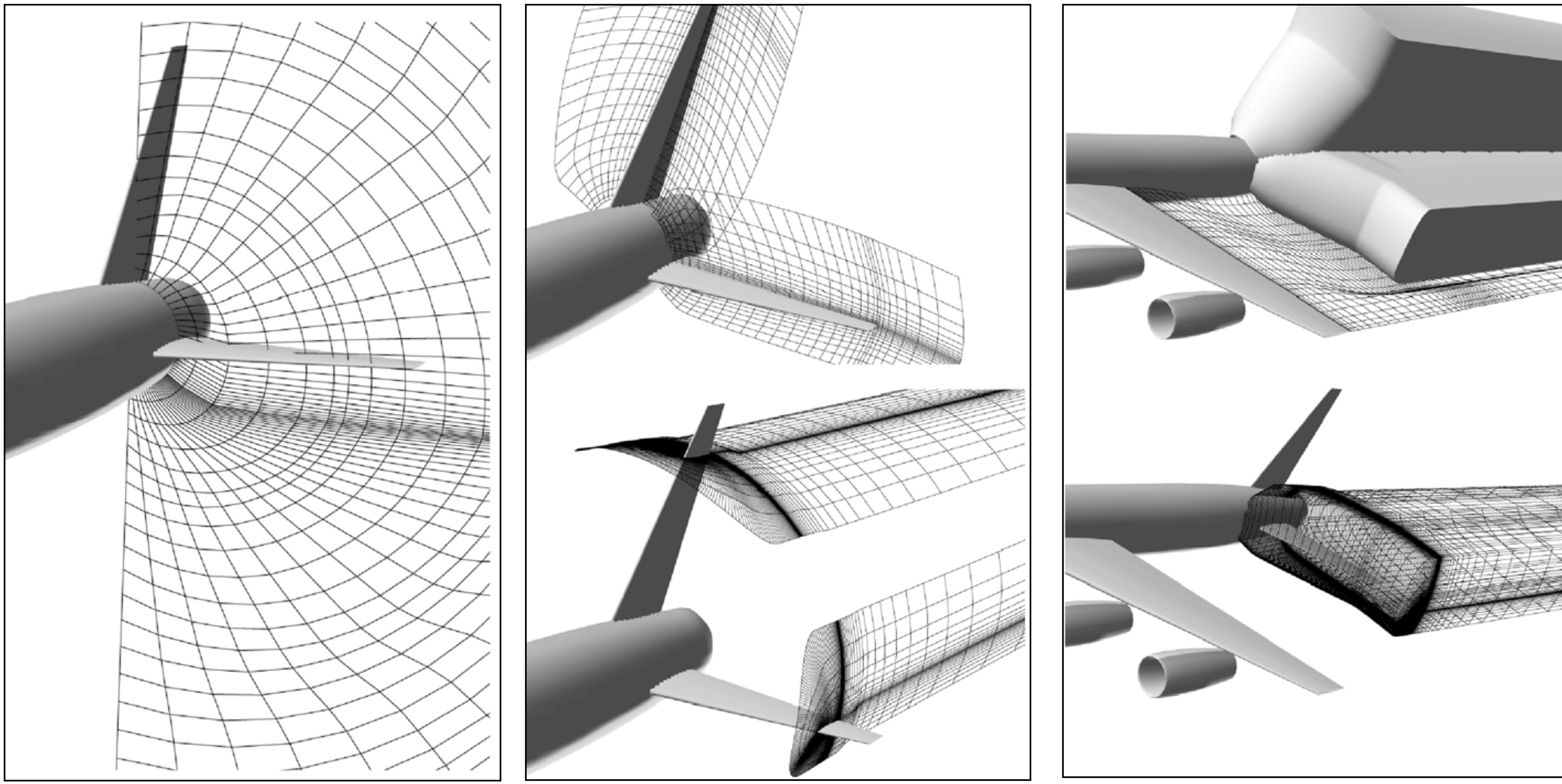
Wing-body Re=50 mill M=0.85



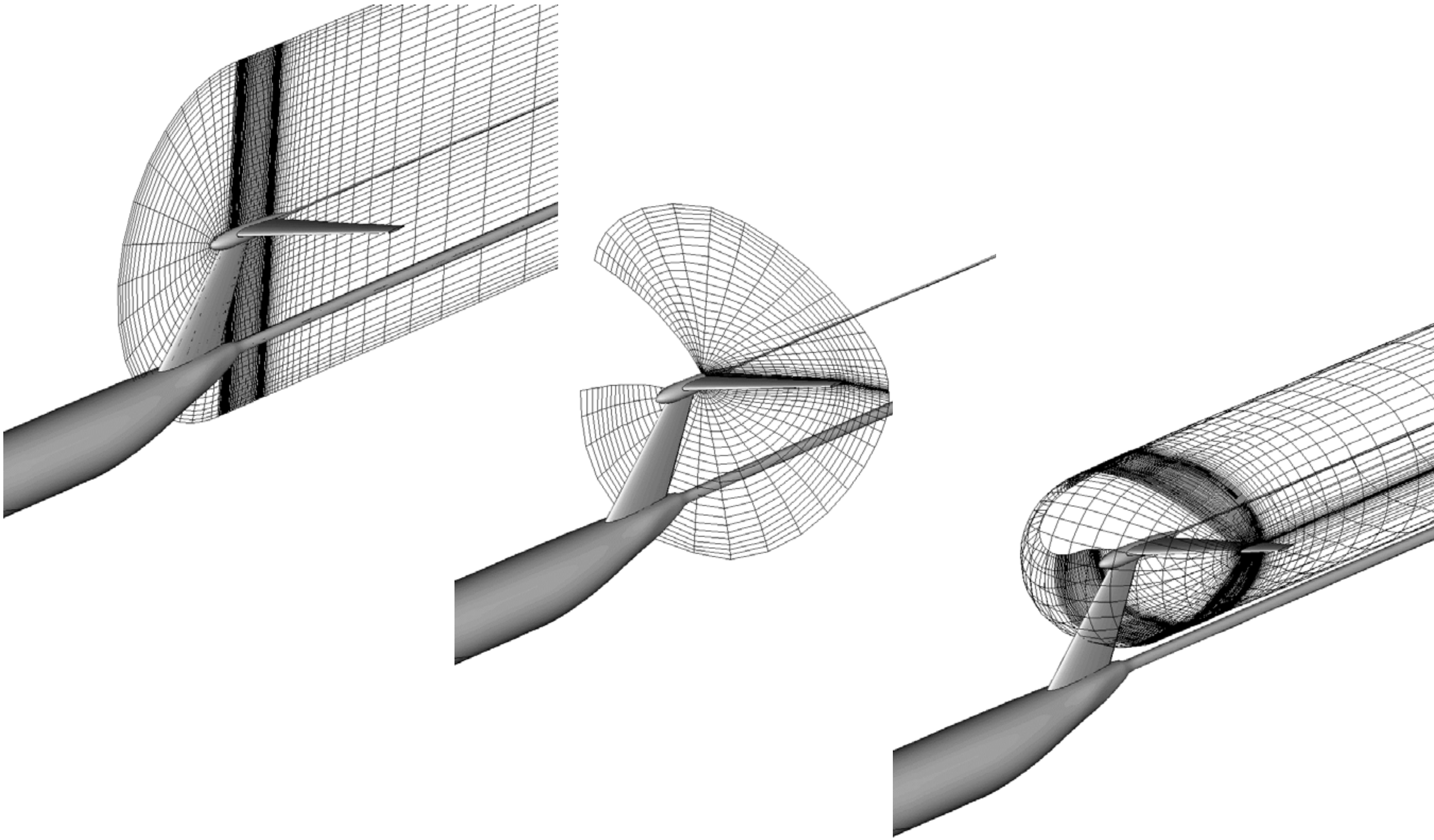
Nacelle grid: **“Chimera” approach**



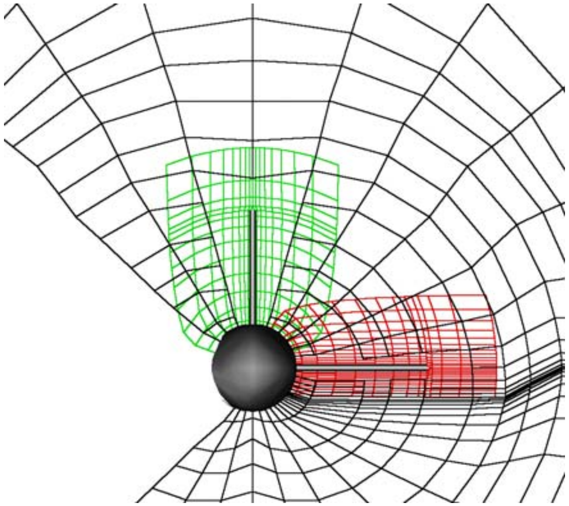
Deck tail grids : **“Chimera” approach.**

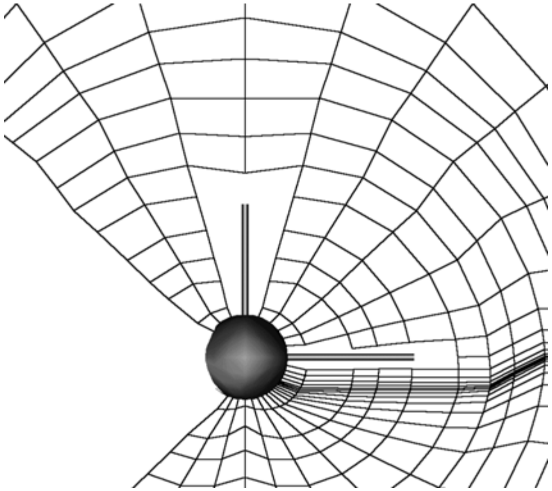


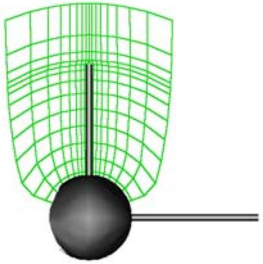
T-type tail grid : **“Chimera” approach.**

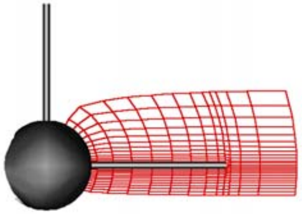


Deck tail: **Grids interaction**

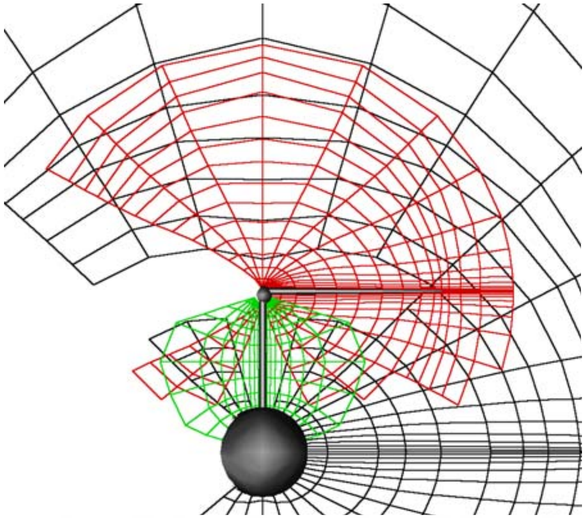




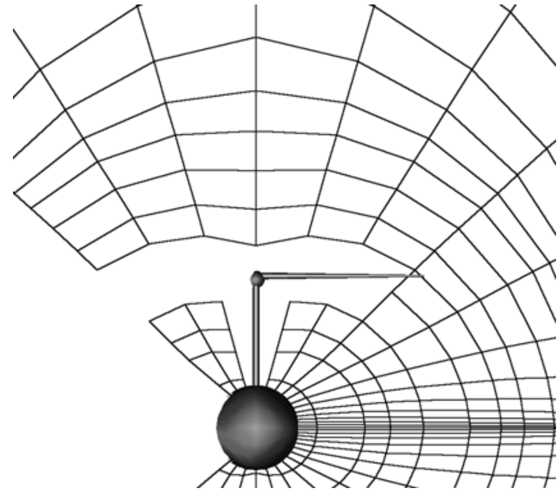




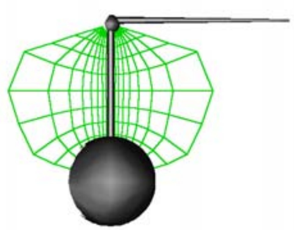
T-type tail: **Grids interaction**



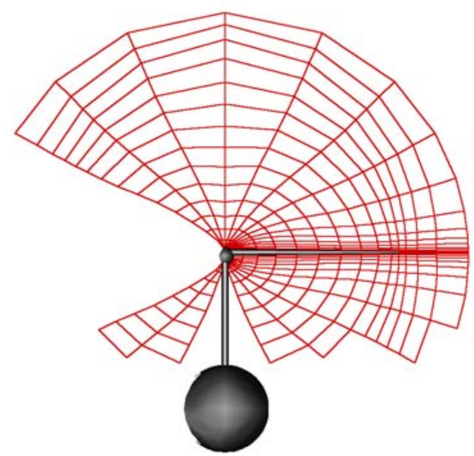
INTERACTED grids



WING-BODY grid



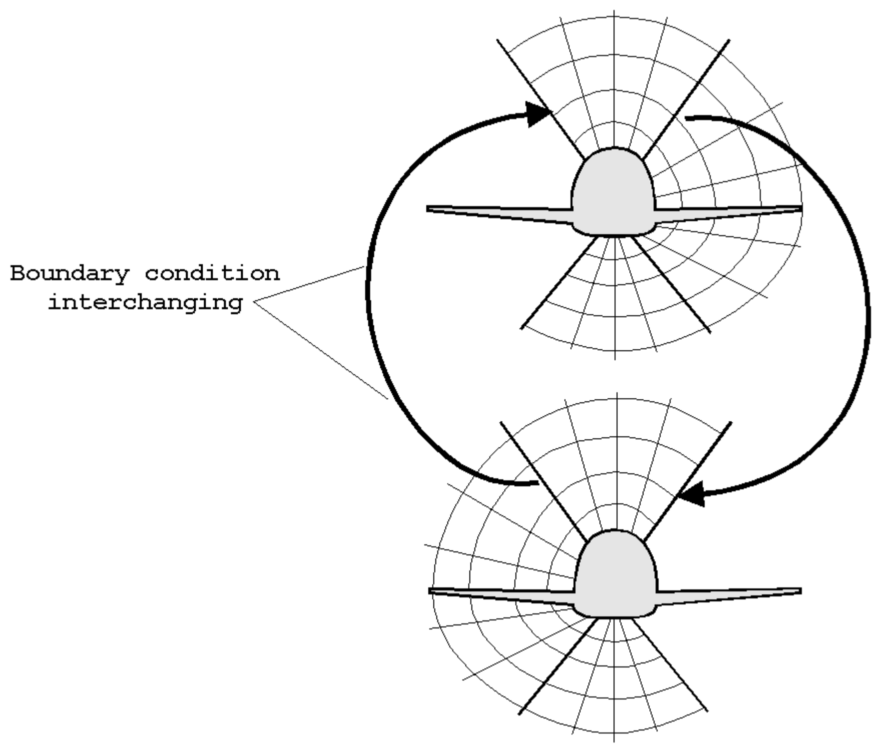
VERTICAL TAIL grid



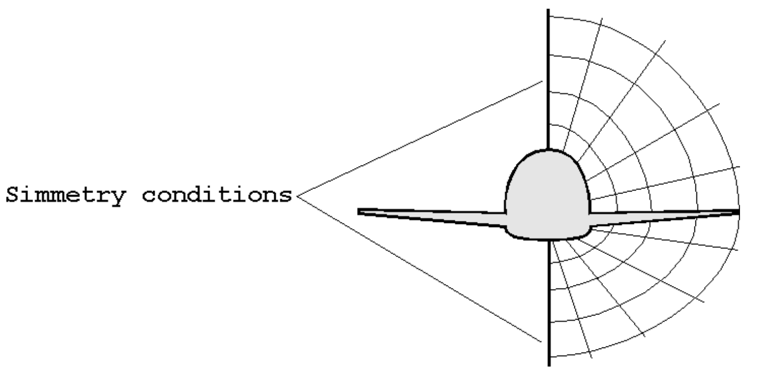
HORISONTAL TAIL grid

Side flow possibility incorporation.

SIDE FLOW

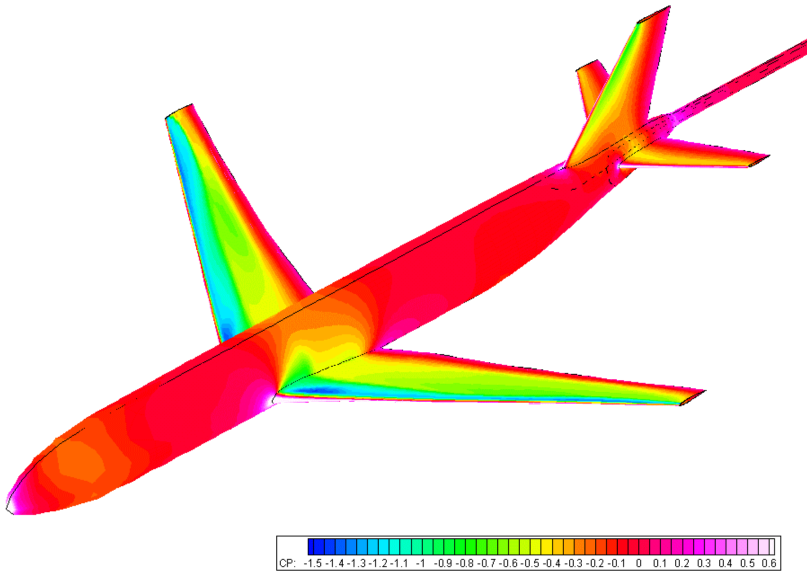


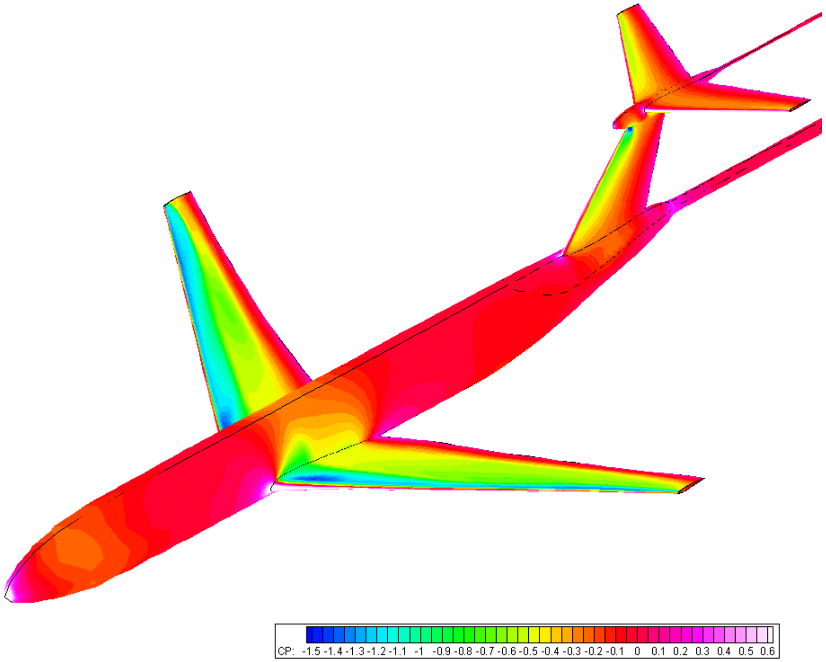
SYMMETRIC FLOW



Deck tail or T-type horizontal tail

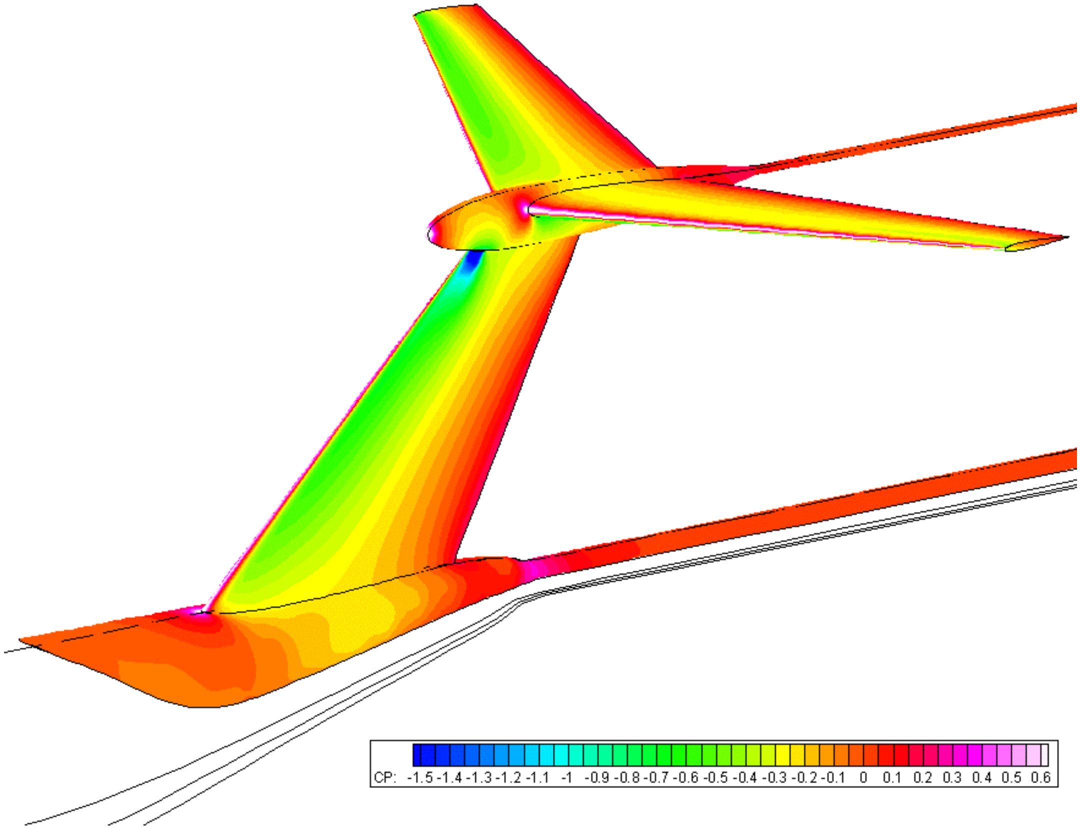
M=.78,	ALPHA=2°,	BETA=3°,	Re=3*10^6





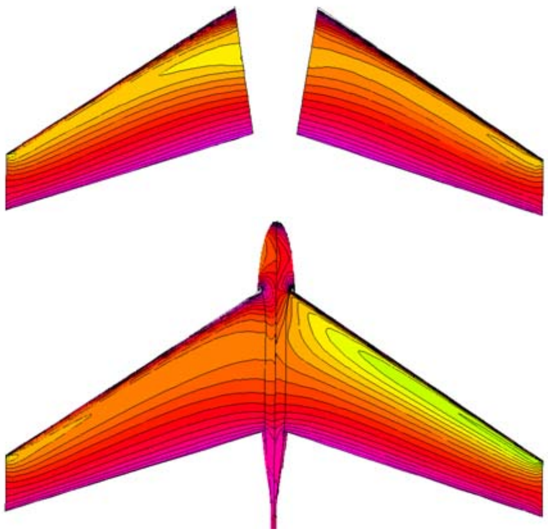
T-type horizontal tail

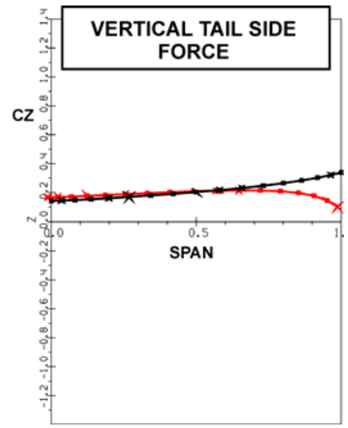
M=.78, ALPHA=2°, BETA=3°, Re=$3*10^6$

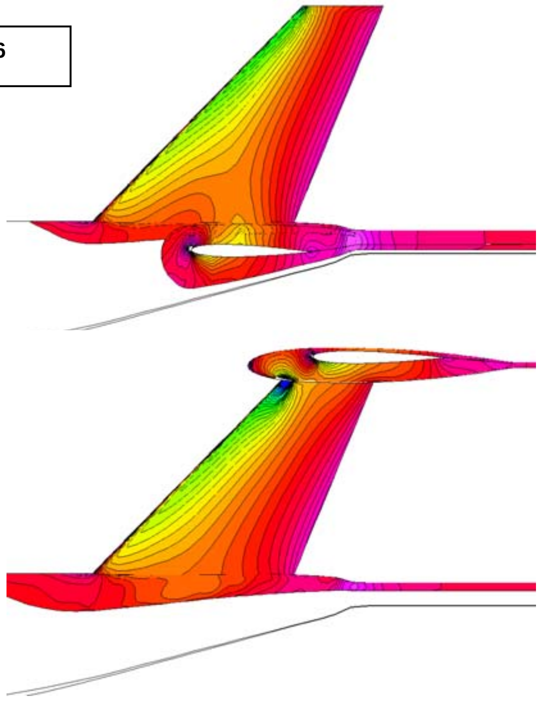


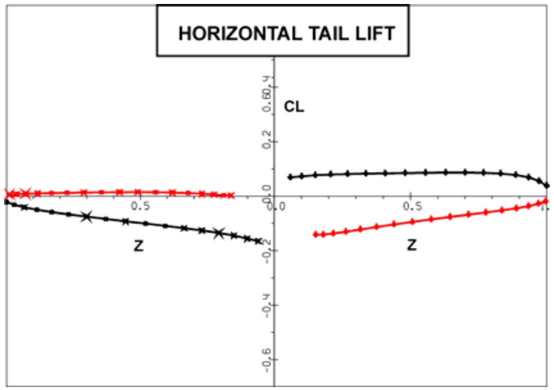
Deck and T-type horizontal tail: **Loads**

M=.78, ALPHA=2º, BETA=3º, Re=3*10^6



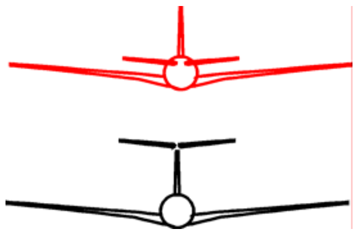






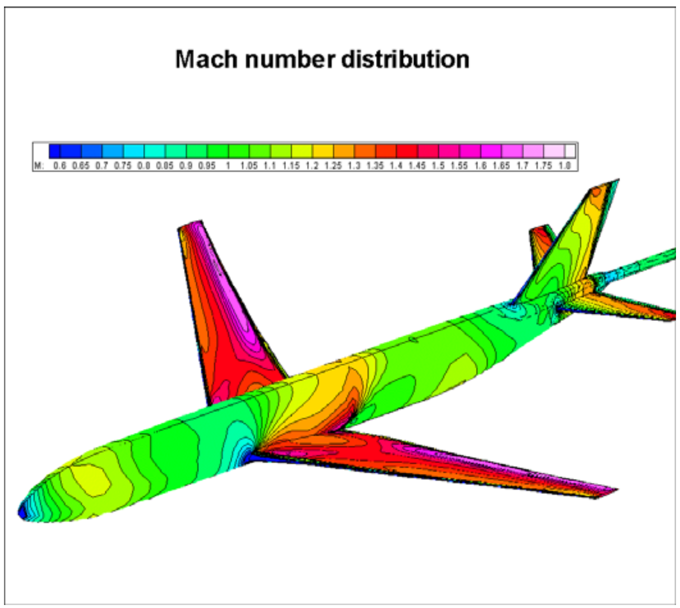
deck tail

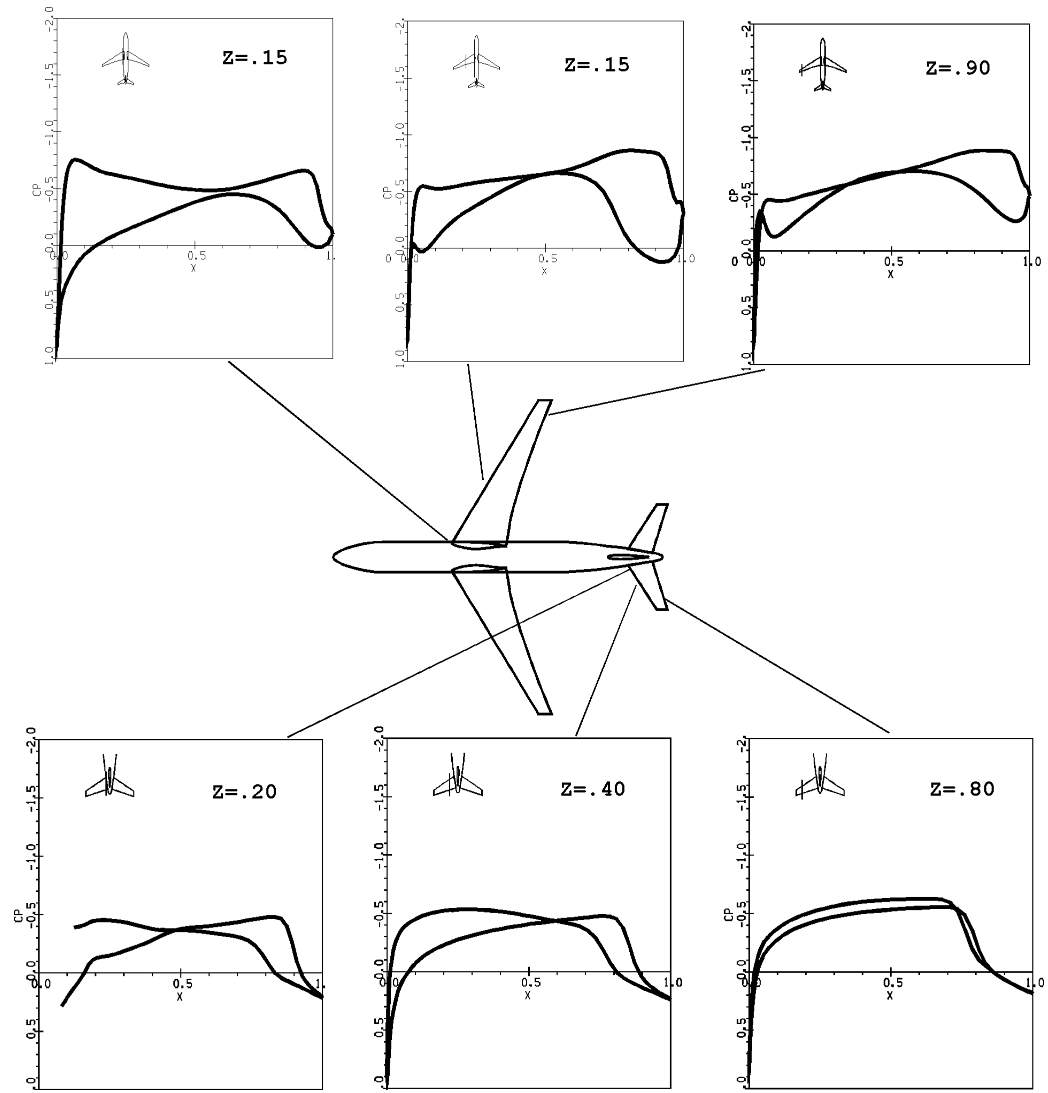
T-type tail



New finite-difference scheme : **High Mach number calculation**

M =.99 ALPHA = 2° Re = 3·10



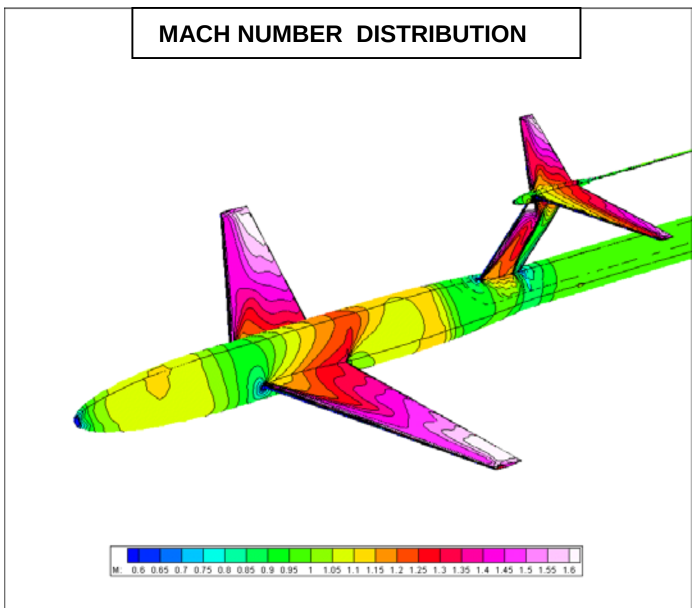


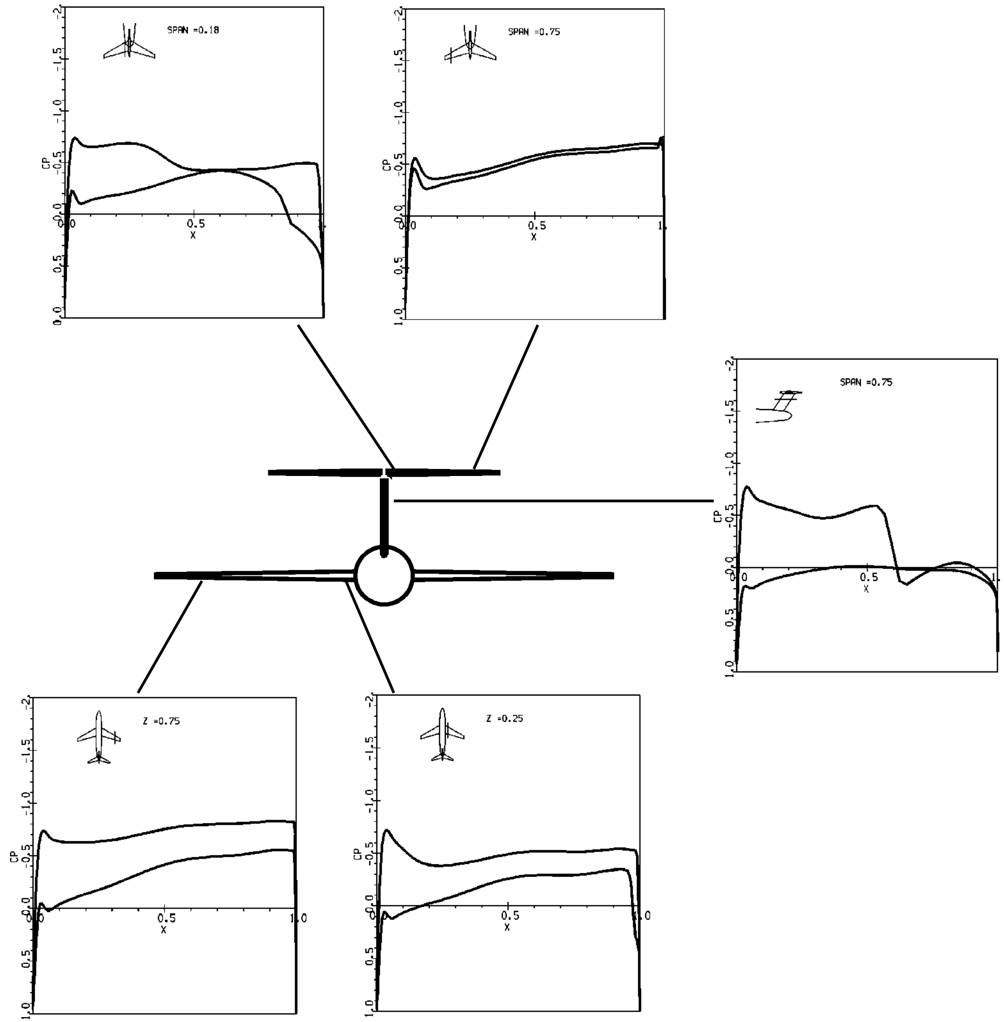
New finite-difference scheme : **High Mach number calculation**

ONERA test

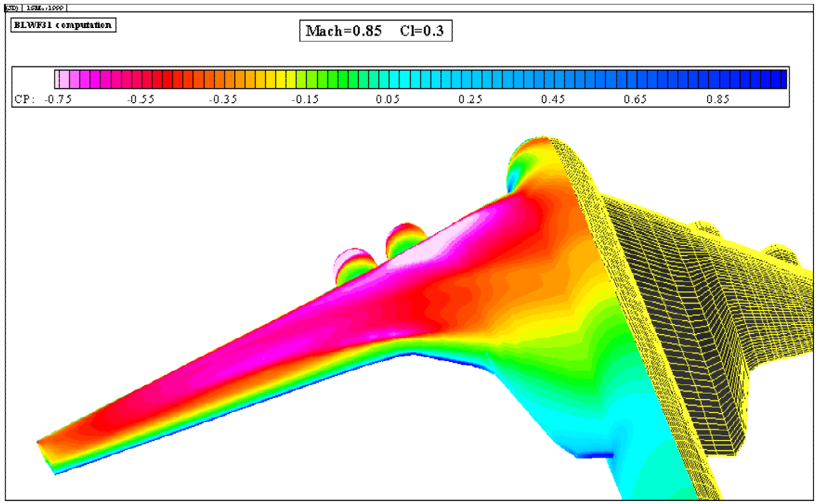
M= .99, ALPHA=3º, BETA=3º

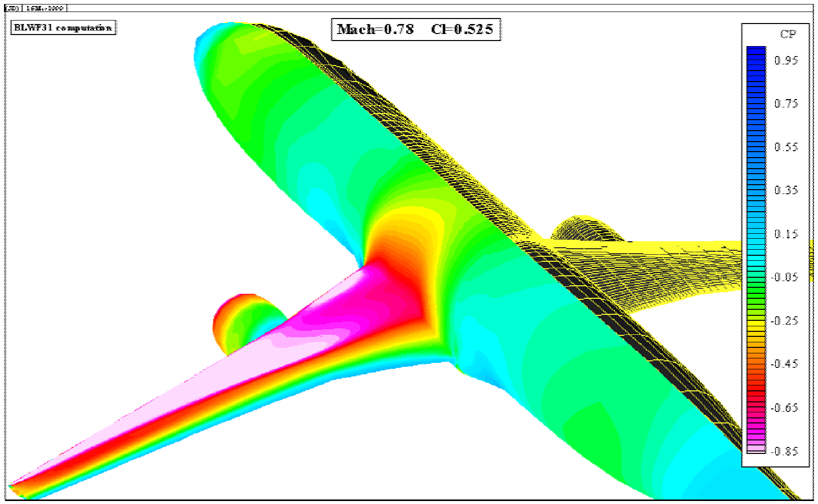
Inviscid

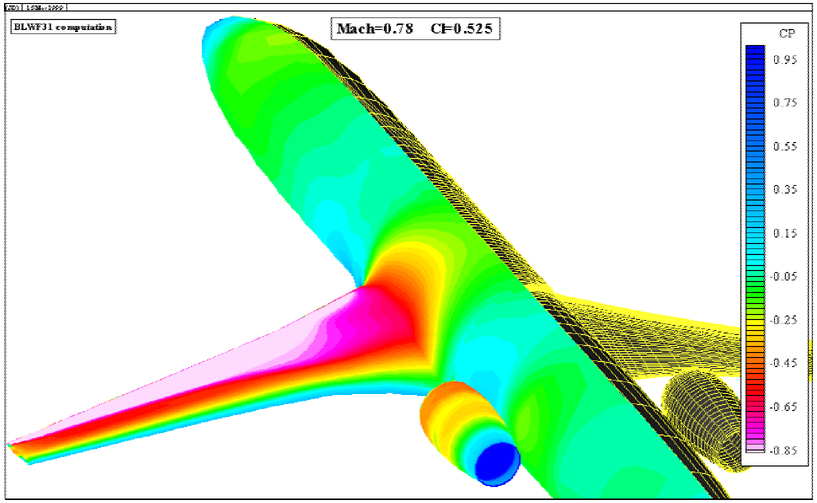


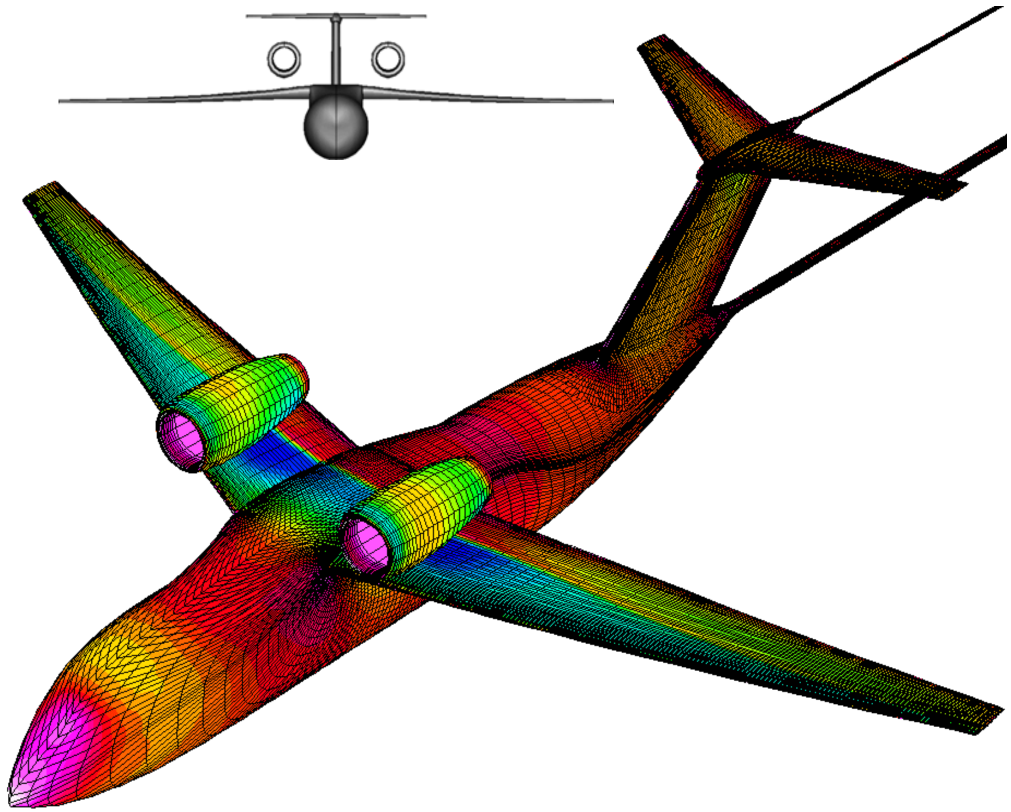


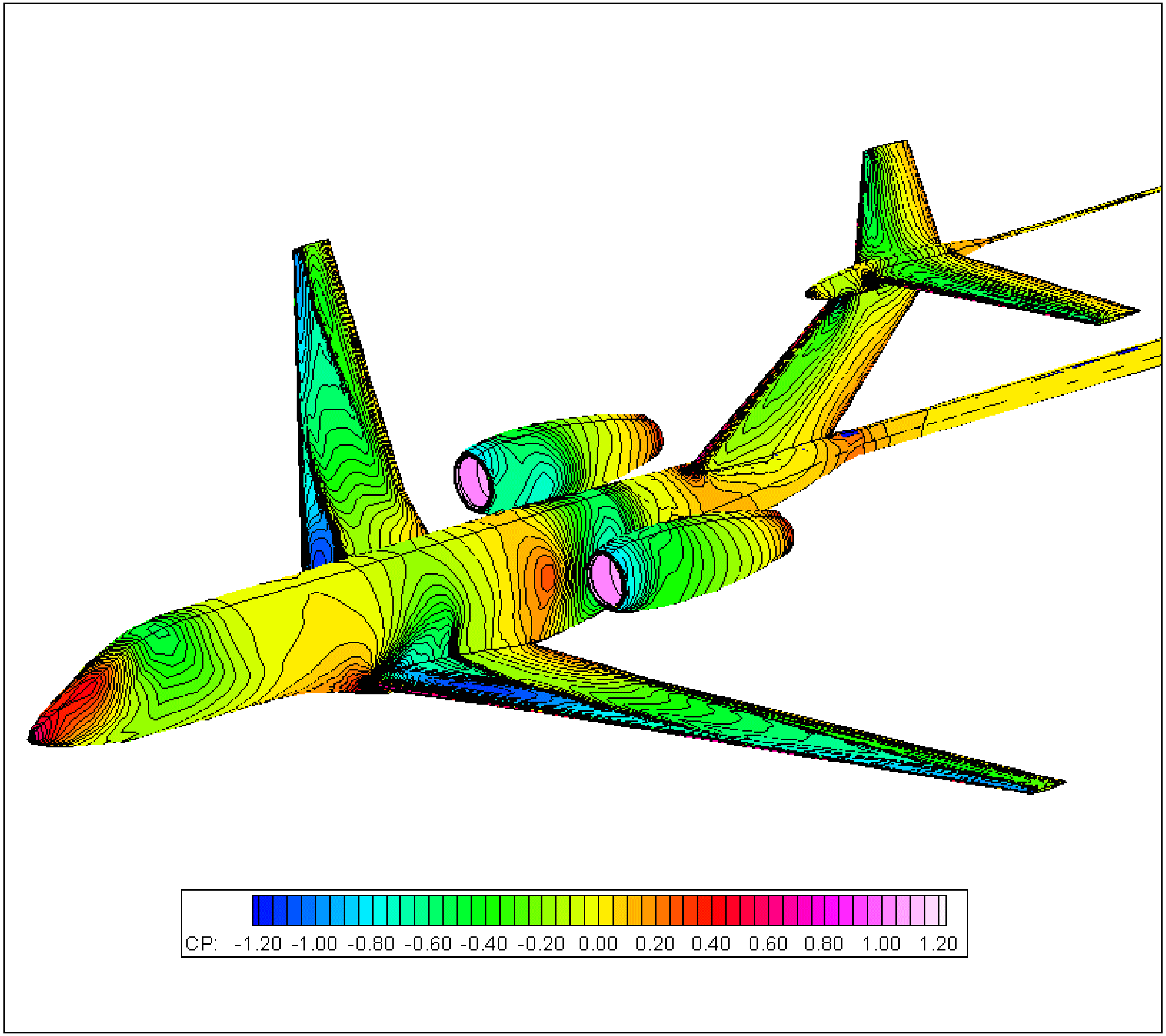
VARIOUS CONFIGURATIONS. TRANSONIC FLIGHT REGIMES.

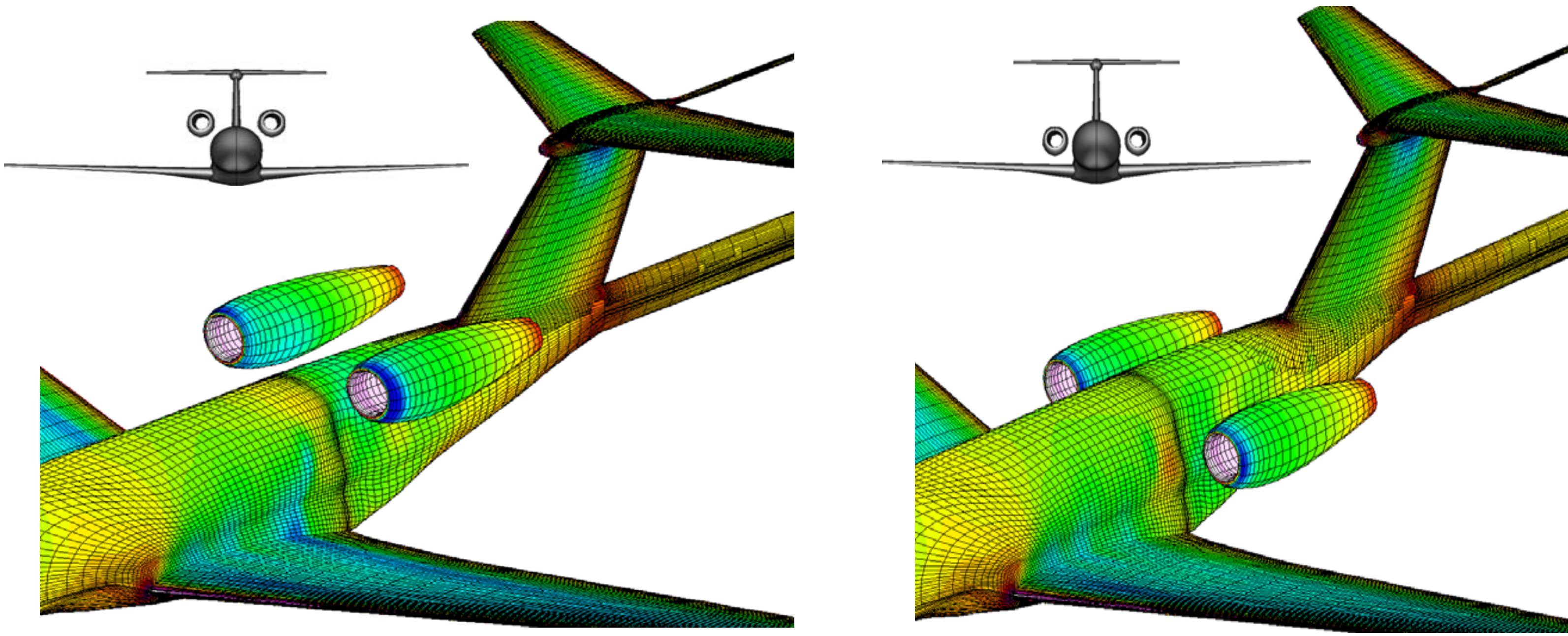




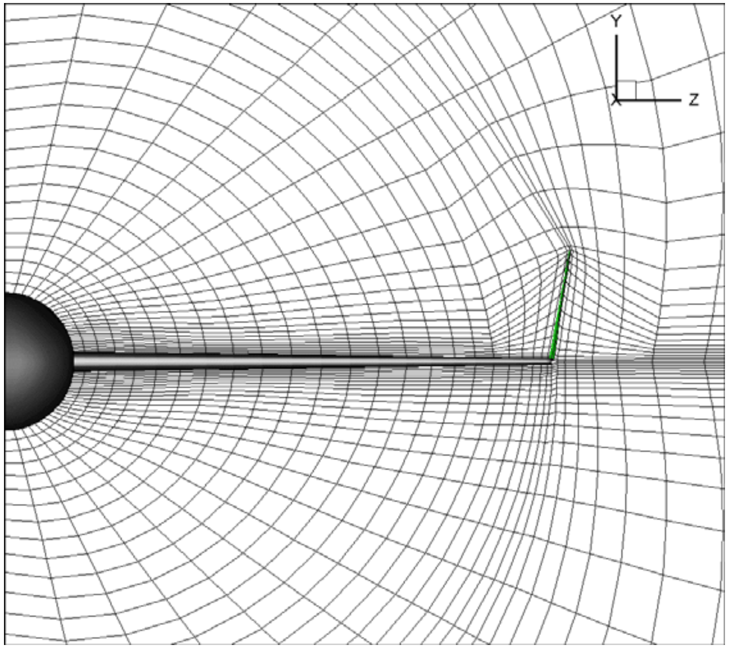


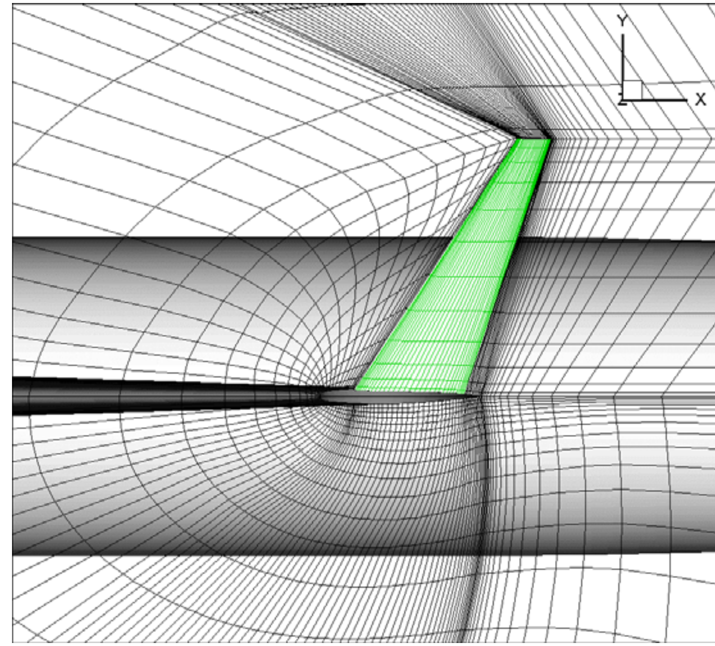



CP: -1.20 -1.00 -0.80 -0.60 -0.40 -0.20 0.00 0.20 0.40 0.60 0.80 1.00 1.20

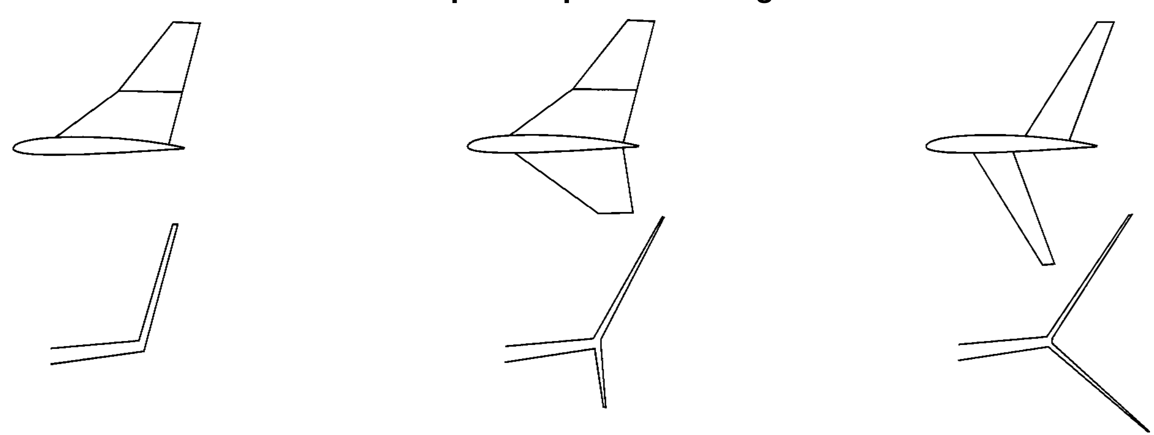


Winglets : **Computational grid**

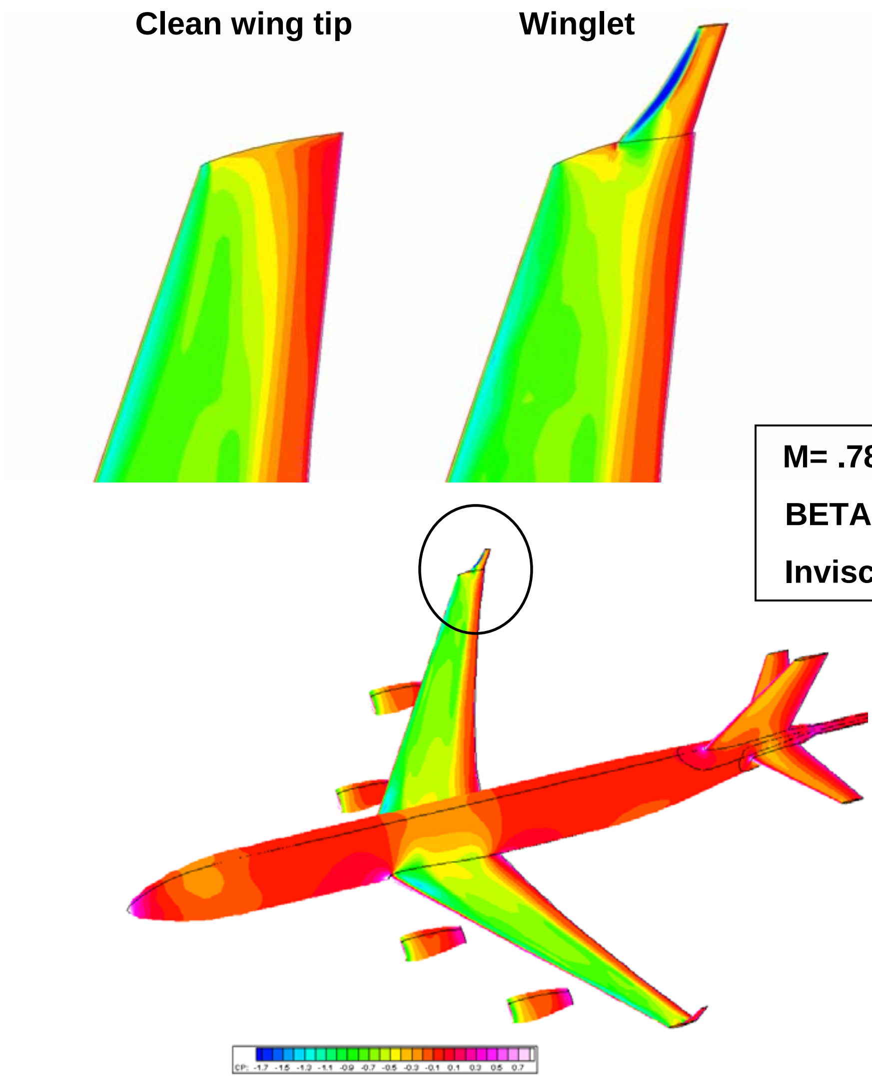


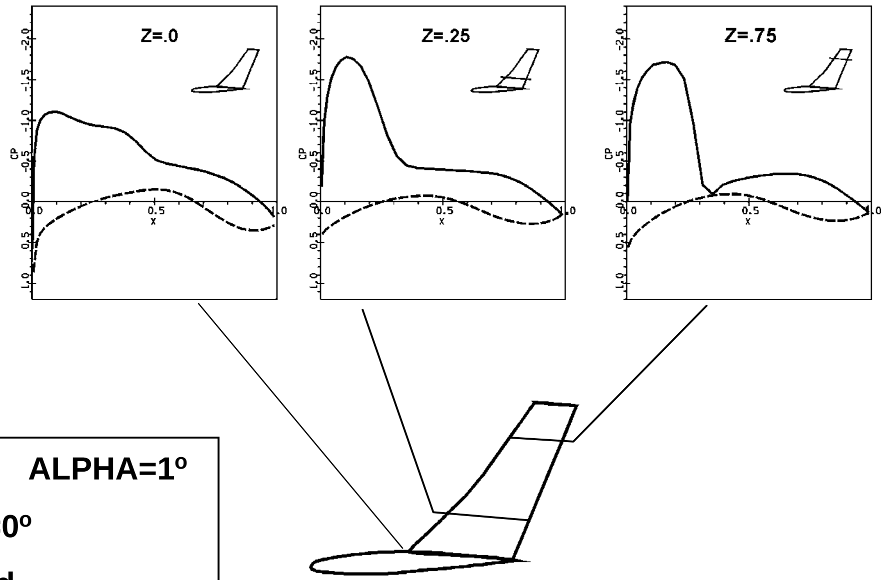


Some examples of possible winglets



Winglets : **Winglet pressure distribution**

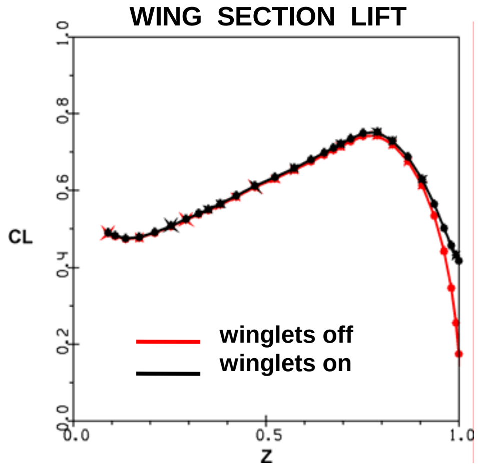




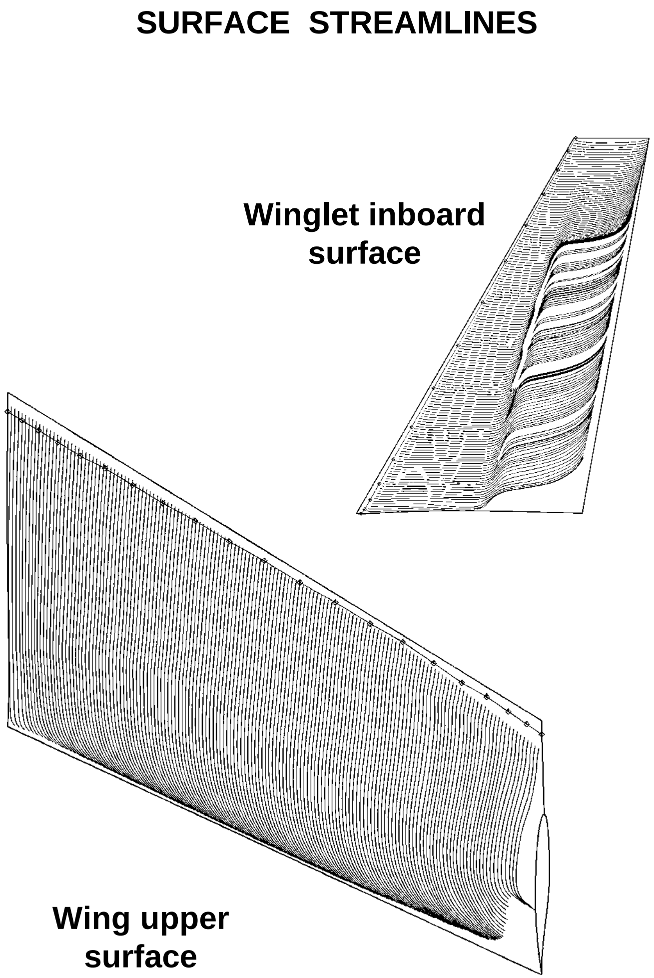
M= .78, ALPHA=1º

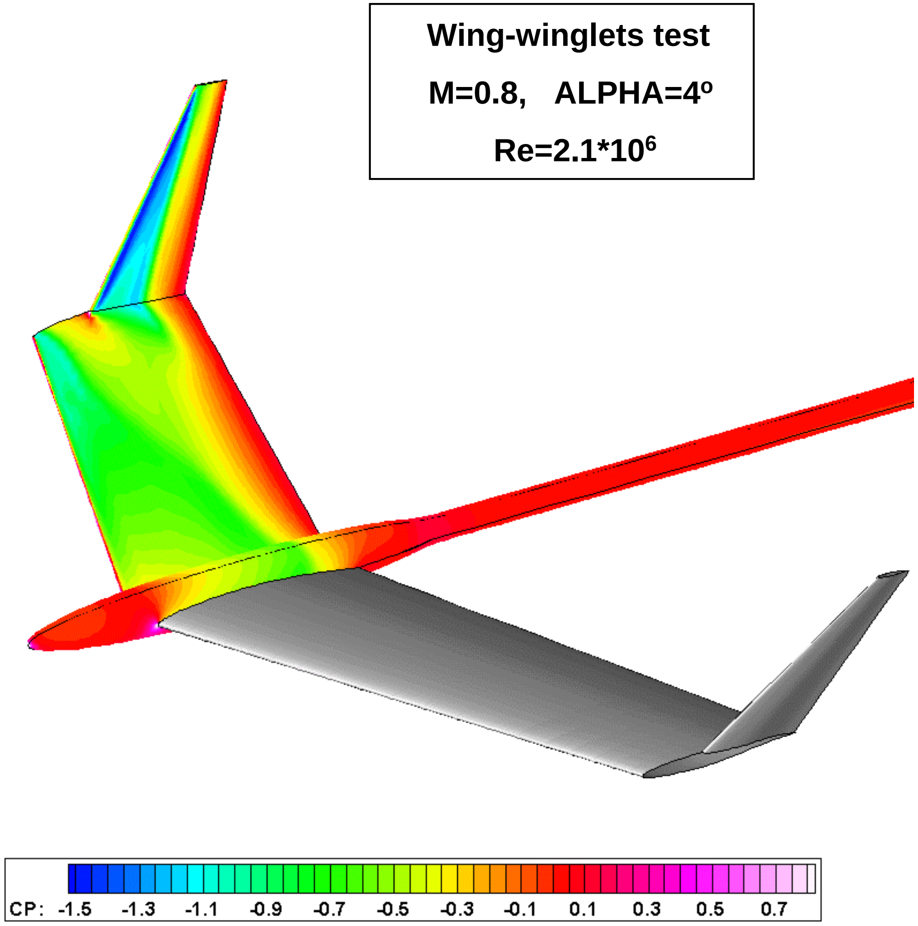
BETA=0º

Inviscid

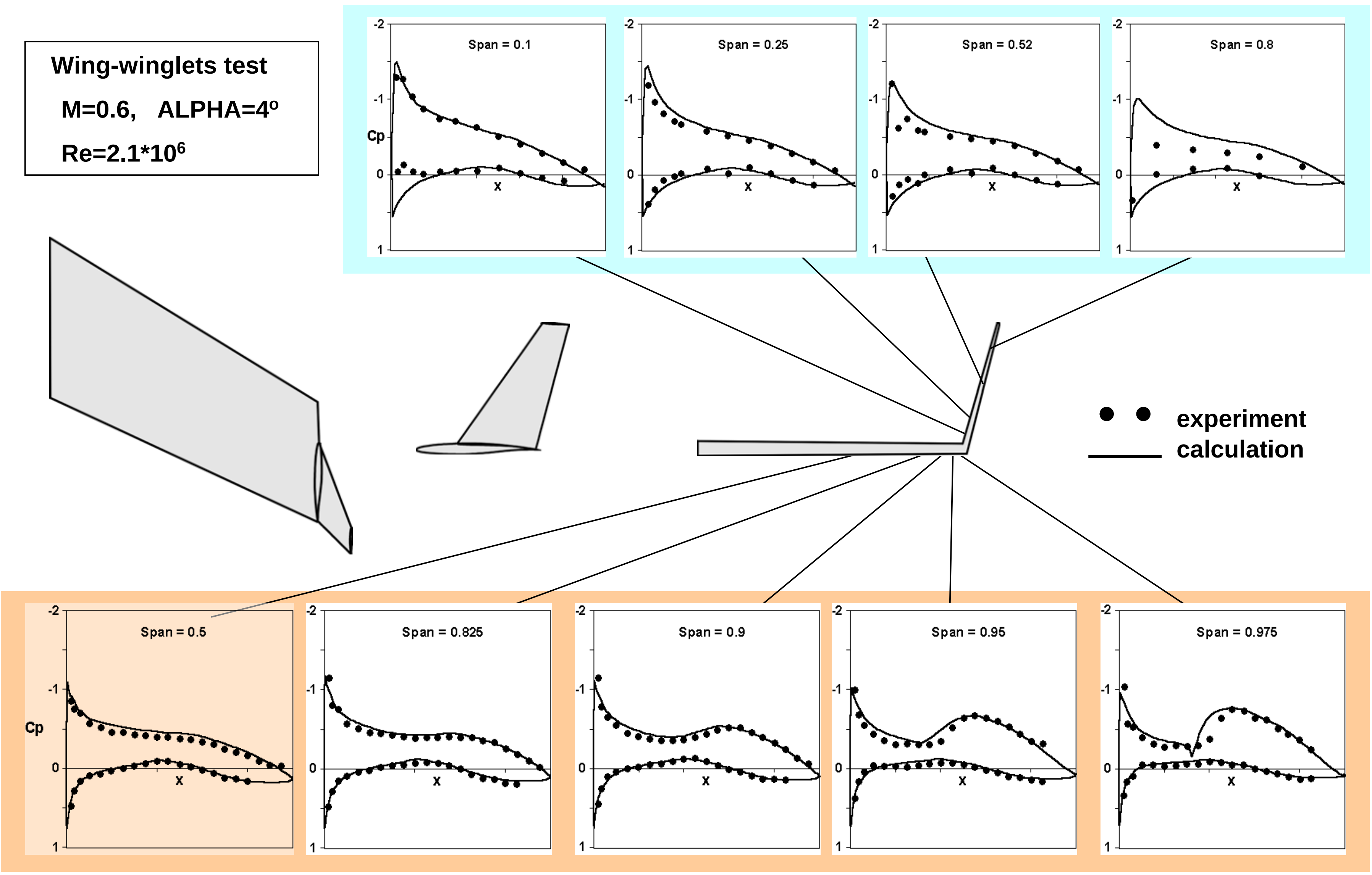


Winglets : **Cp distribution. Surface streamlines.**





Winglets : **Section Cp distribution. M=.6, Alpha=4.**

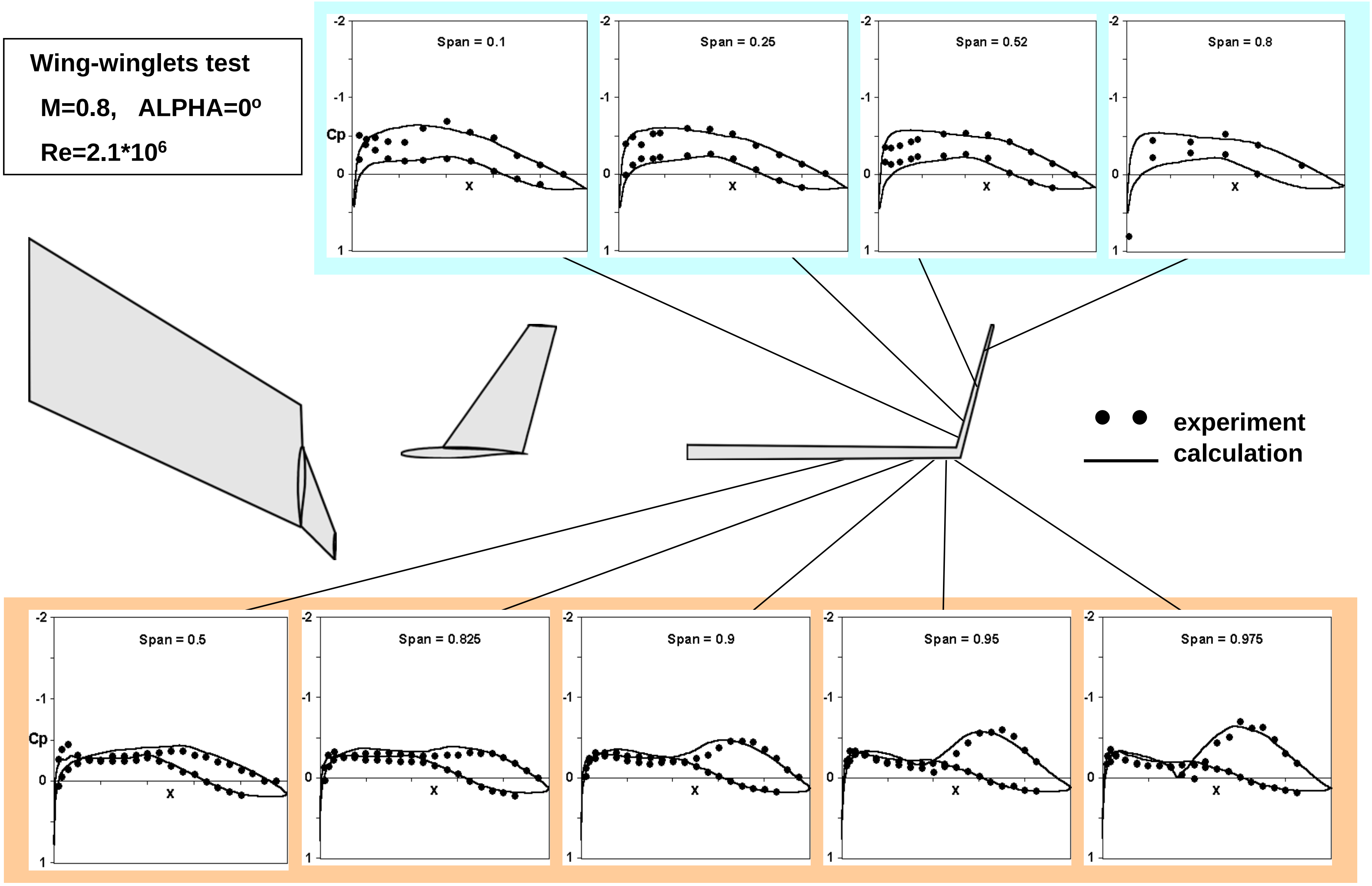


Winglets : **Section Cp distribution. M=.8, Alpha=0.**

Wing-winglets test

M=0.8, ALPHA=0º

Re=2.1*10^6

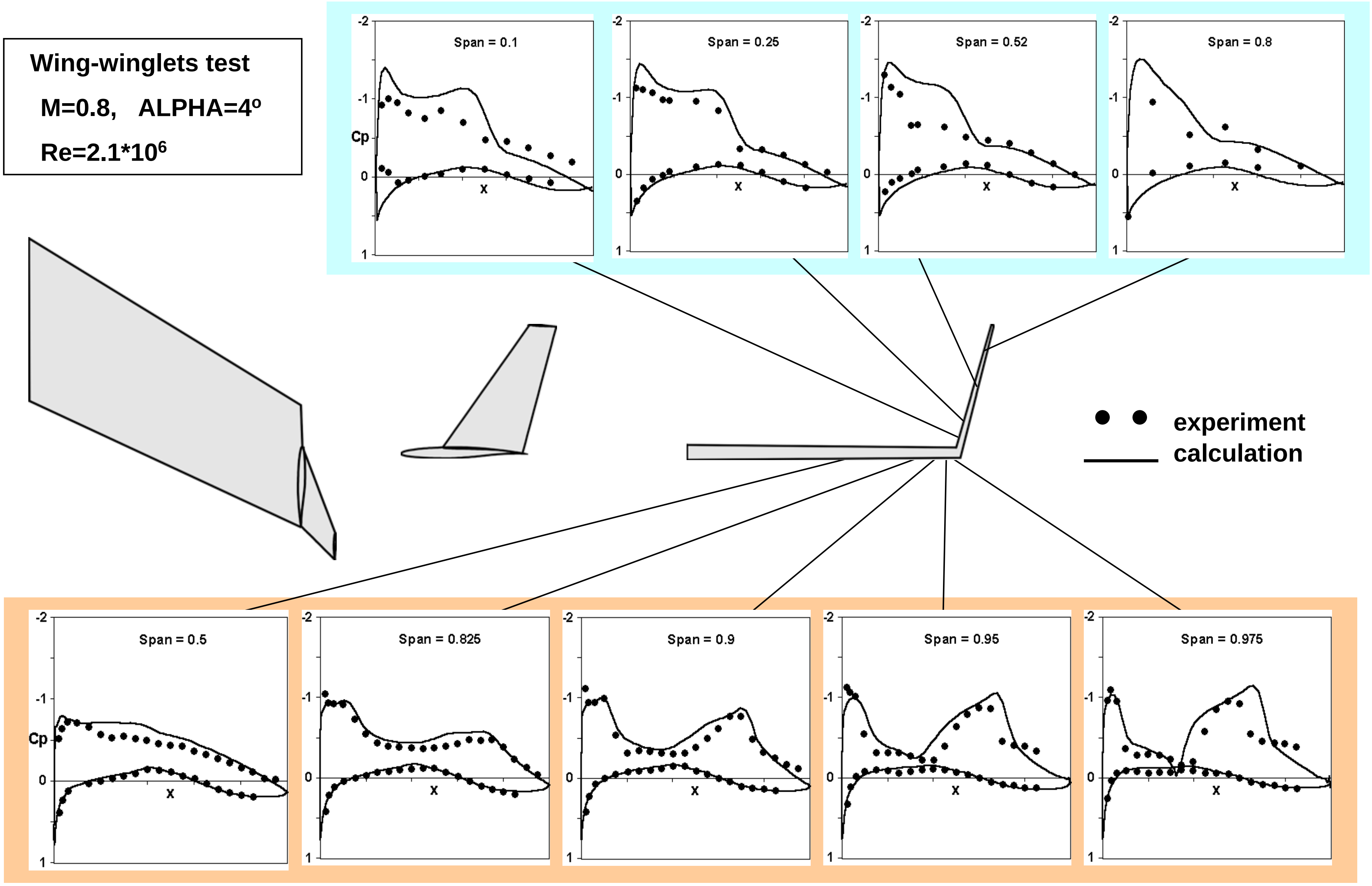


Winglets : **Section Cp distribution. M=.8, Alpha=4.**

Wing-winglets test

M=0.8, ALPHA=4º

Re=2.1*10⁶



MAIN POSSIBILITES (*BLWF28 - BLWF58 versions)*

- Subsonic free stream Mach number (up to M_∞ =1.)
- Side flow.
- Viscous (viscous wakes) on wing, winglets and tail surfaces (moderate separation zones). Prescribed transition.
- Configuration:

    wing/body
    + nacelles (near the wing or near the body)
    + tail (vertical or/and horizontal, deck tail or T-type tail)
    + winglets on a wing (upper or/and lower winglets);
    isolated body (isolated body +tail) configurations.

Additional possibilities:

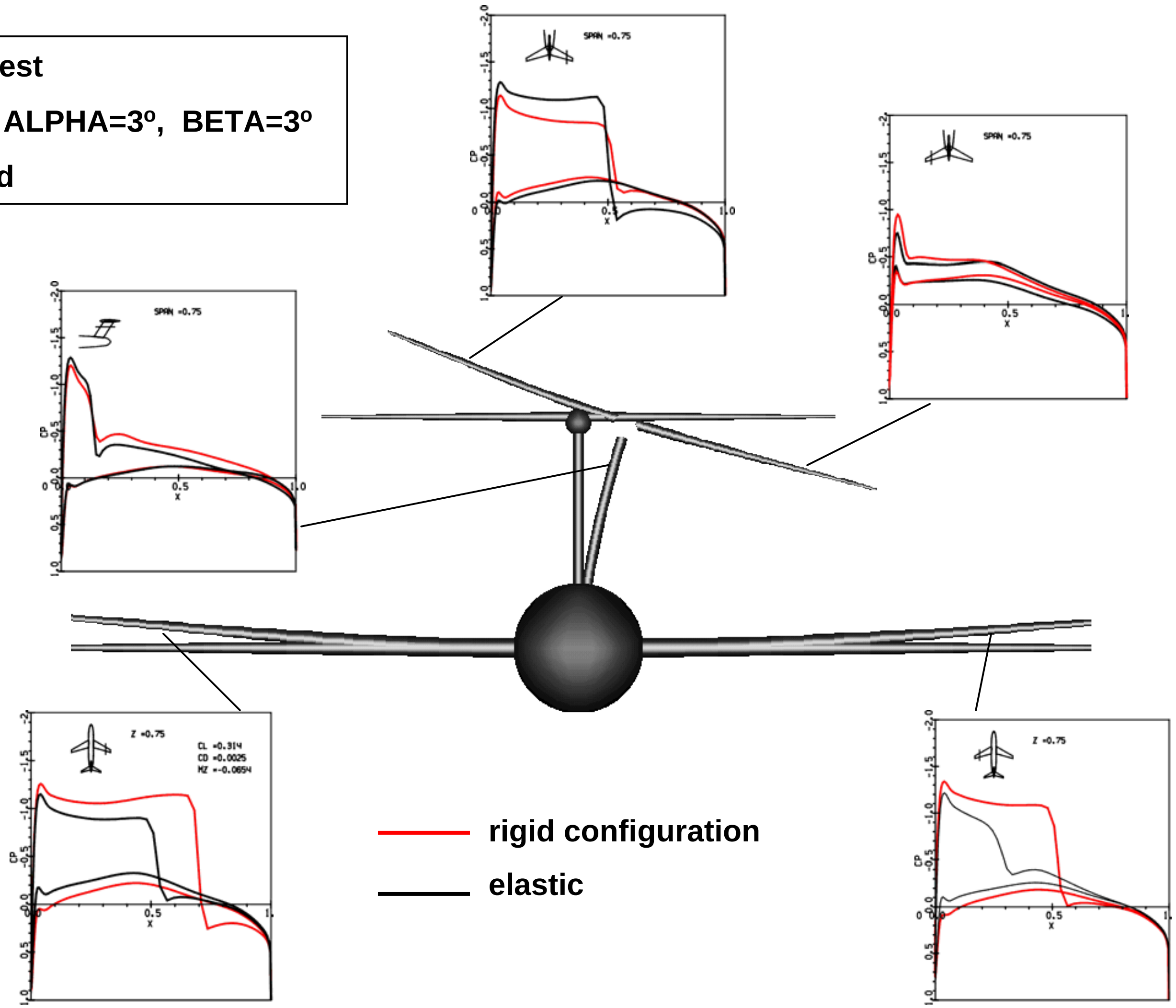
- Control surfaces simulation (without gaps) for wing and tail.
- Calculations in view of steady maneuver.
- Calculation in view of elastic deformation of wing, body and tail (simple beam theory is used).
- 3-d boundary layer calculation on a body.
- Propellers slipstream simulation (actuator disk + rigid slipstream model).

T-type horizontal tail: **Elastic effect, Cp distribution**

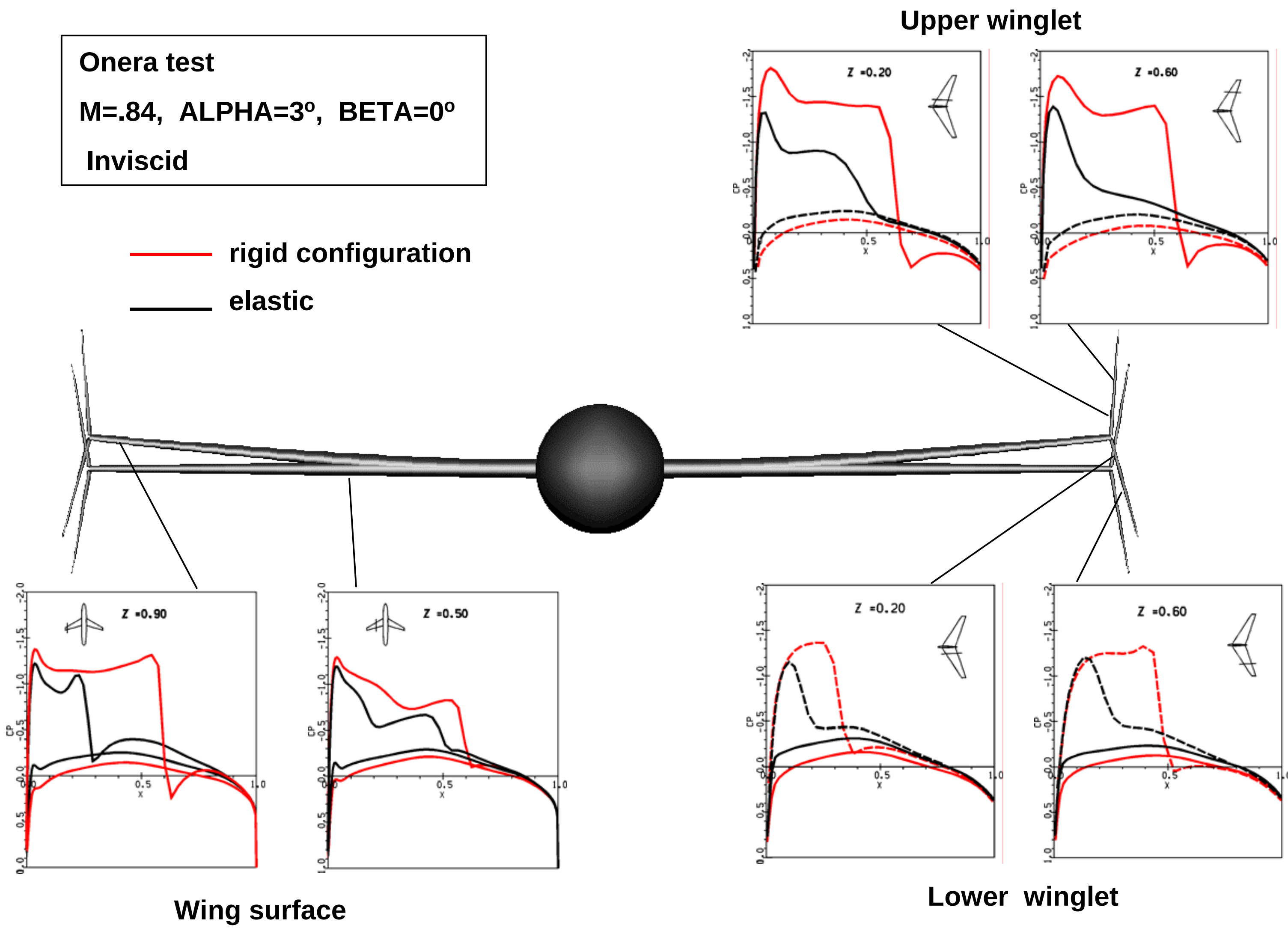
Onera test

M=.84, ALPHA=3º, BETA=3º

Inviscid

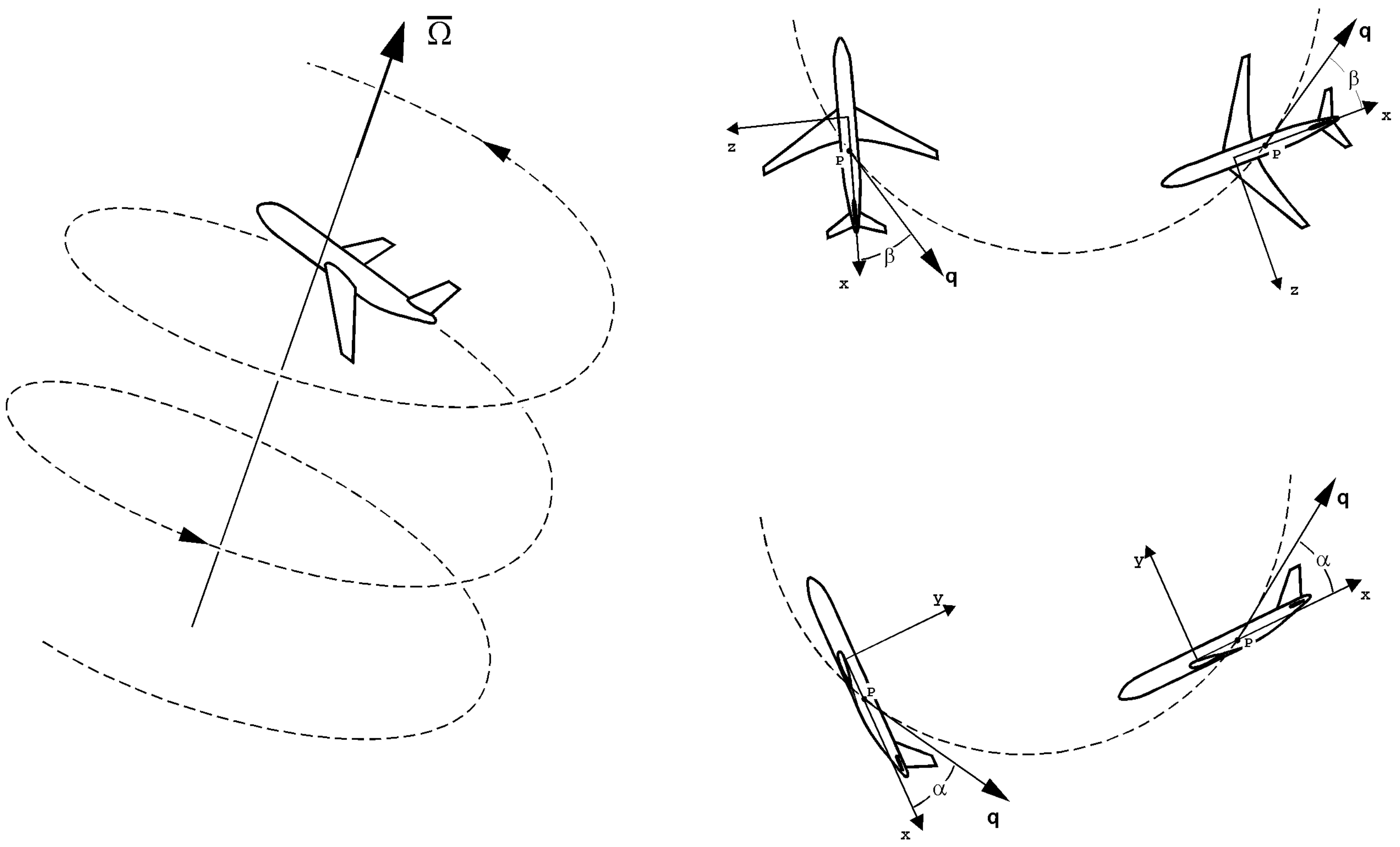


Winglets : **Elastic effect, Cp distribution**



Steady Manoeuvre

α = const. β = const.

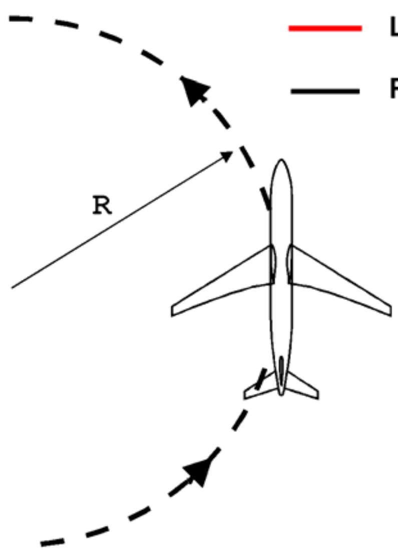


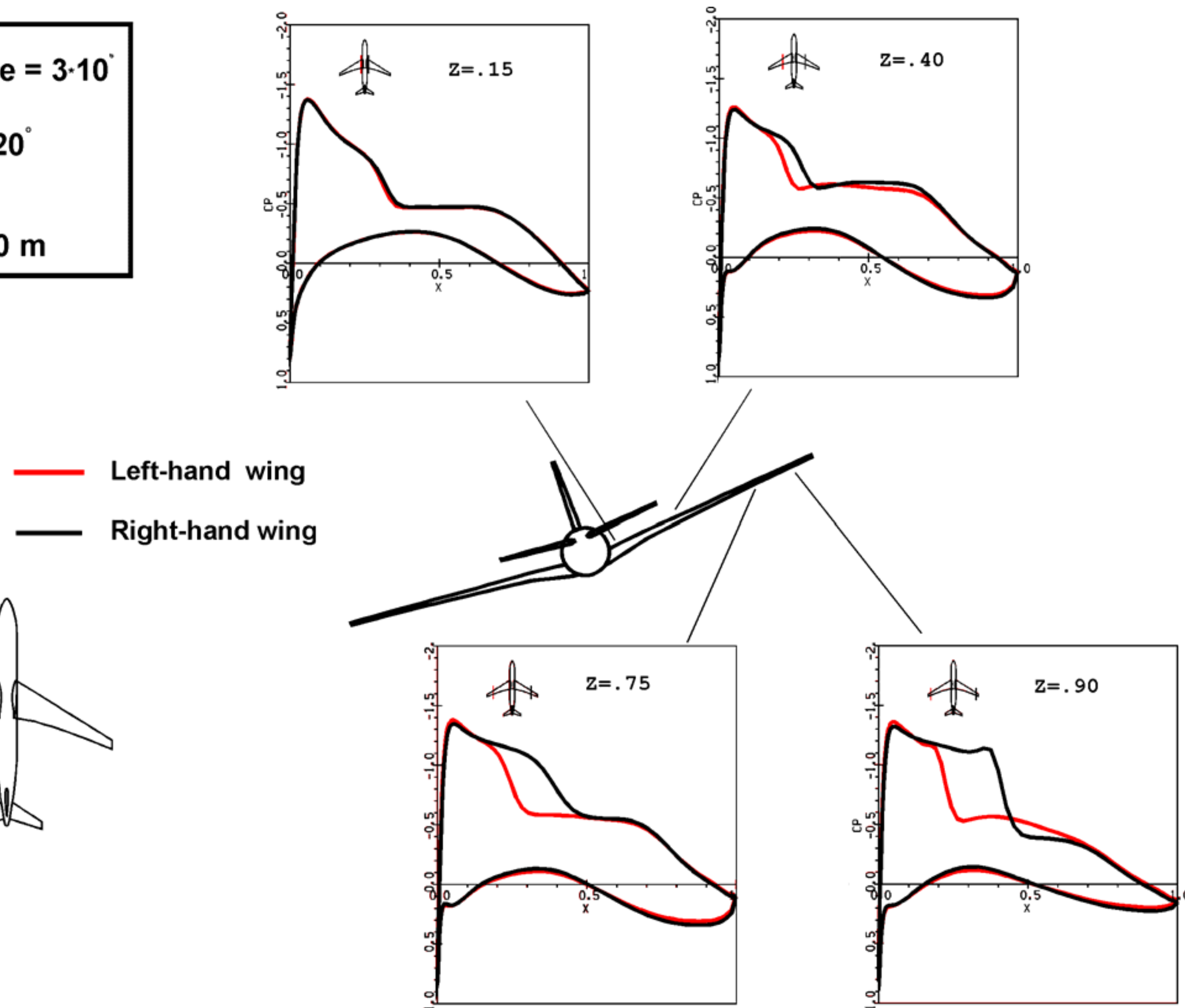
Steady Manoeuvre: **horizontal turn**

M =.78 ALPHA = 2° Re = 3·10

Ω = 10 deg/sec Roll = 20°

V = 230 m/sec R =1320 m



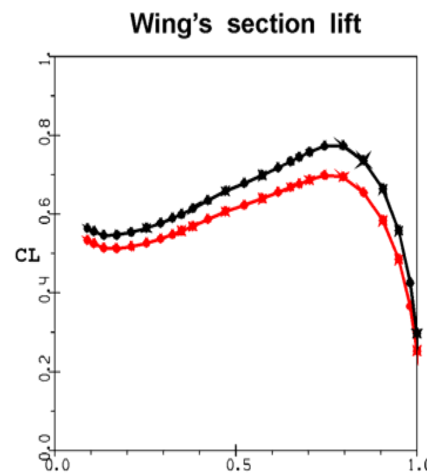


Steady Manoeuvre: **vertical turn**

M =.78 ALPHA = 2° Re = 3·10

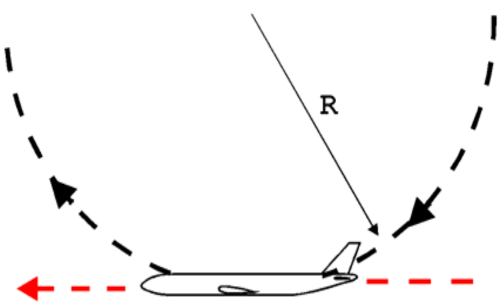
Ω = 10 deg/sec

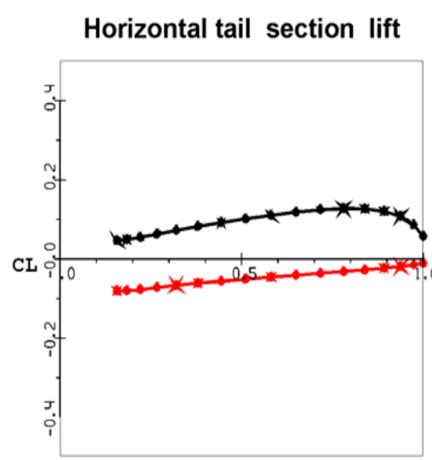
V = 230 m/sec R =1320 m

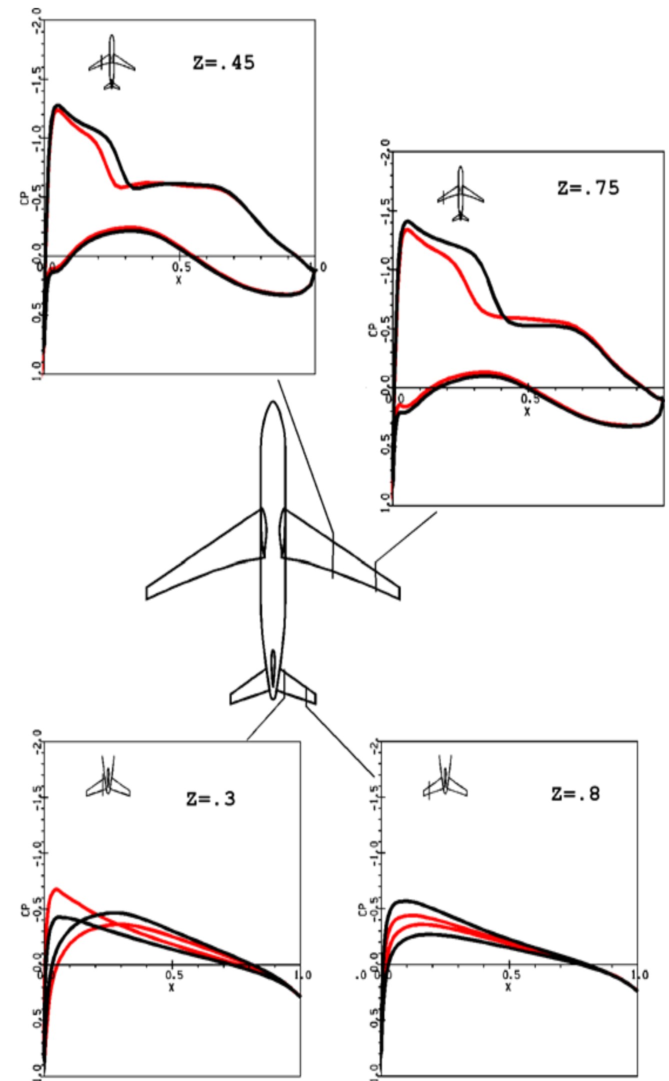


Straight flight

Vertical turn



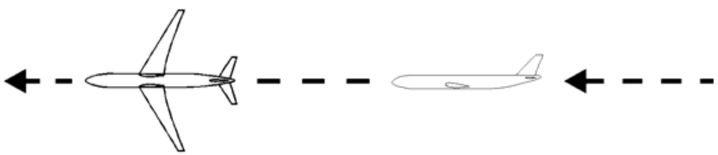


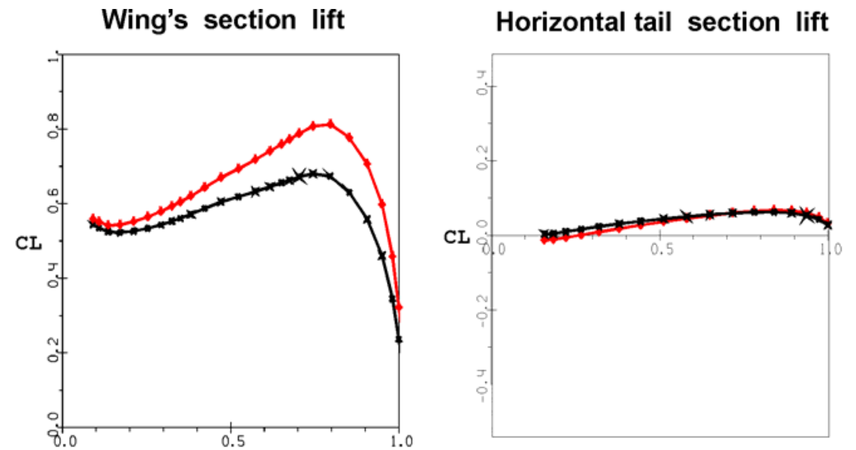


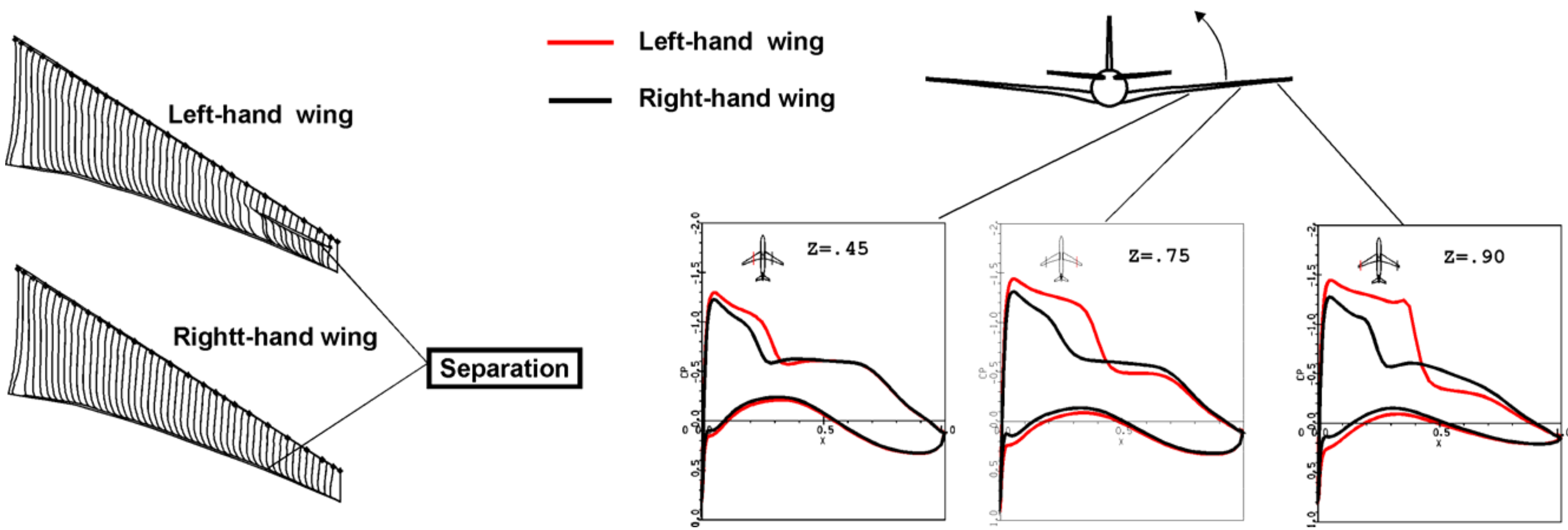
Steady Manoeuvre: **rotation on a roll**

M =.78 ALPHA = 2° Re = 3·10

Ω = 6 deg/sec V = 230 m/sec

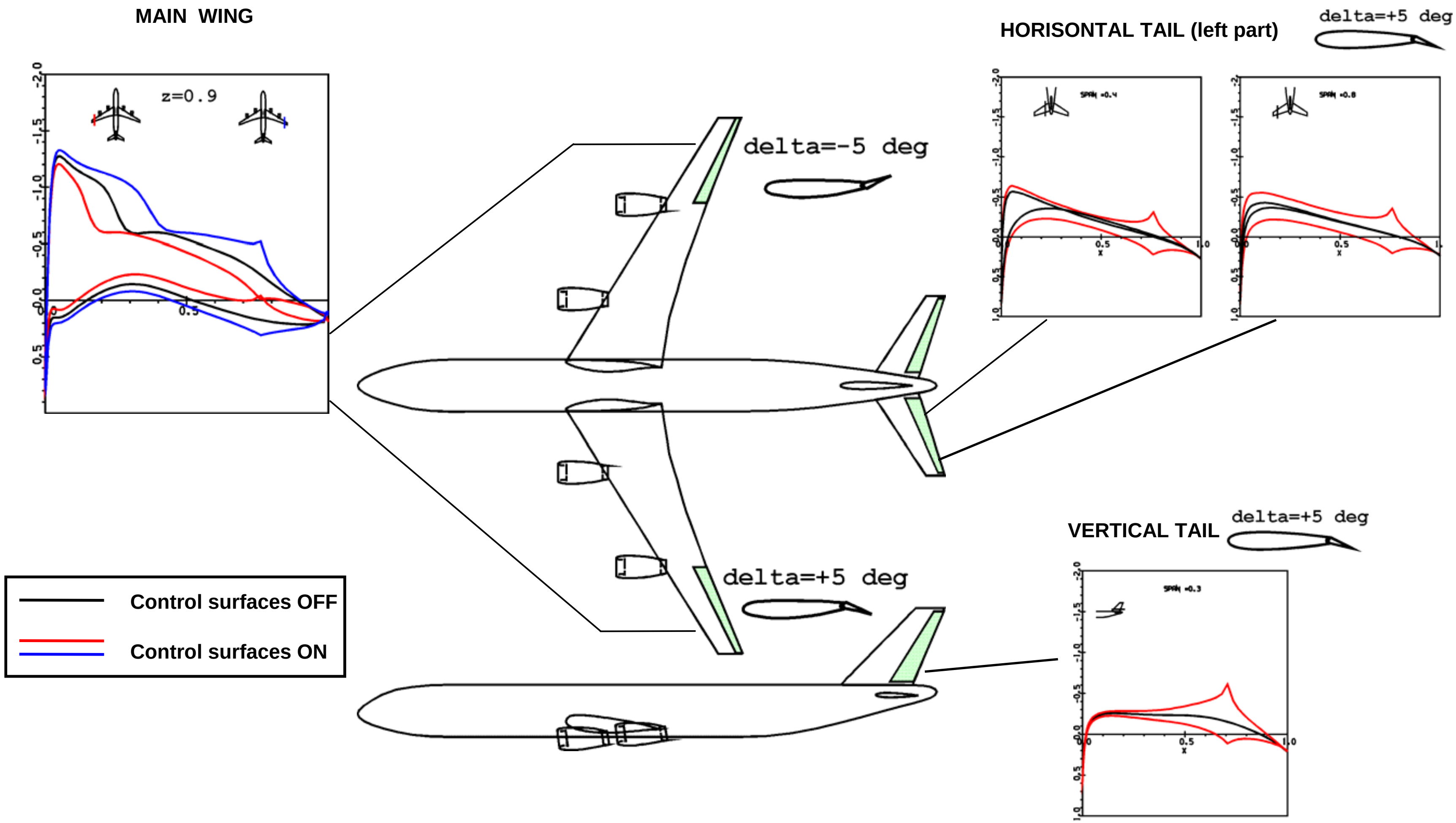






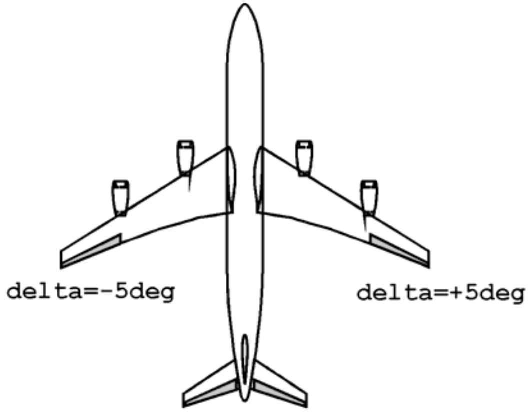
Control surfaces: **Pressure distribution**

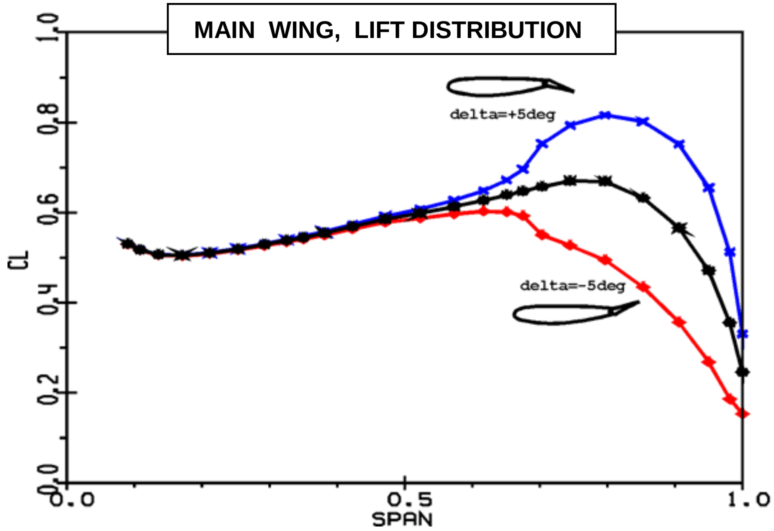
M=.78, ALPHA=2º, BETA=0º, Re=3*10^6

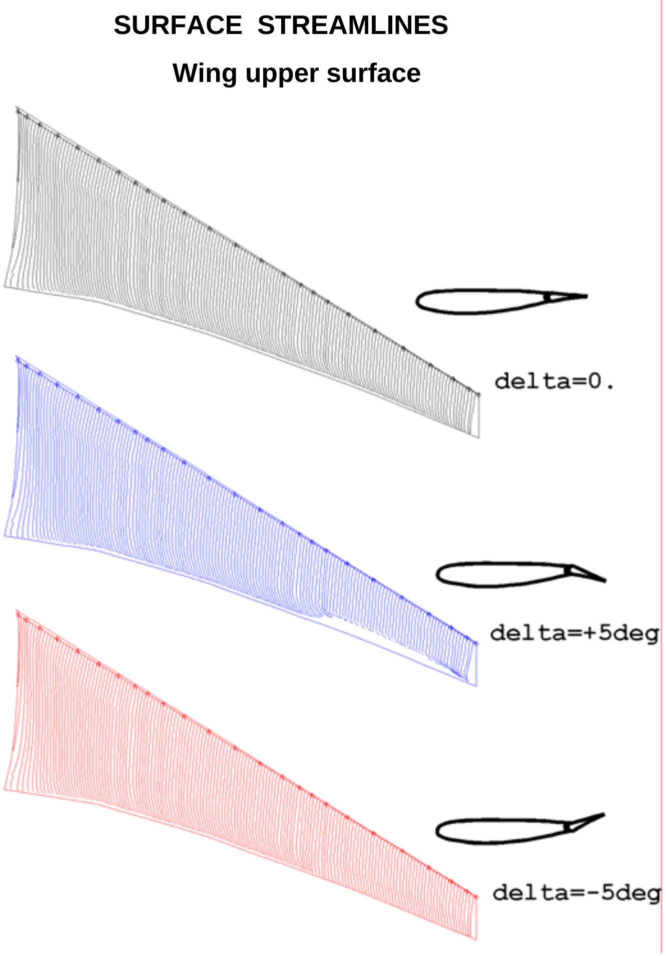


Control surfaces: **Ailerons effect**

M=.78, ALPHA=2º, BETA=0º, Re=3*10⁶



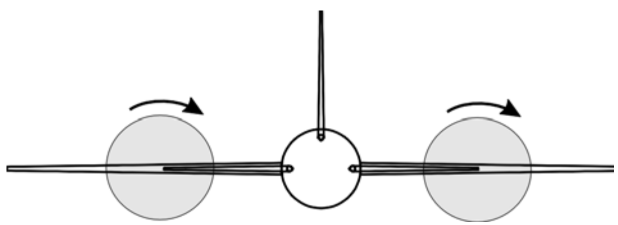




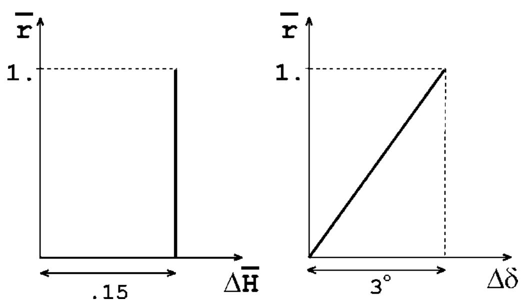
Propeller slipstreams: **Pressure distribution.**

M =.84, ALPHA=3^o,

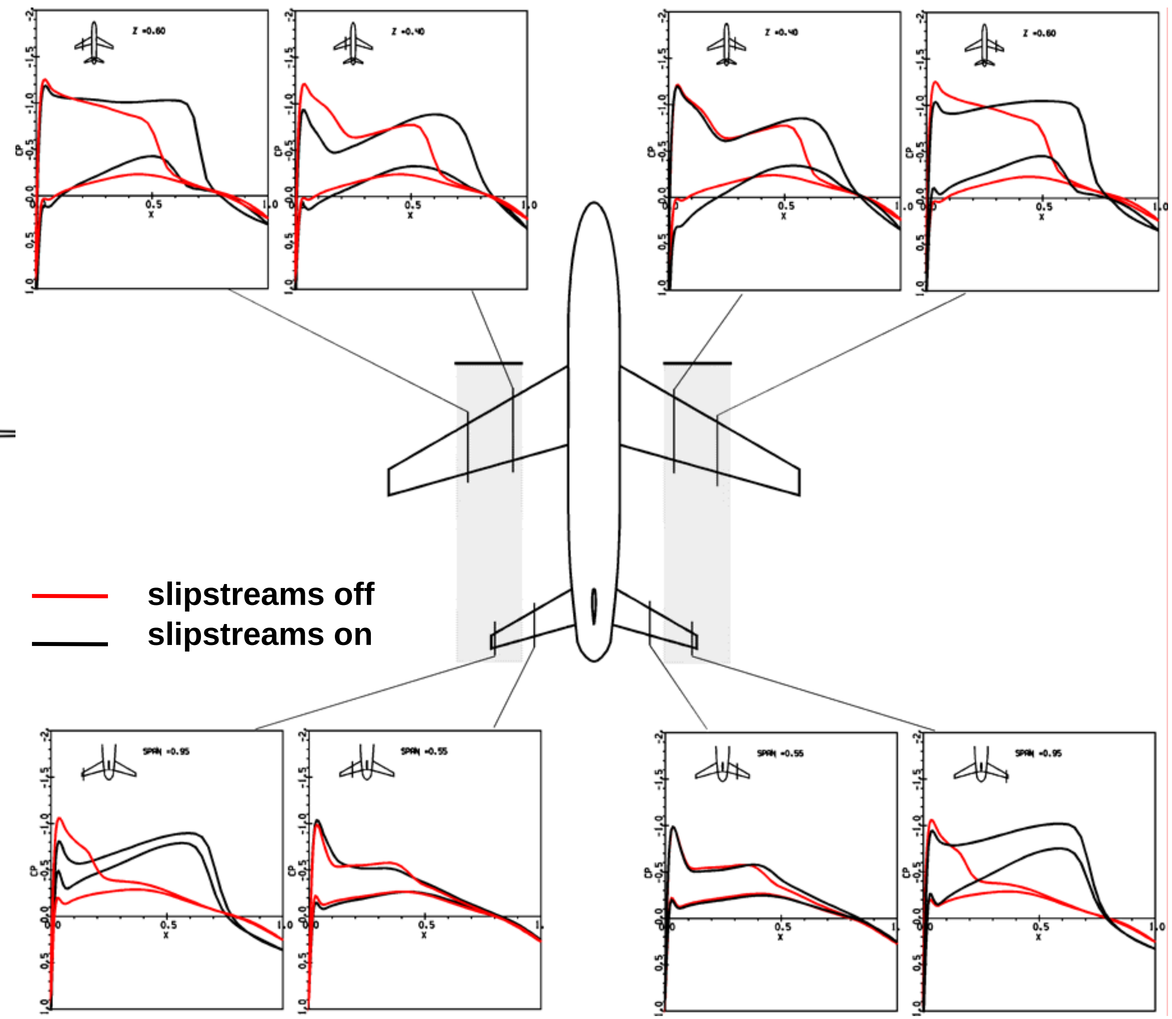
BETA=0^o, Re=3*10^6



Back view



Propeller parameters



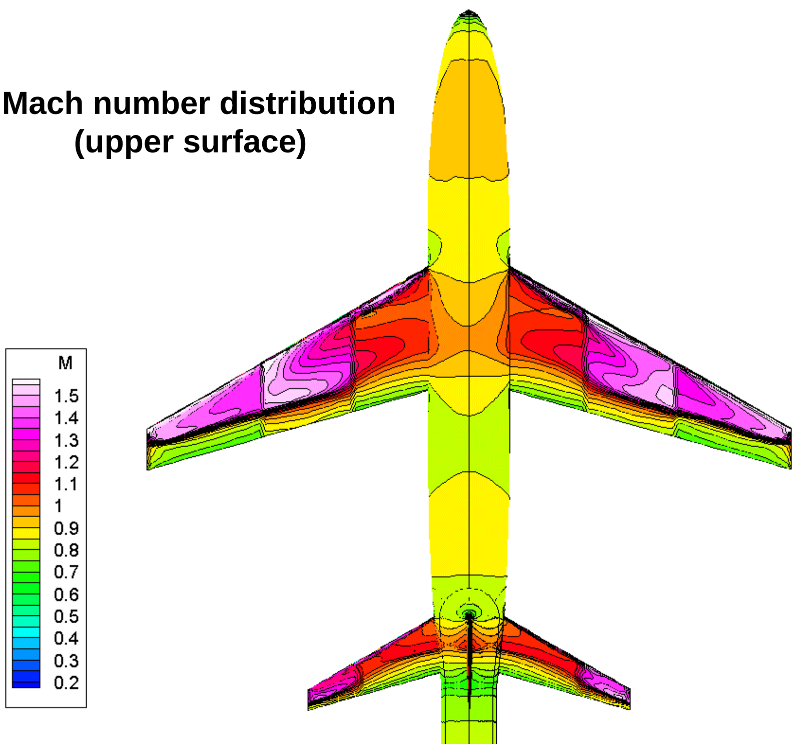
Propeller slipstreams: **Loads.**

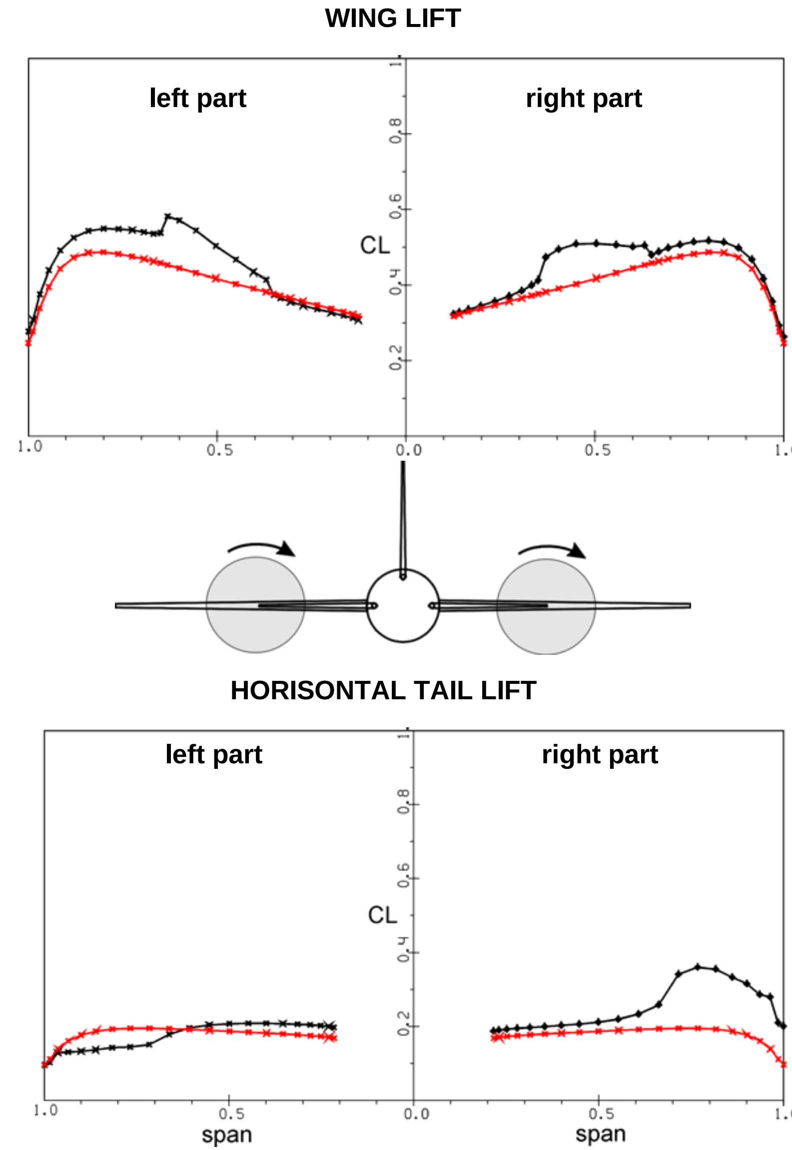
M =.84, ALPHA=3º,

BETA=0º, Re=3*10⁶

slipstreams off (red line)
slipstreams on (black line)

Mach number distribution (upper surface)



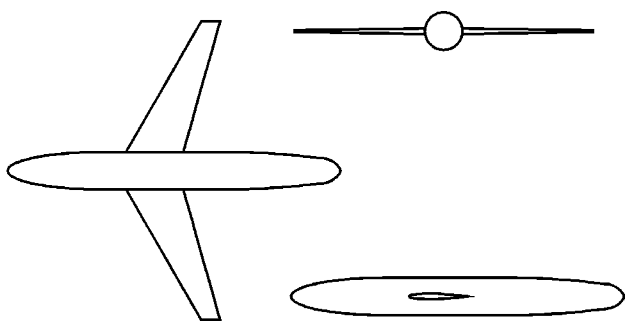


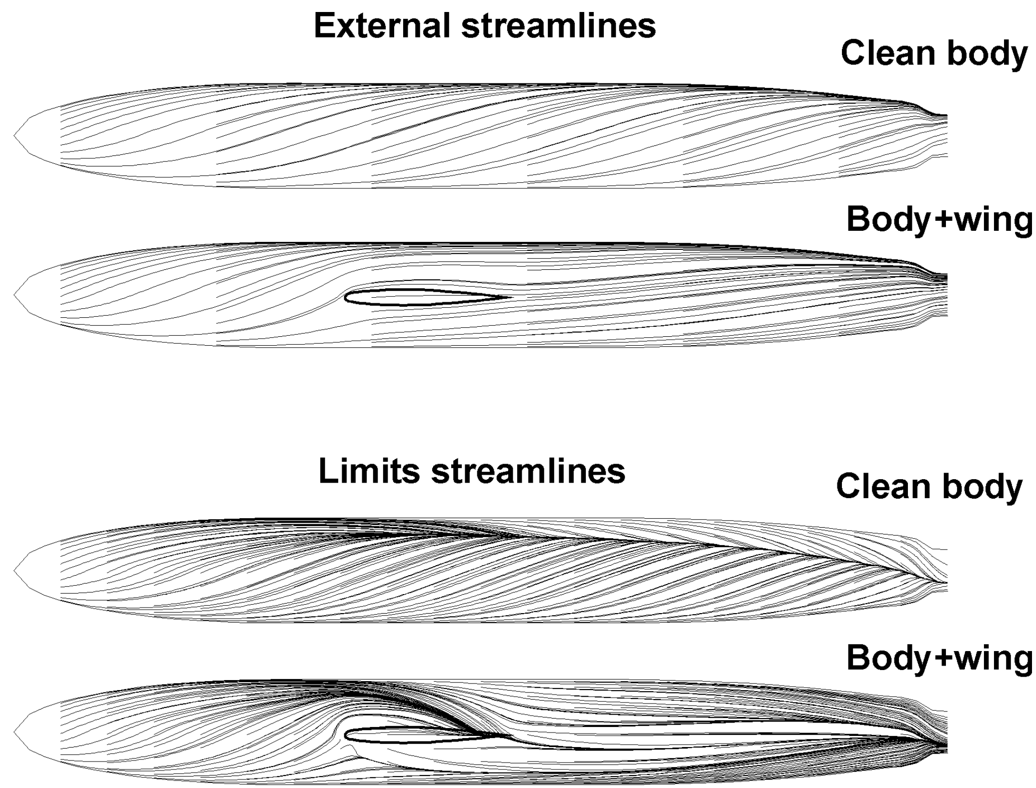
Boundary layer on a body: **Streamlines**

Onera test

M= .6, ALPHA=10°

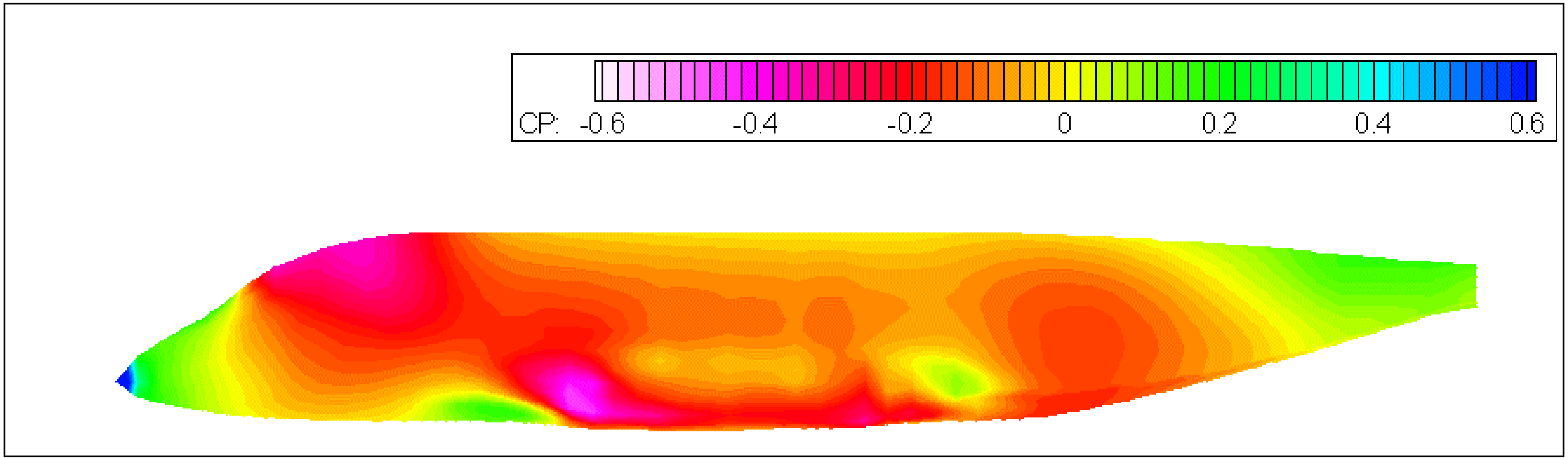
Re=3*10⁶



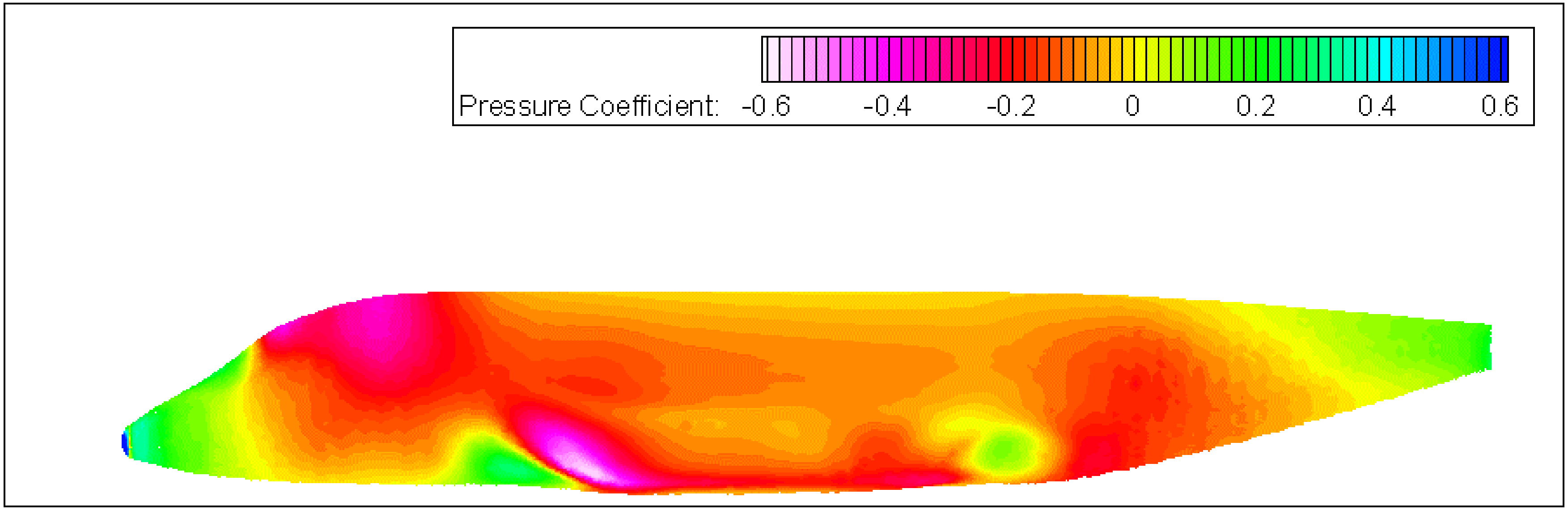


Cp distribution

BLWF computation Side view

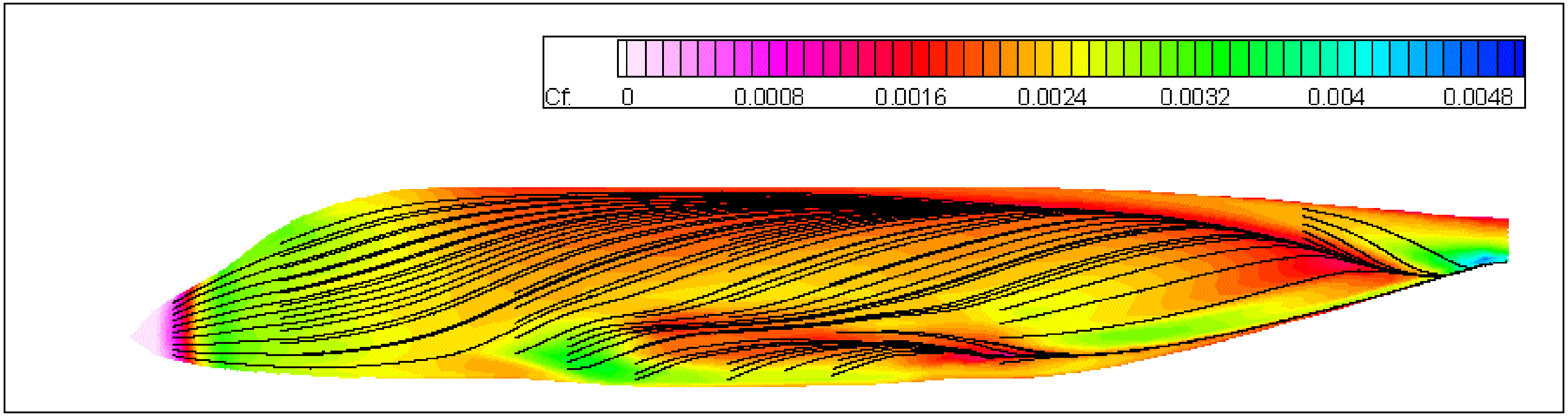


NS computation

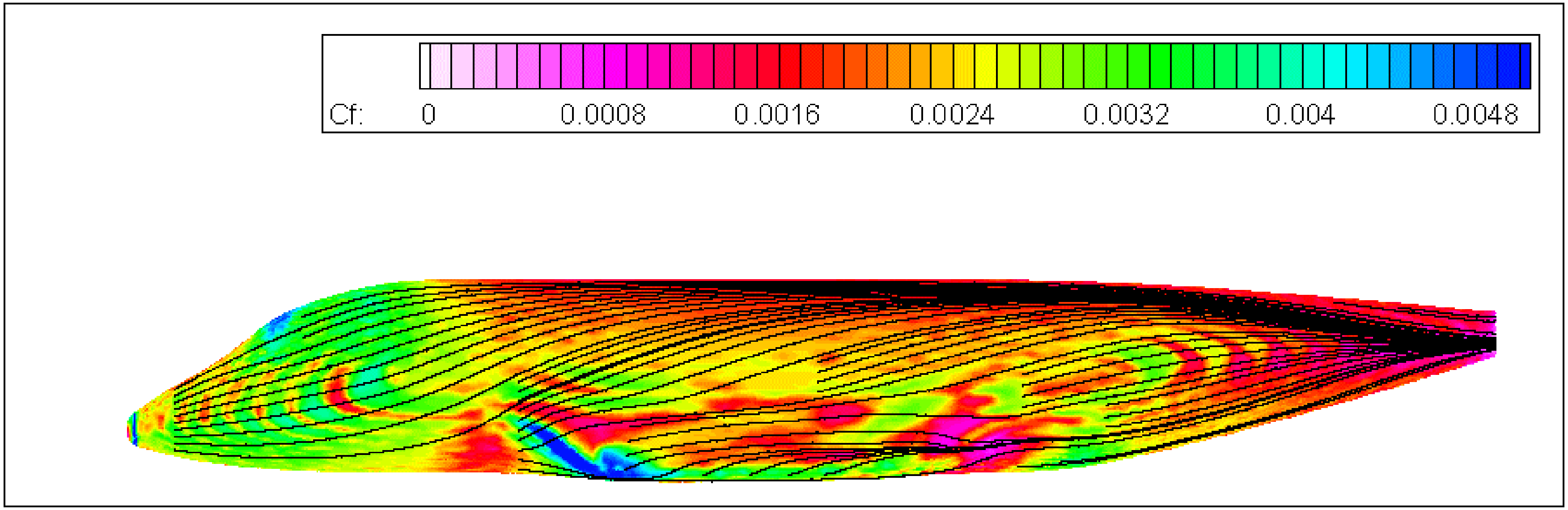


Surface streamlines and Cf distribution

BLWF computation Side view

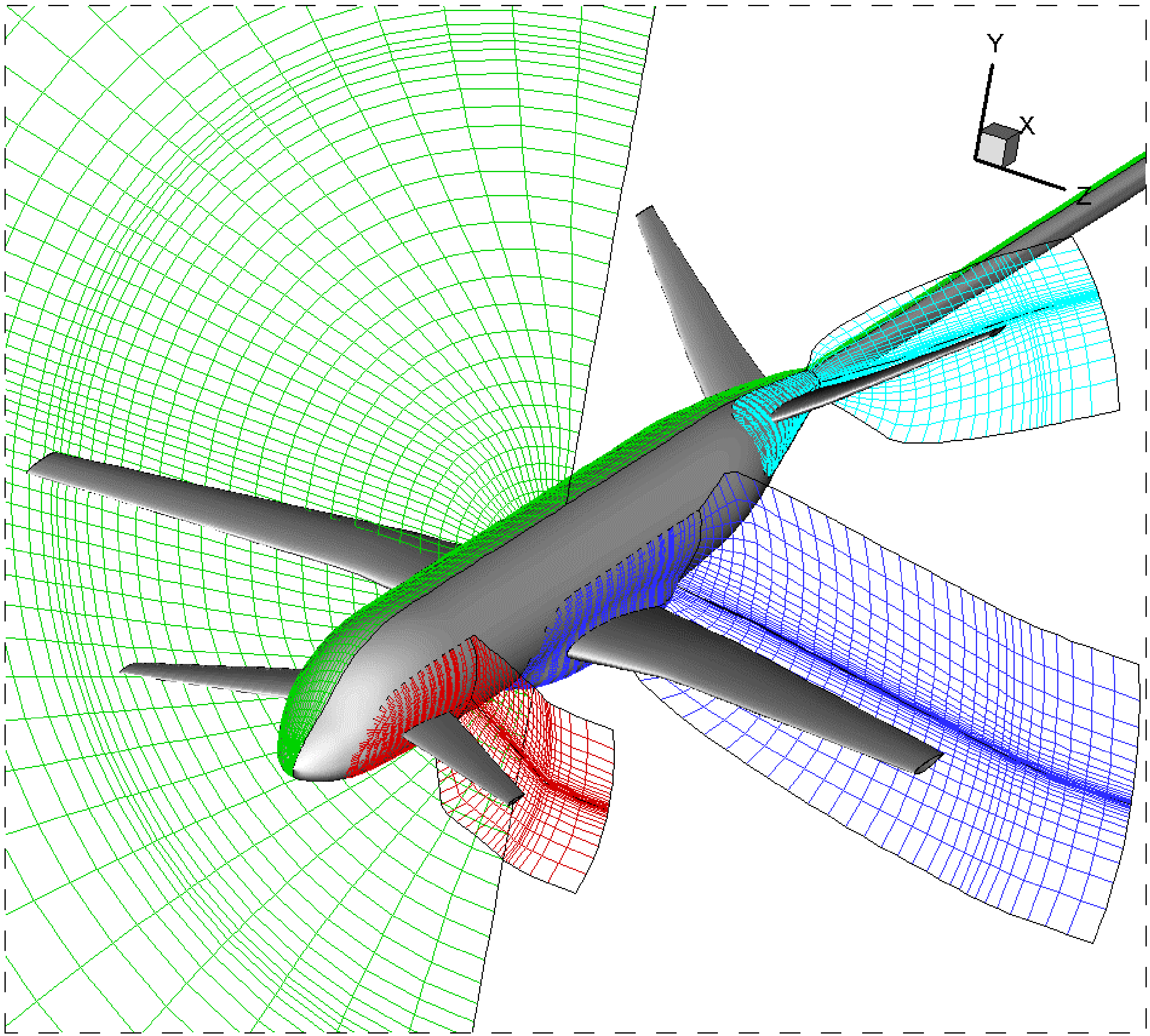


NS computation



BLWF100, BLWF110

- the versions based on Euler equations



Y
X
Z

Fast implicit scheme for solving steady Euler equations.

$$\partial_t W + \nabla \cdot F(W) = 0 \qquad F(W) = \begin{pmatrix} \rho \vec{q} \\ \rho u \vec{q} + p \vec{i} \\ \rho v \vec{q} + p \vec{j} \\ \rho w \vec{q} + p \vec{k} \\ \rho h \vec{q} \end{pmatrix} \qquad W = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho e \end{pmatrix}$$

Approximation:

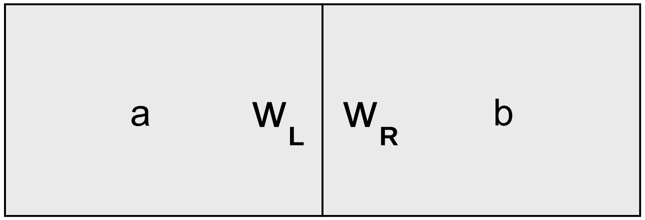
- finite volume, cell centered approach;
- Osher scheme for numerical fluxes definition
  (the main advantage – differentiability);
- energy equation is not solved – the total enthalpy is fixed

Fast implicit scheme for solving steady Euler equations.

Newton like iterative procedure:

- On iteration the system of linear equation for the correction is constructed on the basis of the Newton's fluxes linearization:

$$F = \frac{1}{2}(F_L + F_R) - \frac{1}{2}\int_{w_L}^{w_R} \left| \partial F / \partial w \right| \, dw$$



$$\Downarrow$$

$$\delta F = \left(\frac{\partial F}{\partial w}\right)_L^+ \delta w_L + \left(\frac{\partial F}{\partial w}\right)_R^- \delta w_R$$

$$\delta F \approx \left(\frac{\partial F}{\partial w}\right)_a^+ \left(\frac{\partial w}{\partial Q}\right)_a \delta Q_a + \left(\frac{\partial F}{\partial w}\right)_b^- \left(\frac{\partial w}{\partial Q}\right)_b \delta Q_b$$

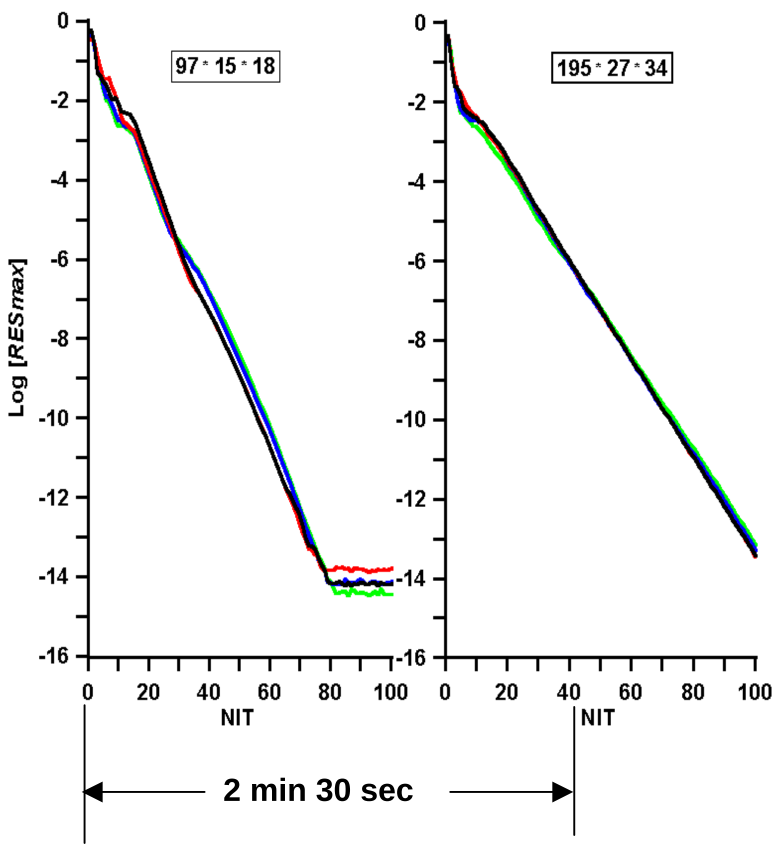
$$Q = (\rho, u, v, w)^T$$

- the approximate solution of the resulting total system of matrix equations for correction is carried out using the **GMRES algorithm preconditioned with simple LU approximate decomposition**

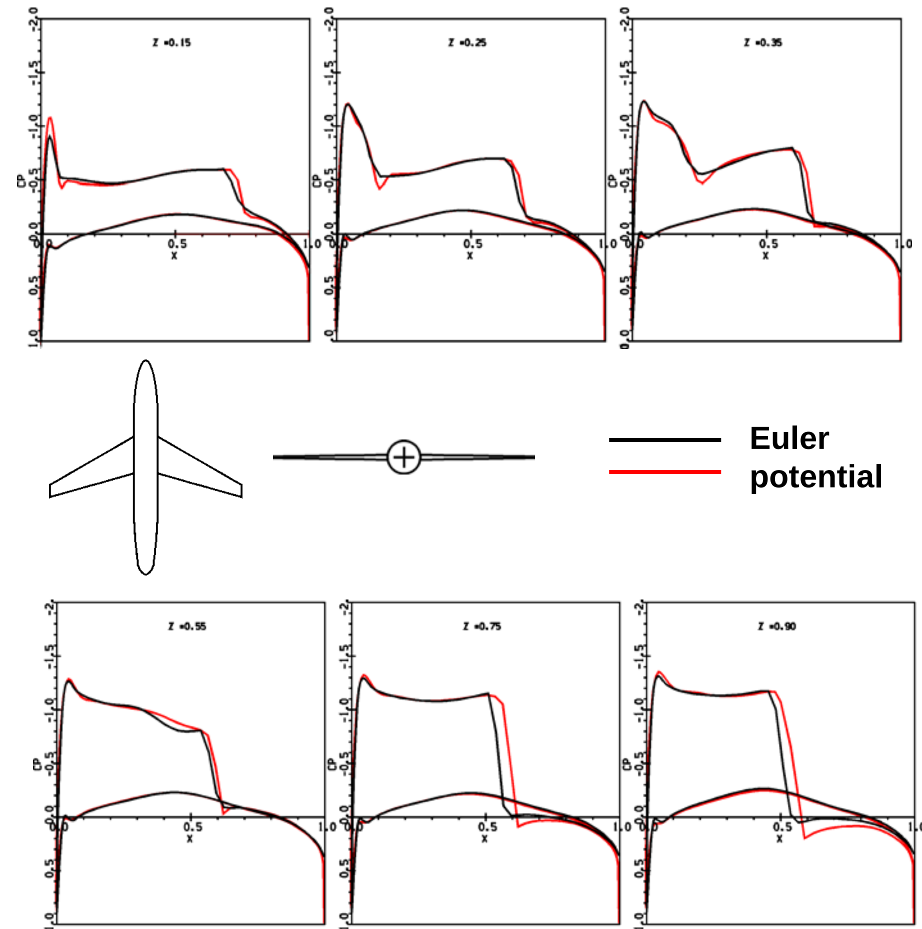
Fast implicit scheme for solving Euler equation.

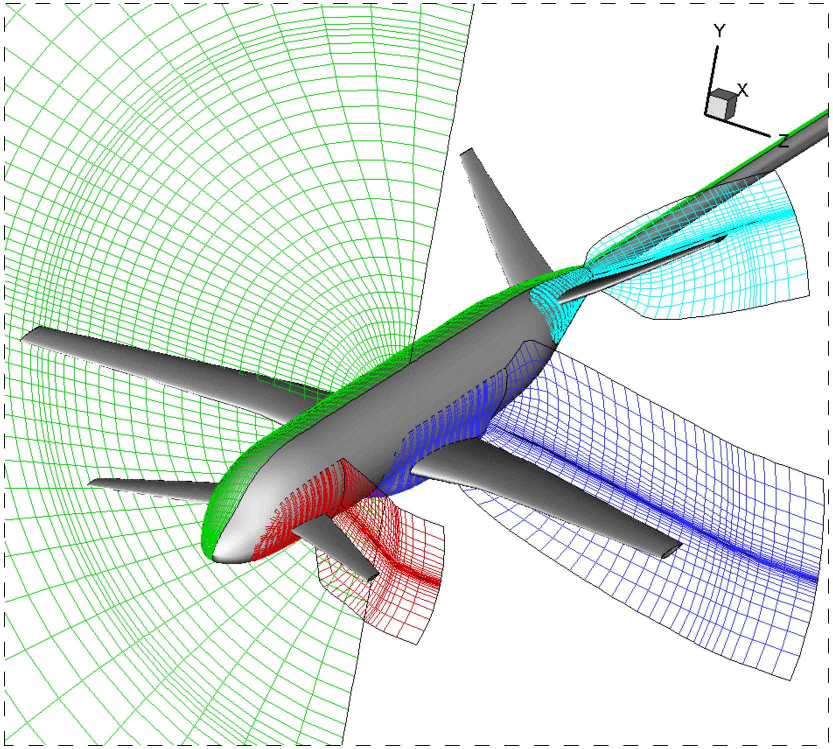
ONERA test
M= .84, ALPHA=3º, BETA=0º
Inviscid flow

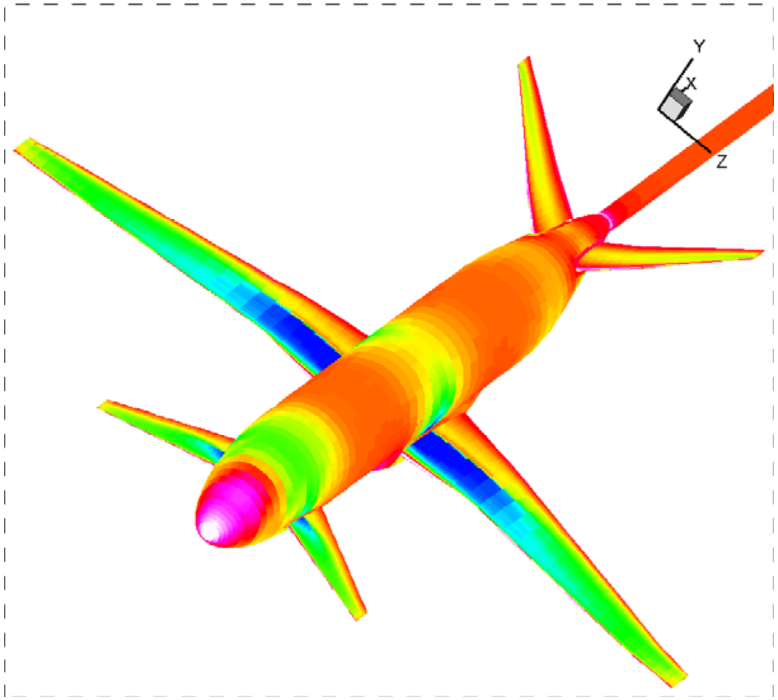
Convergence of the iteration process



1 processor 2400 mg



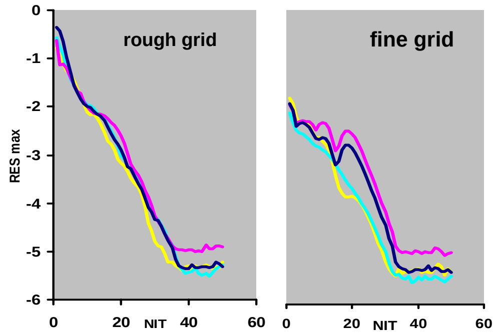

Y
X
Z


Y
X
Z

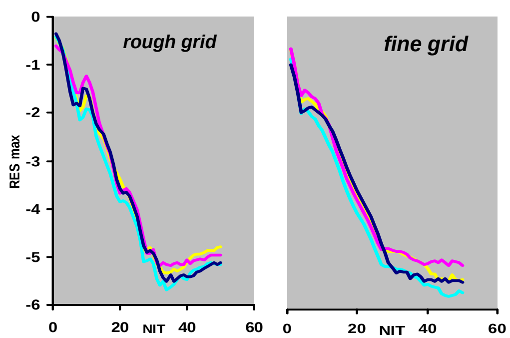
Fast implicit scheme for solving Euler equation.

Convergence of the iteration process

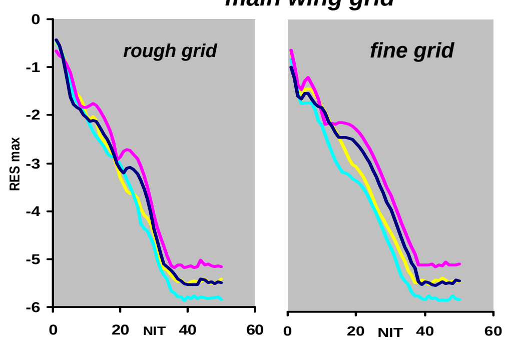
body grid



canard wing grid



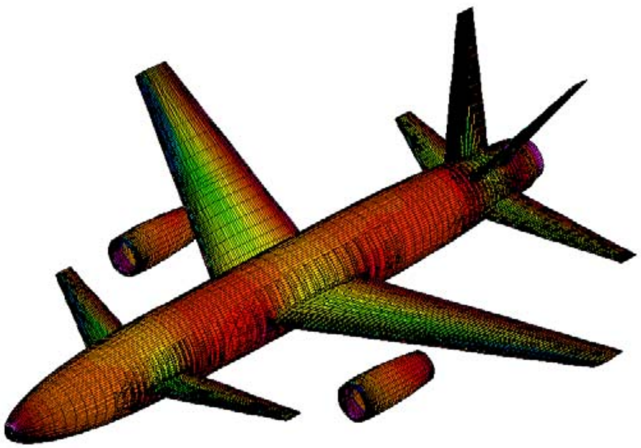
main wing grid



9 min
processor 3000 mhz

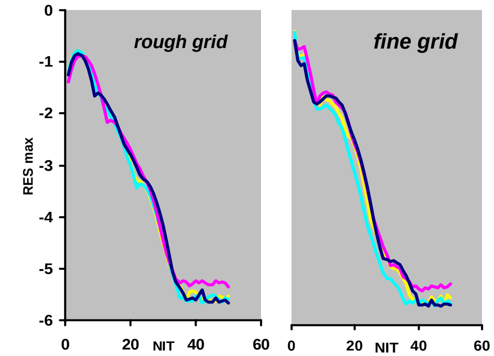
M= .84, ALPHA=3^o, BETA=0^o
Inviscid flow

continuity
x - momentum
y - momentum
z - momentum

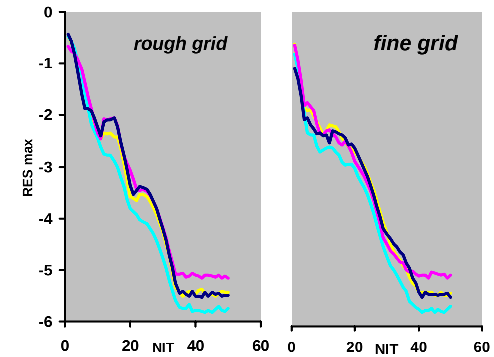


1 processor 3000 Mhz
Total CPU time - 9 min
Total memory - 350 Mb

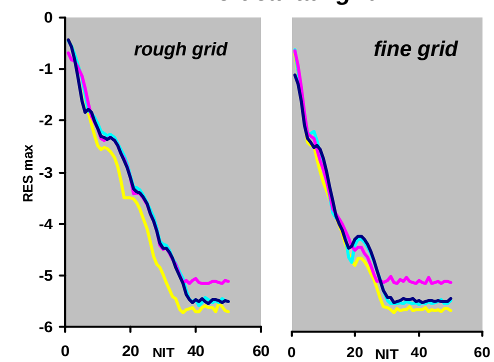
nacelle grid

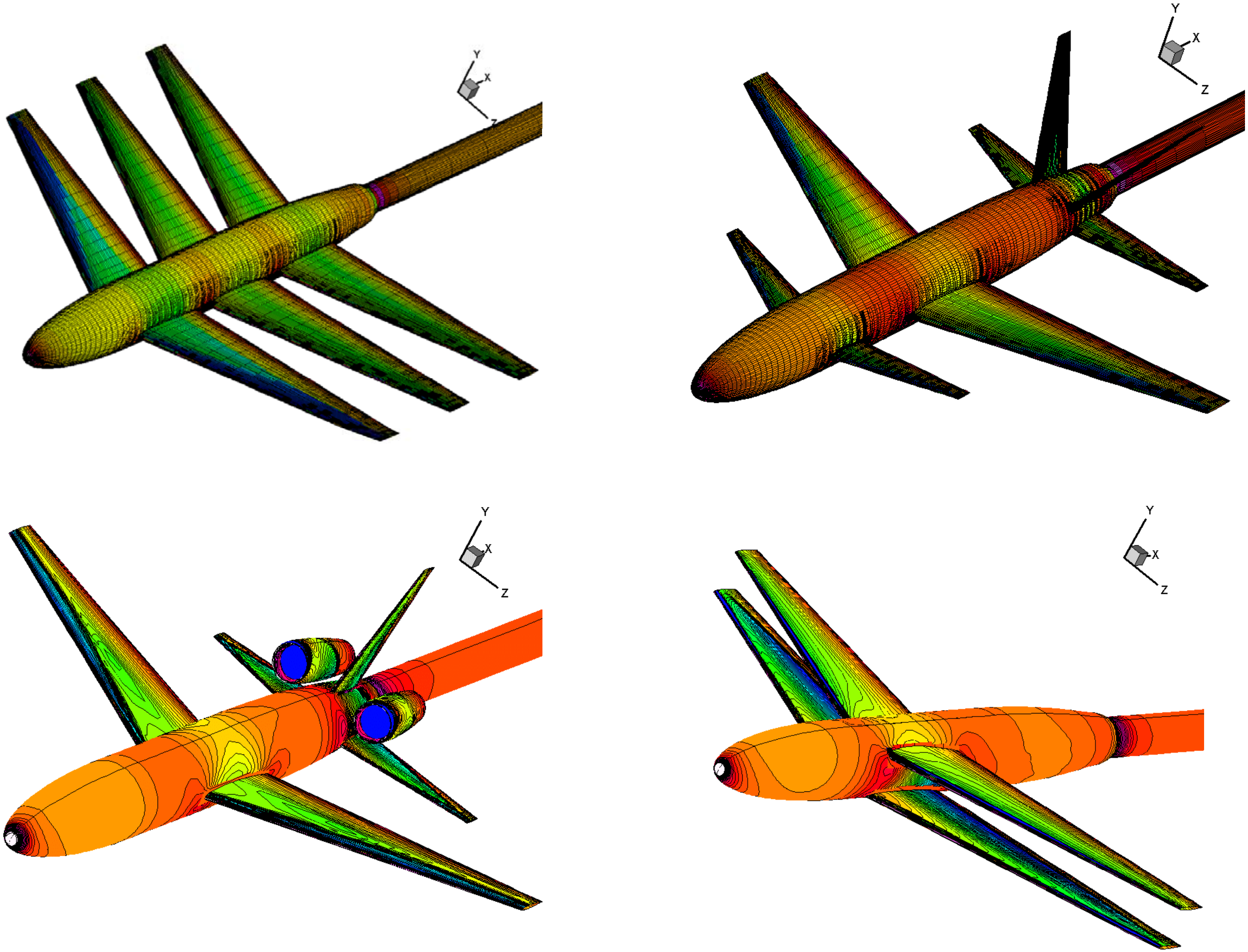


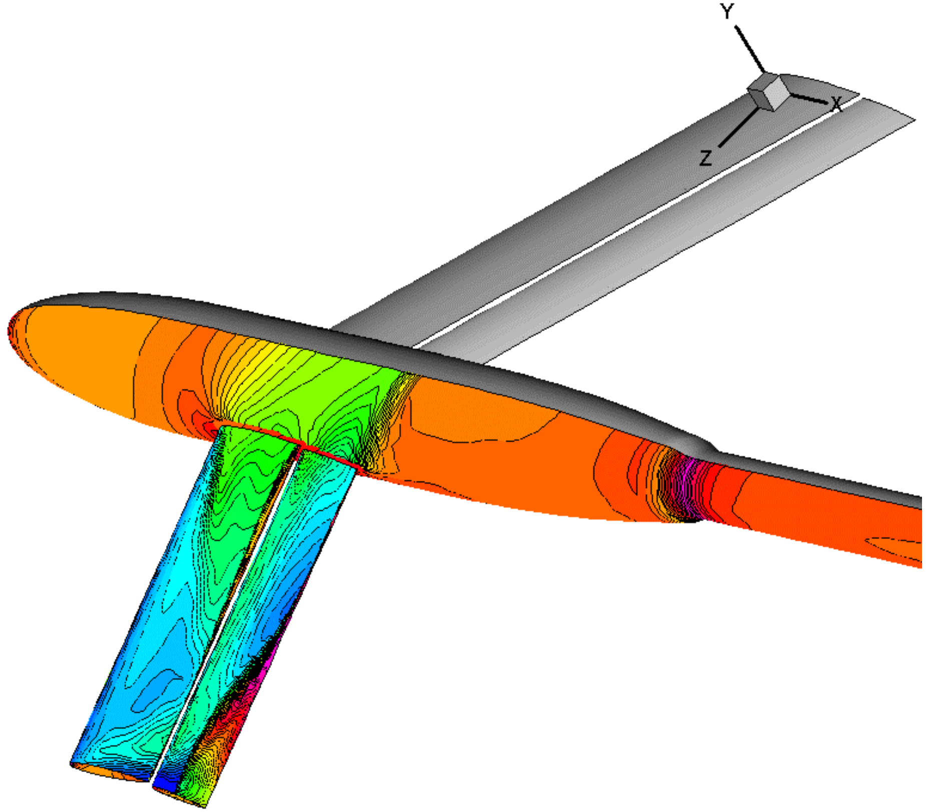
horizontal tail grid

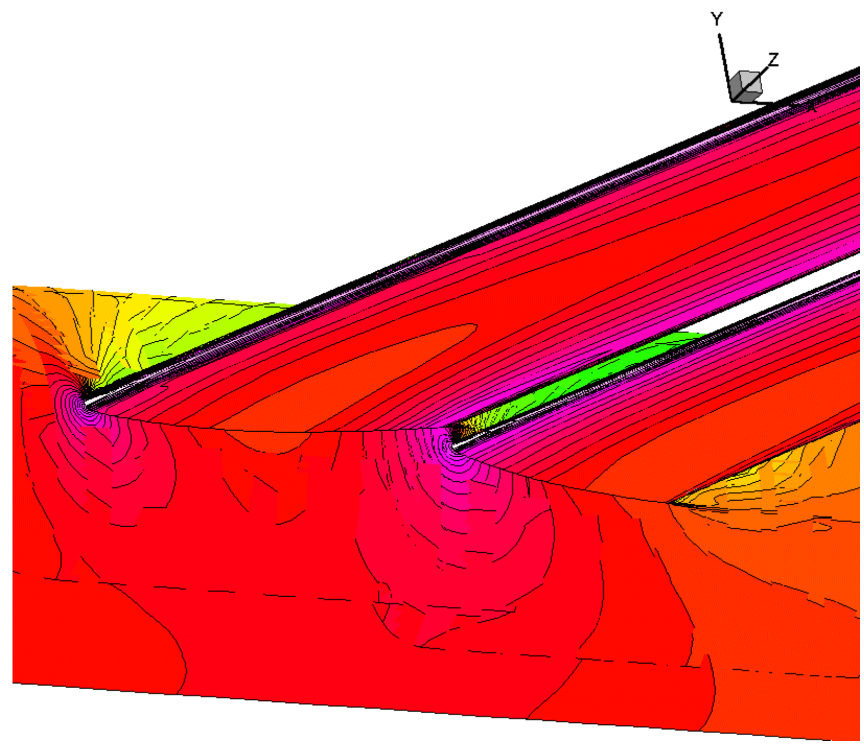


vertical tail grid



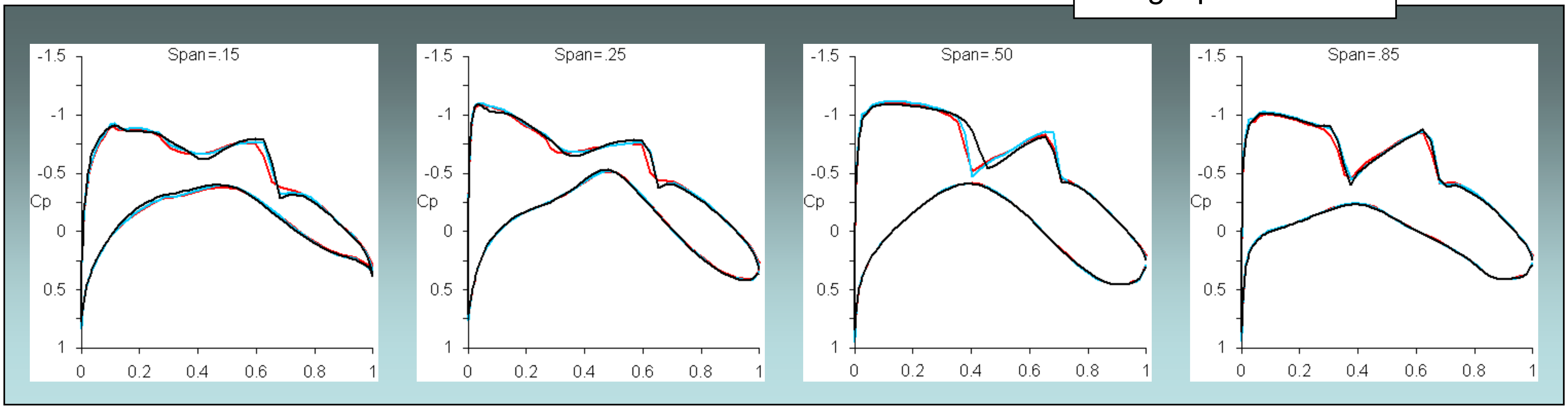

Y
X
Z
Y
X
Z
Y
X
Z
Y
X
Z


Y
X
Z

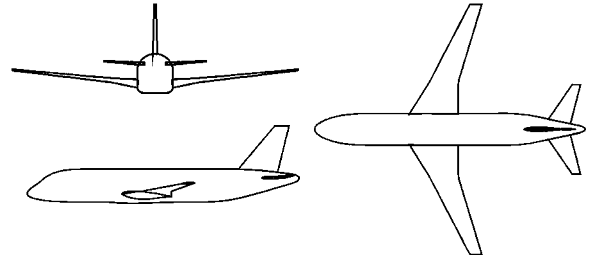

Y
Z

Codes comparison. **RRJ-type configuration. M=0.75, Alpha=2 Inviscid**

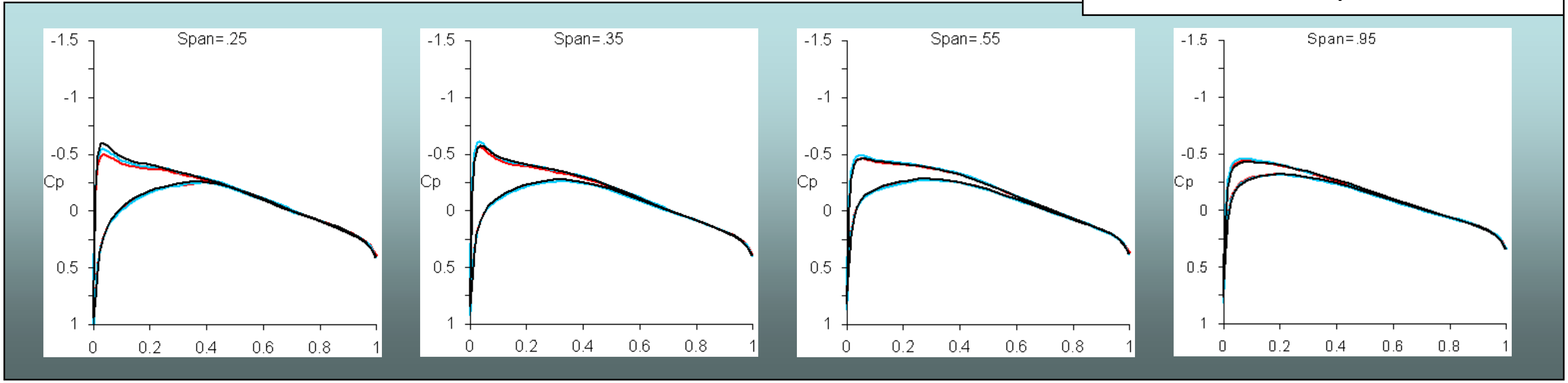
Wing Cp distribution



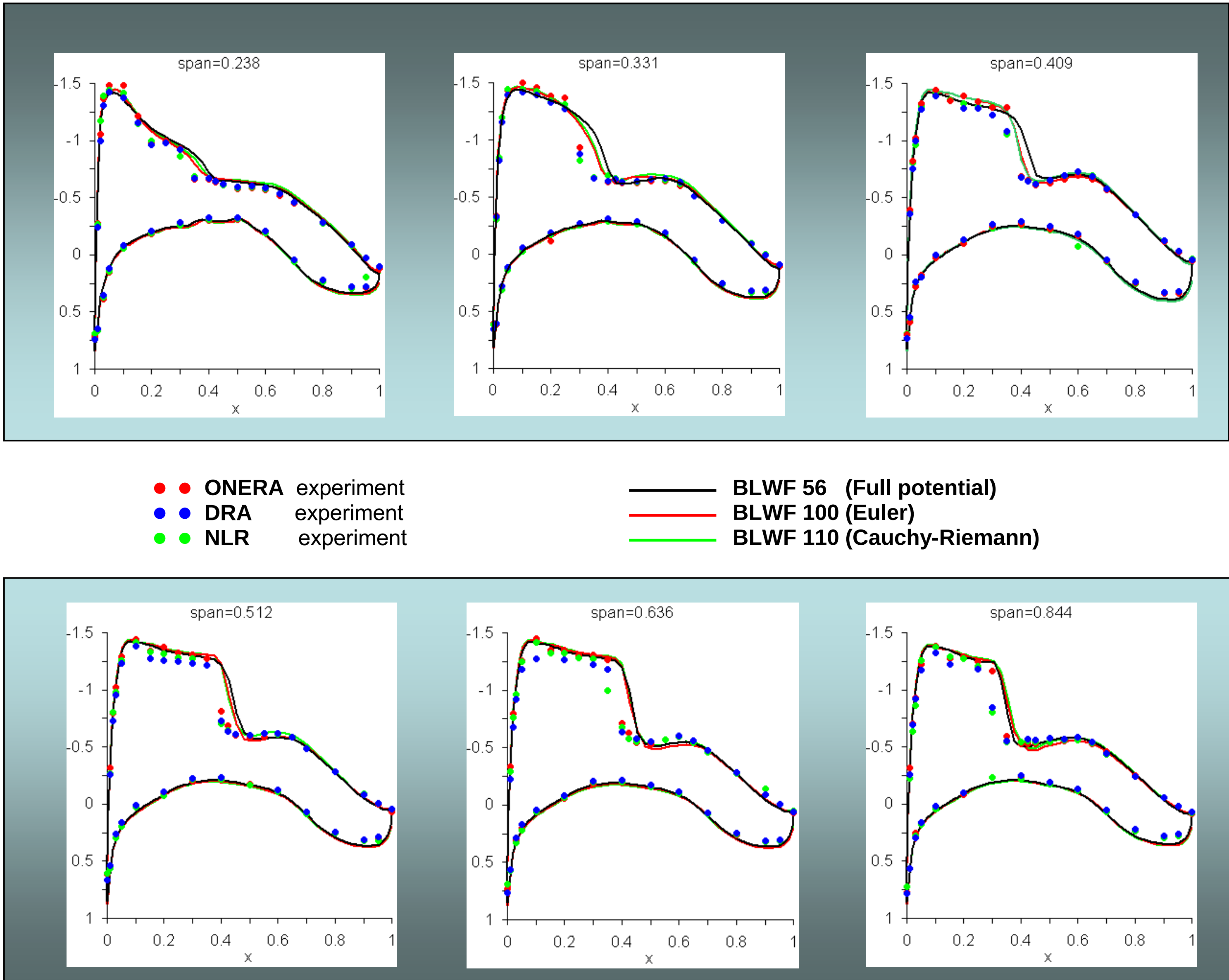
BLWF 56 (Full potential)
BLWF 100 (Euler)
BLWF 110 (Cauchy-Riemann)



Horisontal tail Cp distribution.

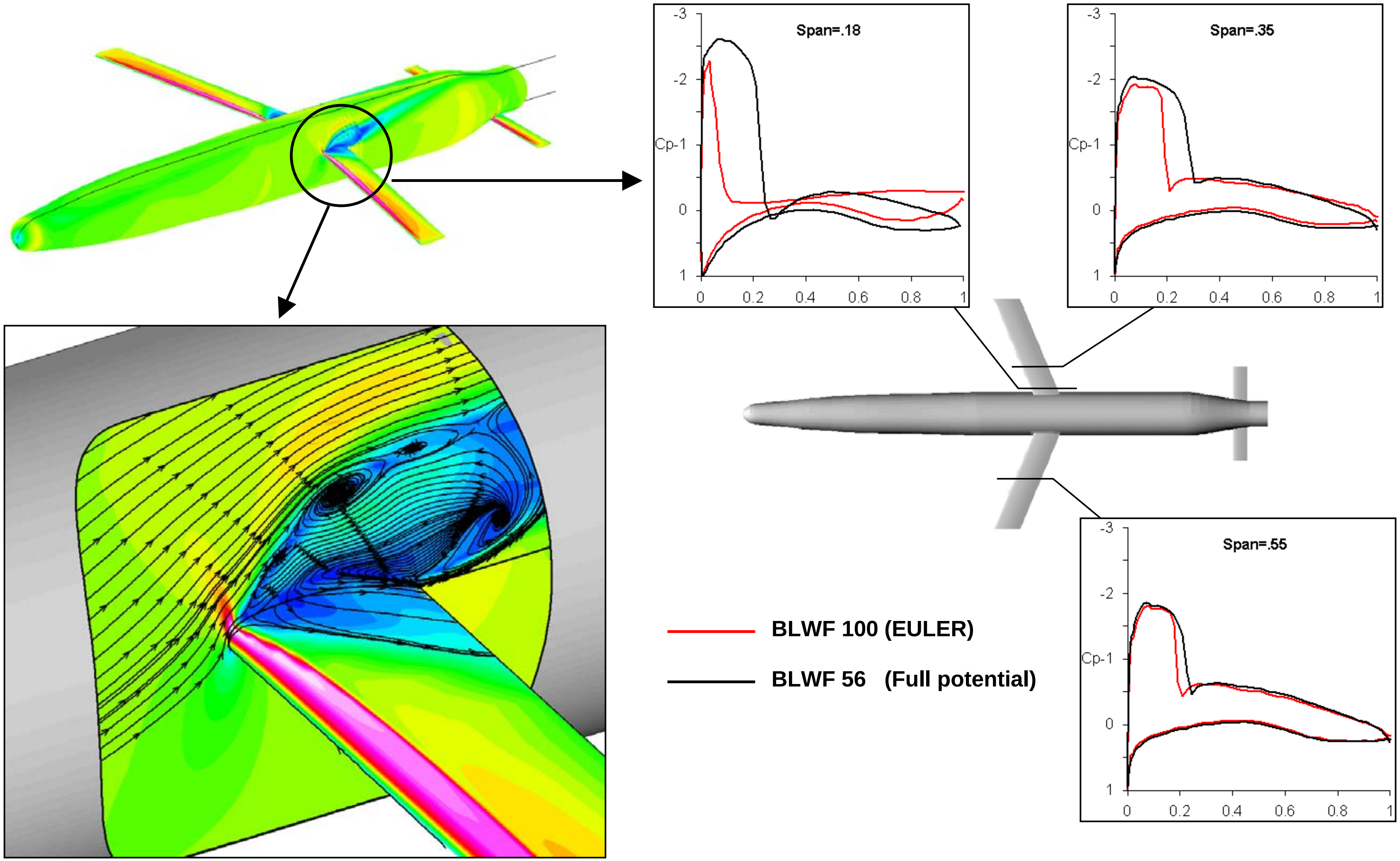


Codes comparison. **DLR-F4 test: M=0.75, al=0.9, Re=3*10^6**



Degradation of the inviscid Euler solution.

Inverse swept wing configuration   M=0.70   Alpha=4.5



Cauchy–Riemann formulation .

<u>Euler formulation</u>

total enthalpy = const

unknowns: ρ, u, v, w

$$\rho_t + div\,(\rho\,\vec{q}) = 0$$

$$(\rho\,u)_t + (\rho\,u^2 + p)_x + (\rho\,uv)_y + (\rho\,uw)_z = 0$$

$$(\rho\,v)_t + (\rho\,vu)_x + (\rho\,v^2 + p)_y + (\rho\,vw)_z = 0$$

$$(\rho\,w)_t + (\rho\,wu)_x + (\rho\,wv)_y + (\rho\,w^2 + p)_z = 0$$

<u>Cauchy–Riemann formulation</u>

total enthalpy = const
entropy = const

unknowns: u, v, w

$$u_t + [(\rho\,u^2 + p)_x + (\rho\,uv)_y + (\rho\,uw)_z - 2u\,div\,(\rho\,\vec{q})]/\rho = 0$$

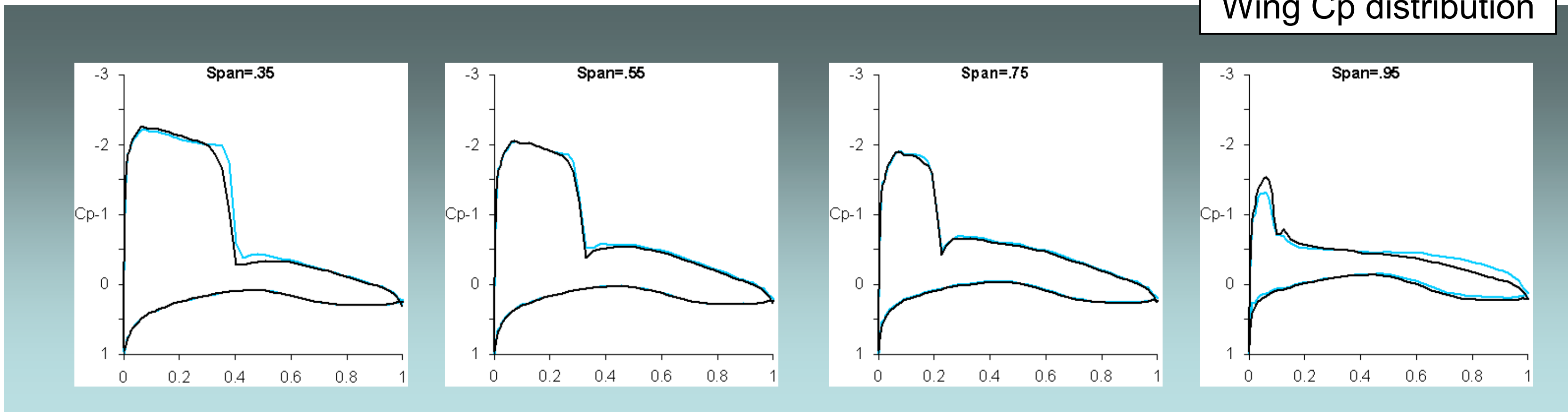
$$v_t + [(\rho\,vu)_x + (\rho\,v^2 + p)_y + (\rho\,vw)_z - 2v\,div\,(\rho\,\vec{q})]/\rho = 0$$

$$w_t + [(\rho\,wu)_x + (\rho\,wv)_y + (\rho\,w^2 + p)_z - 2w\,div\,(\rho\,\vec{q})]/\rho = 0$$

- Cauchy-Riemann formulation is identical to potential flow gas model, but the flow calculation is carried out **without the introducing of the potential**, the velocity components are used as unknowns.

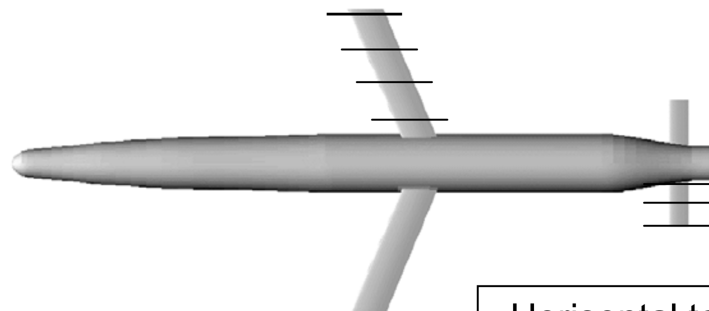
Codes comparison. **Inverse swept wing configuration**
M=0.70 Alpha=6 (Inviscid)

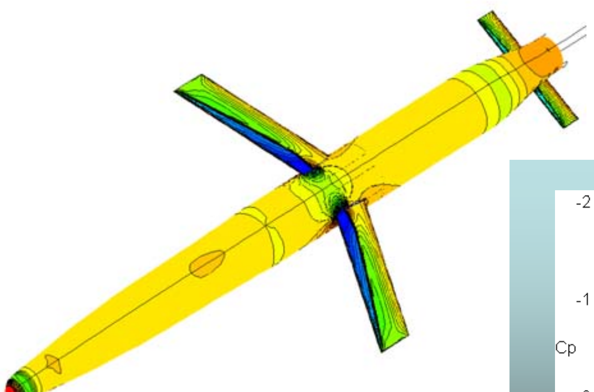
Wing Cp distribution



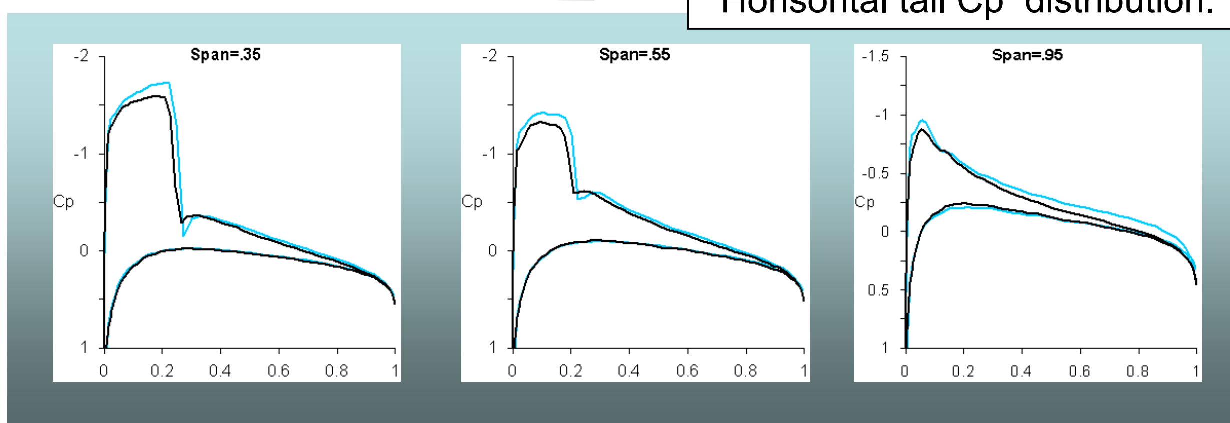
BLWF 56 (Full potential)

BLWF 110 (Cauchy-Riemann)



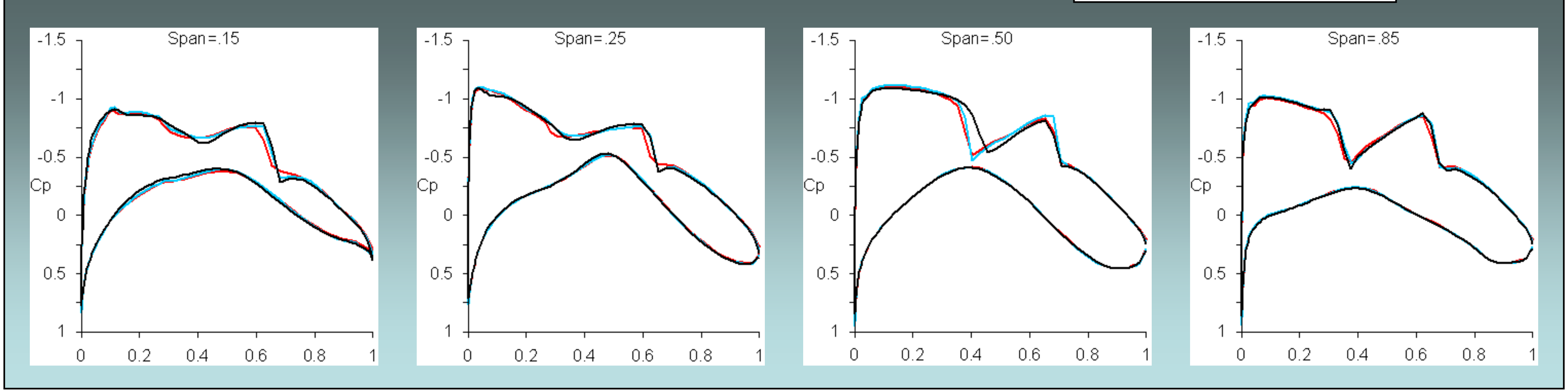


Horisontal tail Cp distribution.

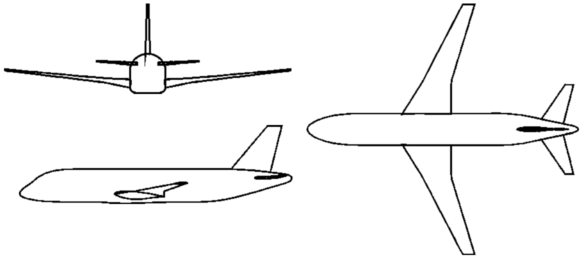


Codes comparison. **RRJ-type configuration M=0.75, Alpha=2 Inviscid**

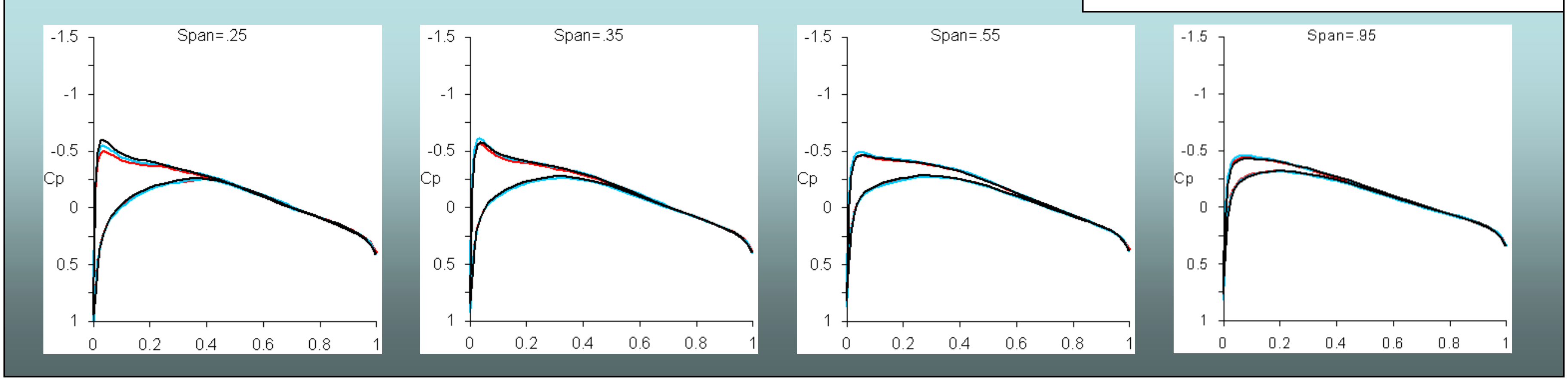
Wing Cp distribution



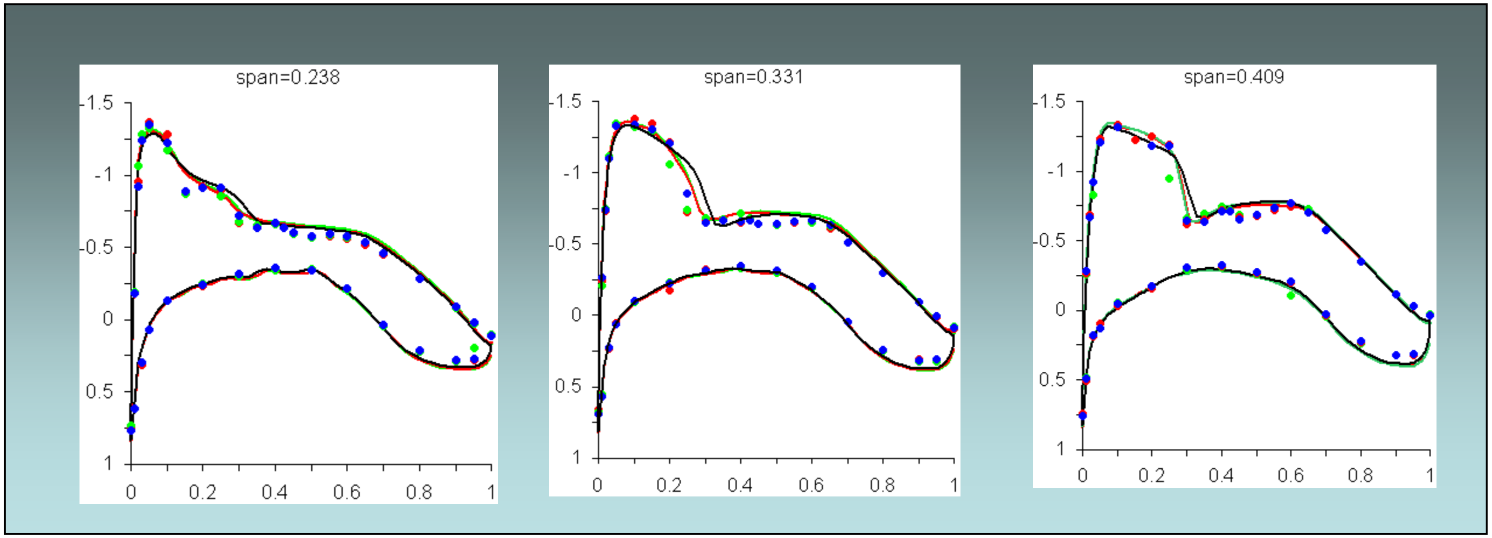
BLWF 56 (Full potential)
BLWF 100 (Euler)
BLWF 110 (Cauchy-Riemann)



Horisontal tail Cp distribution.

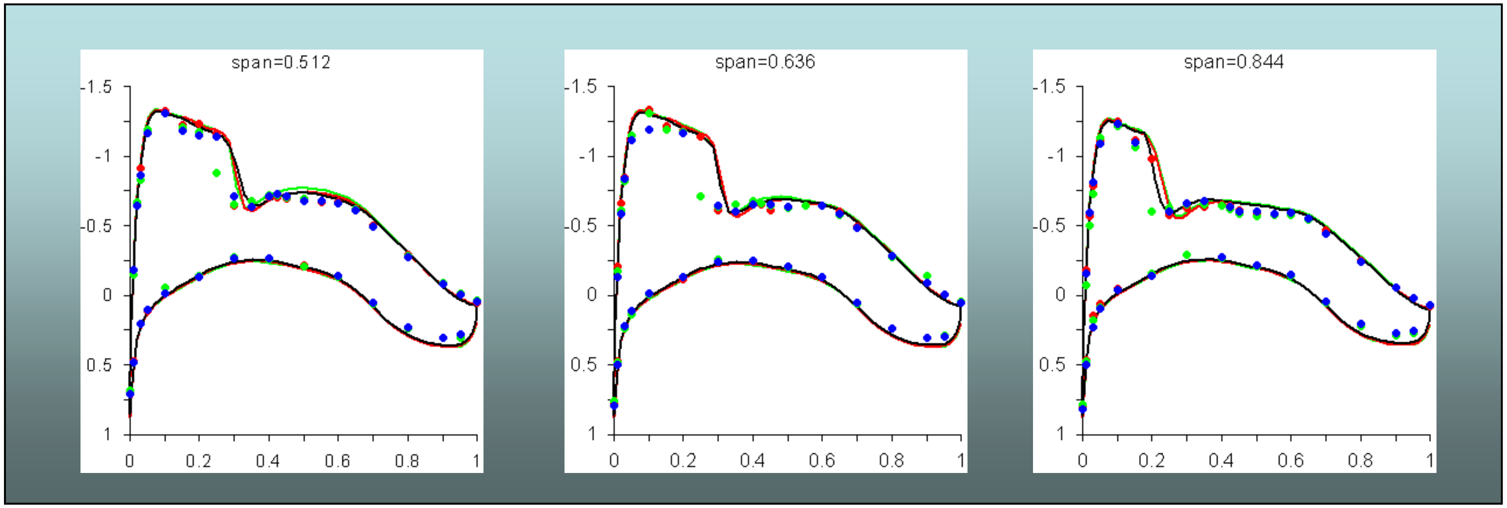


Codes comparison. **DLR-F4 test: M=0.75, al=0.18, Re=3*10^6**

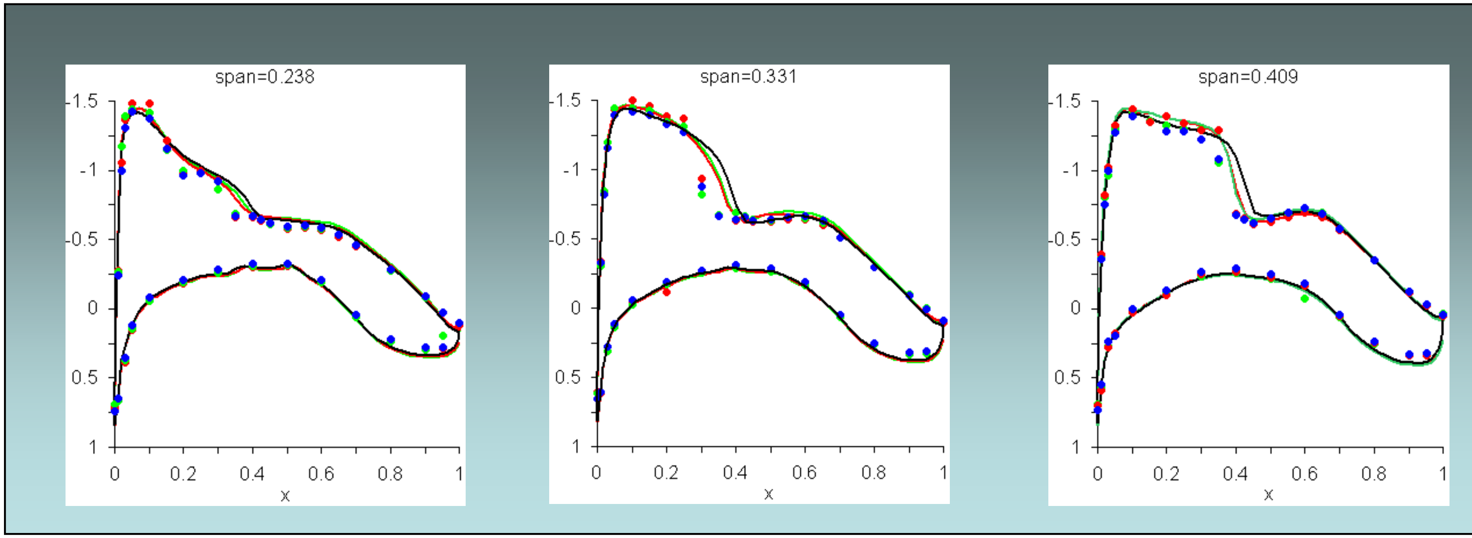


● ● **ONERA** experiment
● ● **DRA** experiment
● ● **NLR** experiment

BLWF 56 (Full potential)
BLWF 100 (Euler)
BLWF 110 (Cauchy-Riemann)

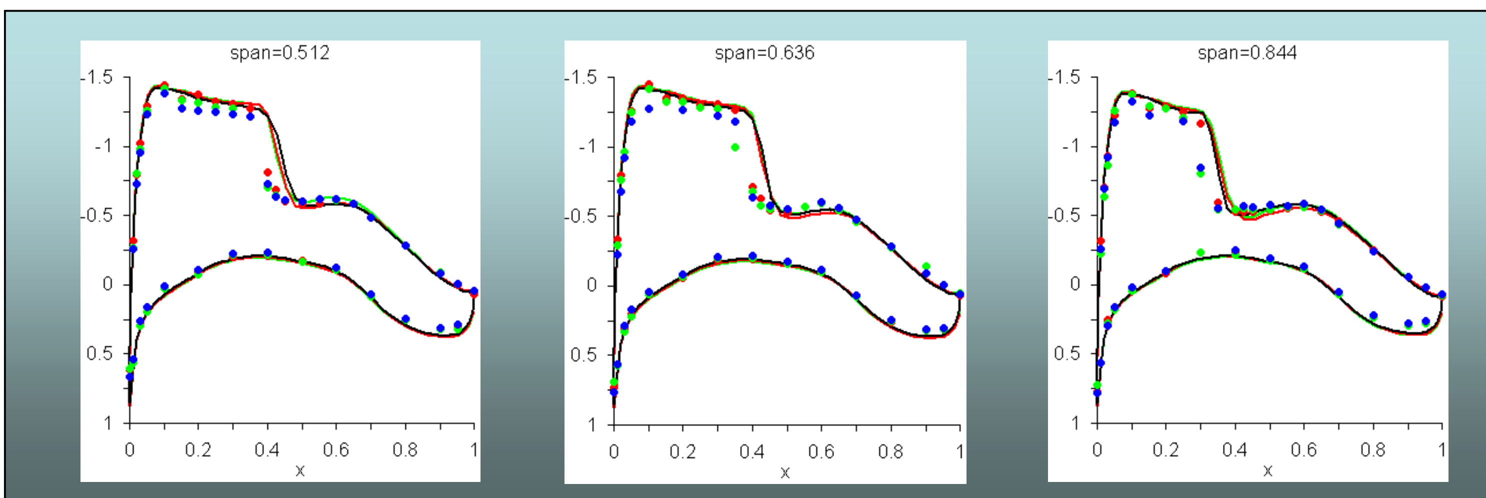


Codes comparison. **DLR-F4 test: M=0.75, al=0.9, Re=3*10^6**



ONERA experiment
DRA experiment
NLR experiment

BLWF 56 (Full potential)
BLWF 100 (Euler)
BLWF 110 (Cauchy-Riemann)



BLWF120

- unsteady time-harmonic calculation.

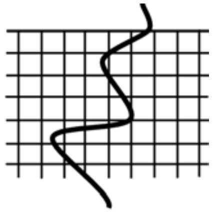
Unsteady time-harmonic problem. **An approach based on linearized full potential equation.**

$$\Phi(r,t) = \Phi_0(r) + \mathrm{Re}\,[\,\varphi(r)\, e^{i\omega t}\,] = \Phi_0 + \varphi_{real} \cos \omega t - \varphi_{imag} \sin \omega t$$

$M_\infty = 0$: Helmholtz equation

$$\Phi_{tt} - \nabla^2\Phi = 0 \quad \Rightarrow \quad \omega^2\varphi + \nabla^2\varphi = 0$$

The main difficulties



1. Computational mesh must be dense enough in the whole field for the describing of the wave-type solution.
2. Sommerfeld condition require the high-resolved solution near the external boundary of the computational region.
3. The usual solvers are not applicable to Helmholtz -type equation:
   - absence of a diagonal dominance in the resulting system of finite-difference equations;
   - the resulting system is not positive defined.

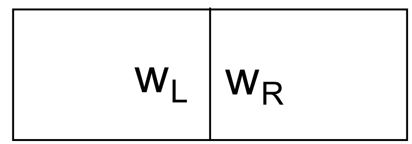
Unsteady time-harmonic problem. **An approach based on linearized Euler equations.**

$$w(r,t) = w_0(r) + \mathrm{Re}\,[\,\Delta w\, e^{i\omega t}\,]$$

$$\Delta W = \Delta W_{real} + i\,\Delta W_{imag} = \begin{pmatrix}\Delta\rho \\ \Delta\vec{q}\end{pmatrix}$$

Entropy preservation: $\Delta p = c_0^2\,\Delta\rho$

<u>Space flaxes</u>:



$$F(r,t) = F_0(r) + \mathrm{Re}\,[\,\Delta F\, e^{i\omega t}\,]$$

$$F = \frac{1}{2}(F_L + F_R) - \frac{1}{2}\int_{w_L}^{w_R} \left|\partial F/\partial w\right| dw \quad \Rightarrow \quad \Delta F = (\partial F_o/\partial w)_L^{+}\,\Delta w_L + (\partial F_o/\partial w)_R^{-}\,\Delta w_R$$

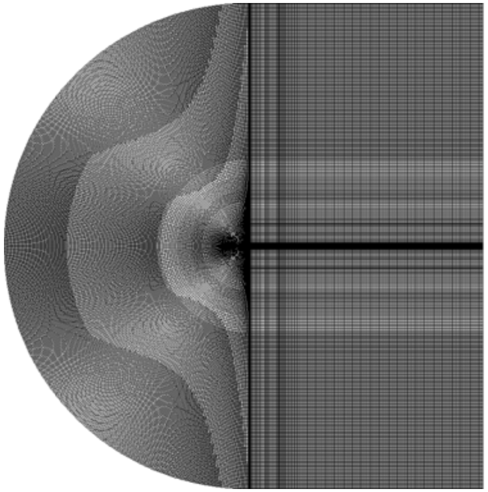
<u>Time derivatives</u>:

$$\partial w/\partial t = i\omega\,\Delta w\; e^{i\omega t}$$

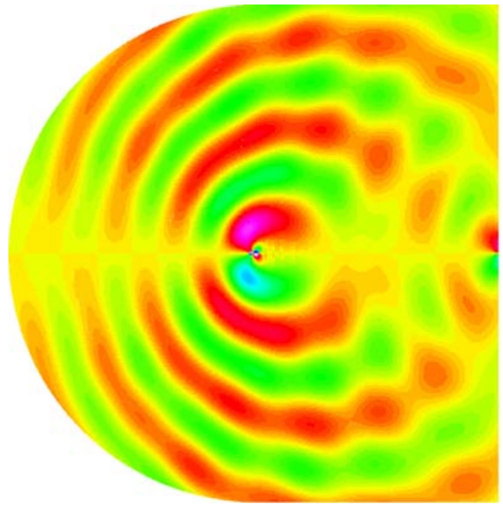
Flat Plate Harmonic Motion : **Influence of the Far-Field Mesh density**

M=0.35, Sh=1.5

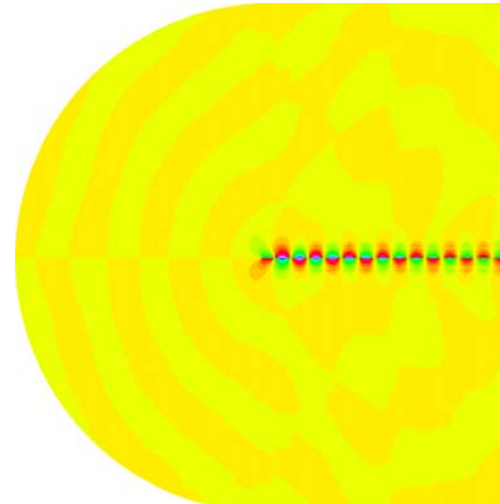
Dense mesh



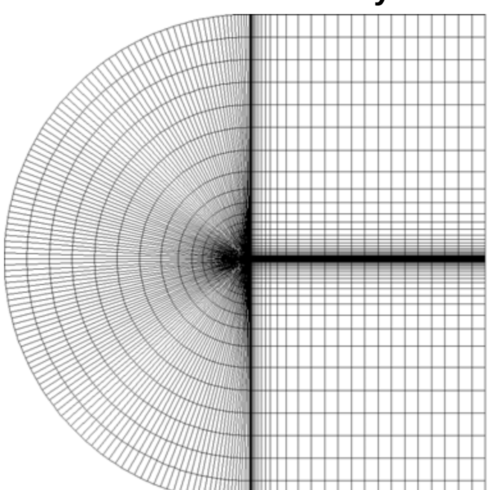
Pressure (real), Sh = 1.5



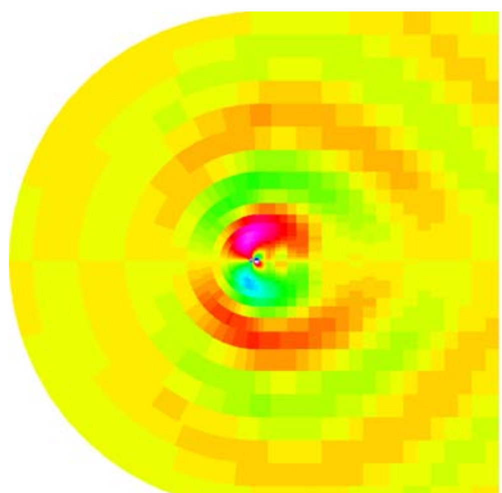
Chordwise velocity (real)



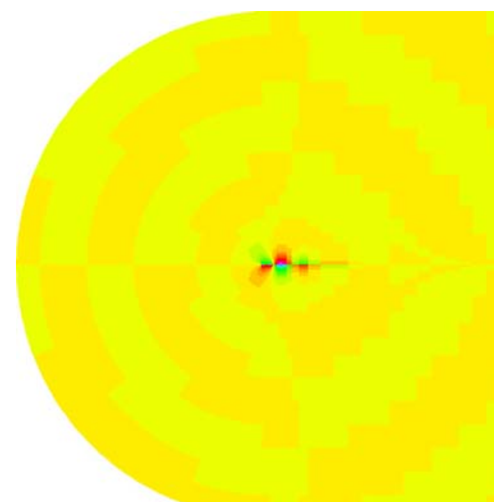
Ordinary mesh



Pressure (real), Sh = 1.5



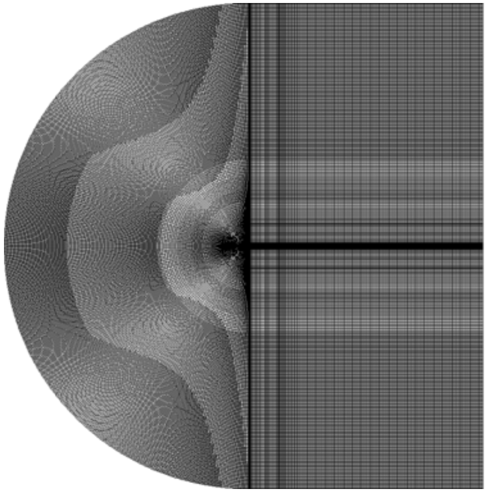
Chordwise velocity (real)



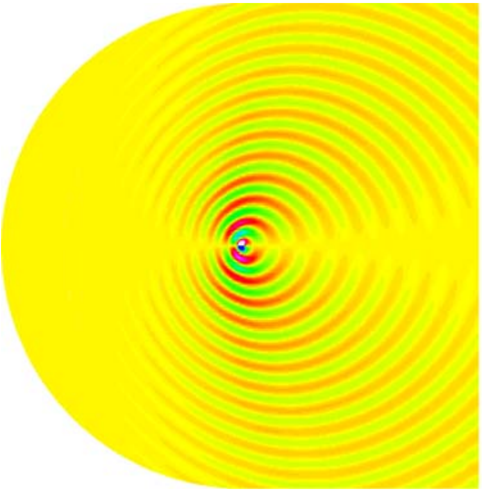
Flat Plate Harmonic Motion : **Influence of the Far-Field Mesh density**

M=0.35

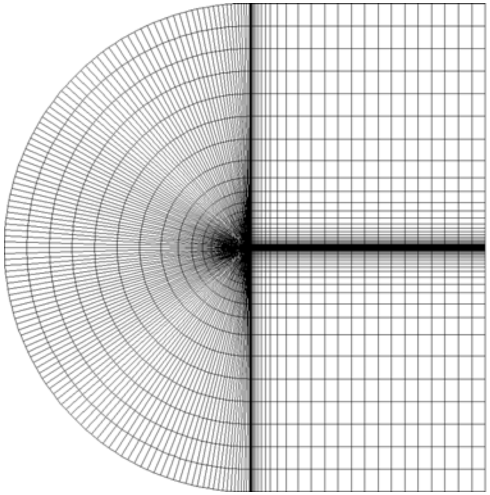
Dense mesh



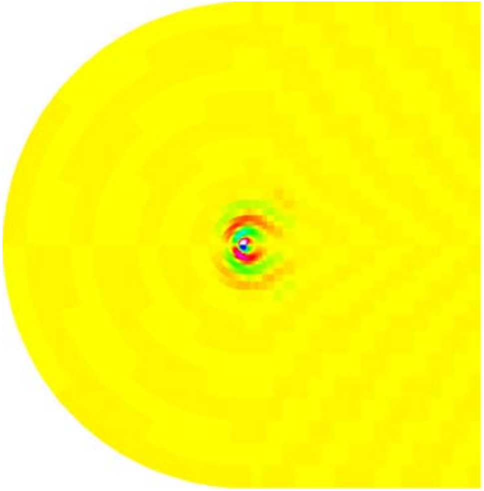
Pressure (real), Sh = 6.5



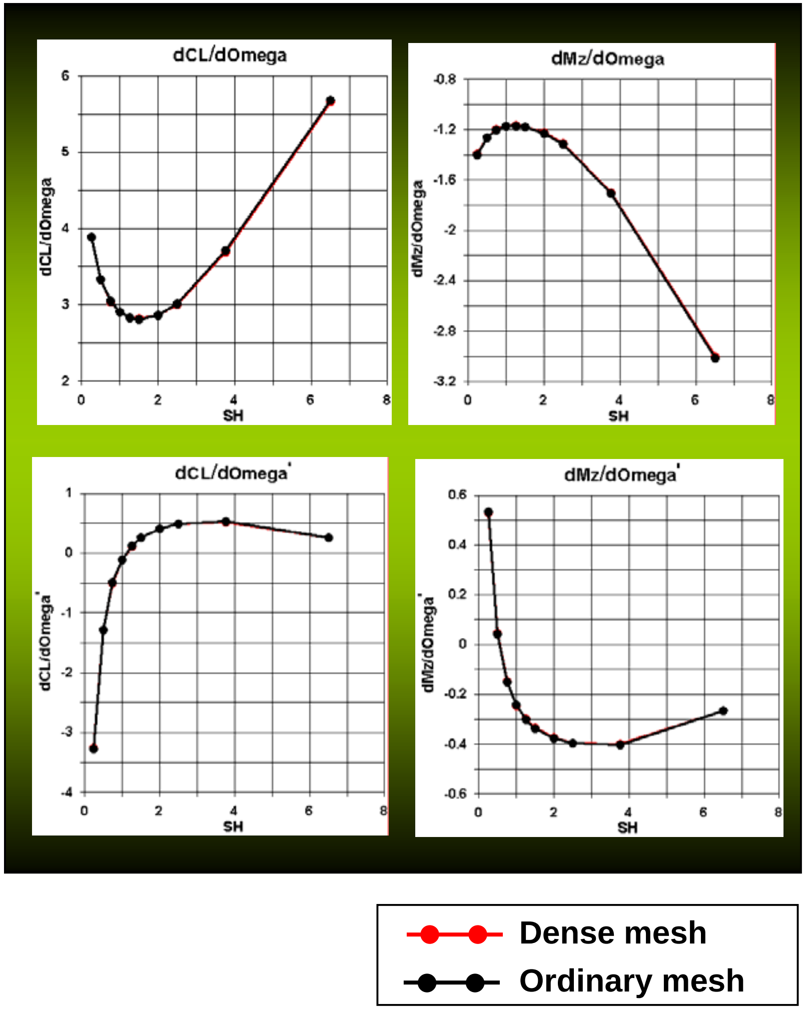
Ordinary mesh



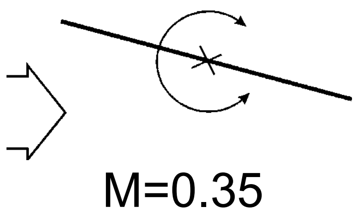
Pressure (real), Sh = 6.5

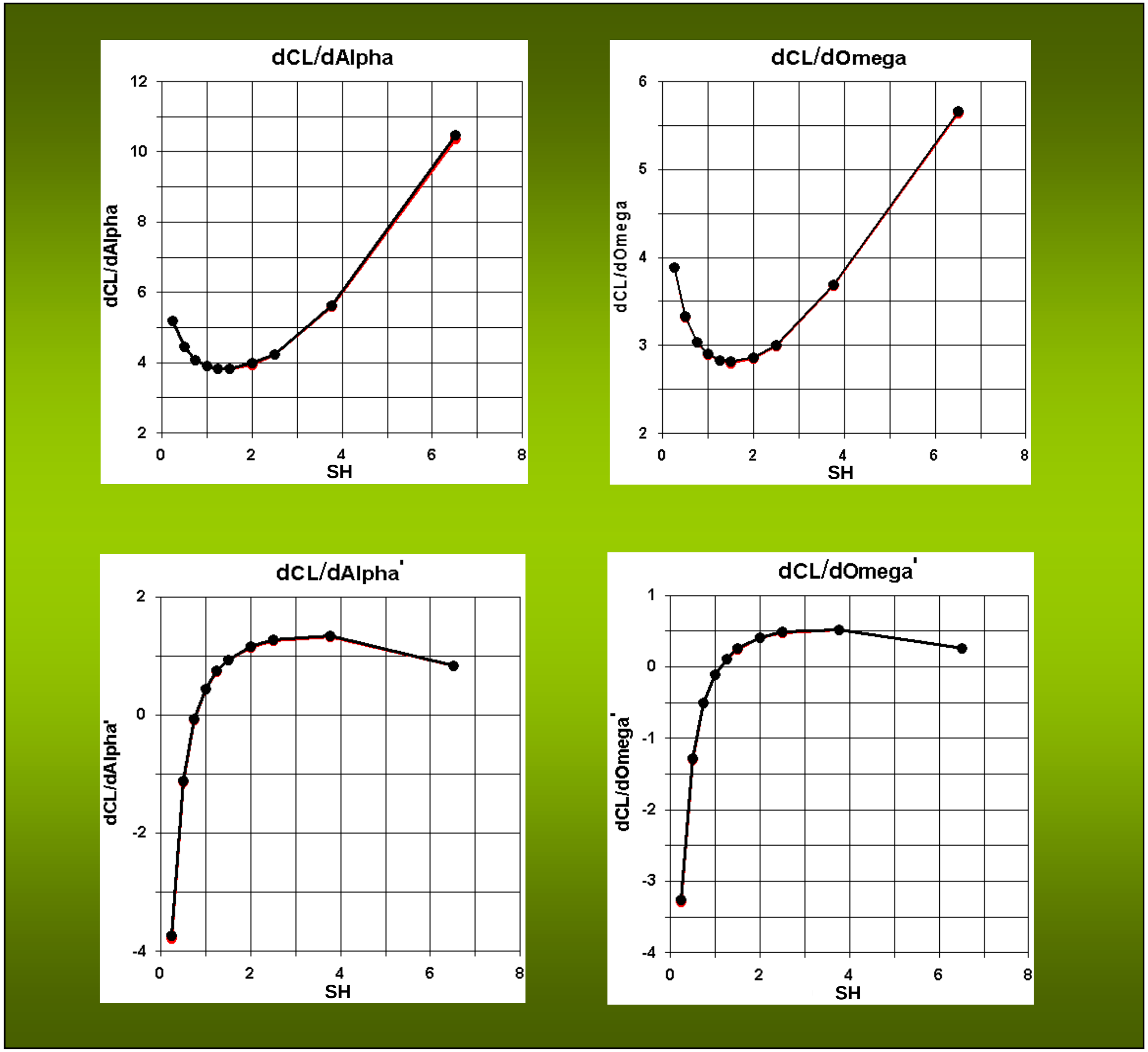


Aerodynamic derivatives

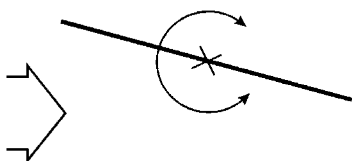


Flat Plate Harmonic Motion : **Lift Derivatives M=0.35**

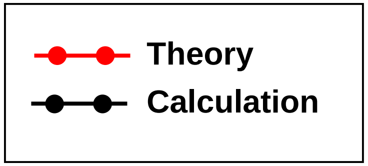


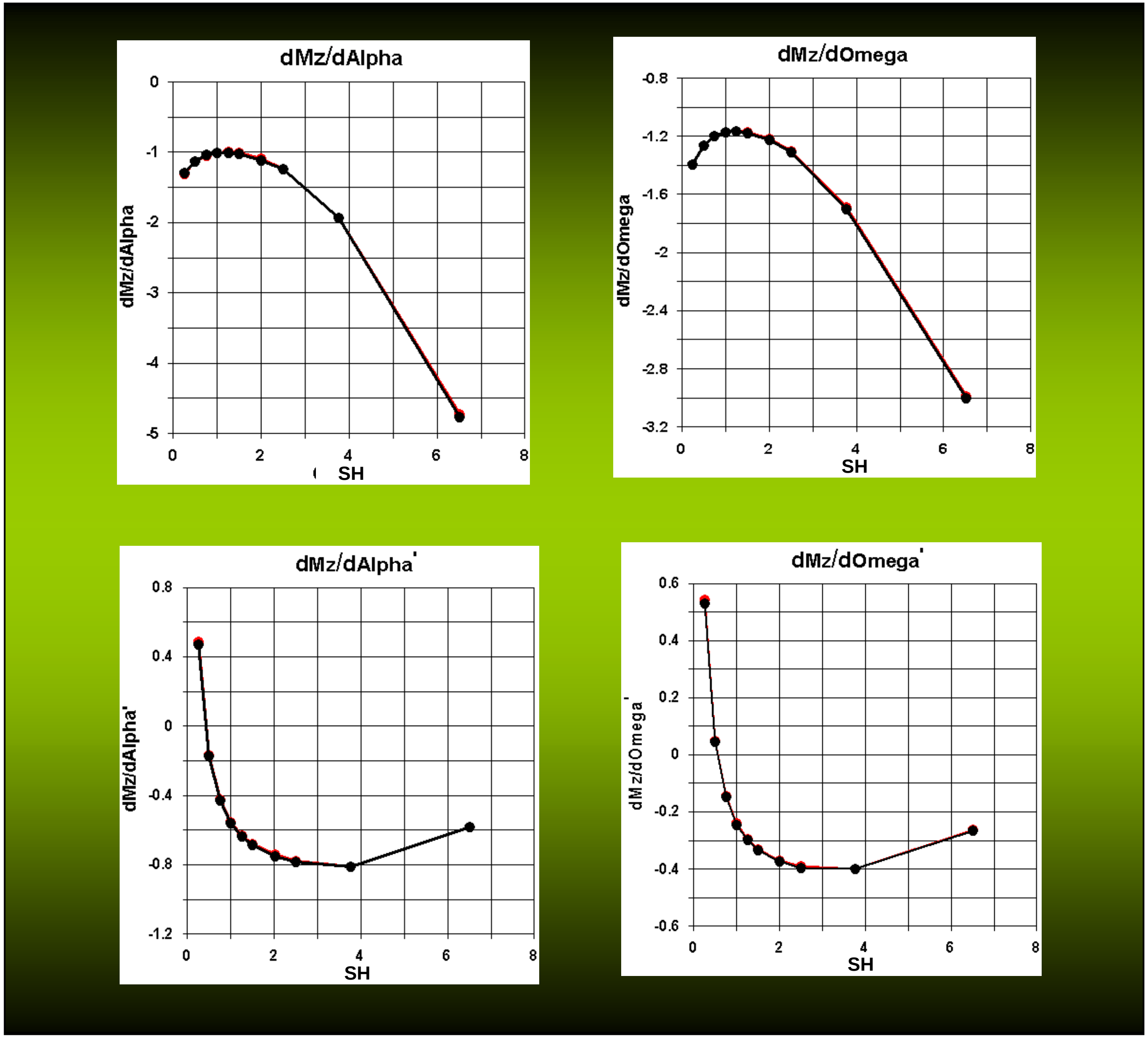


Flat Plate Harmonic Motion : **Pitching Moment Derivatives M=0.35**

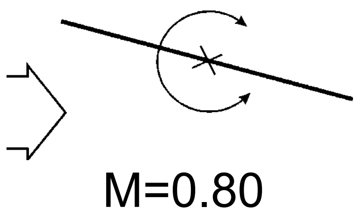


M=0.35

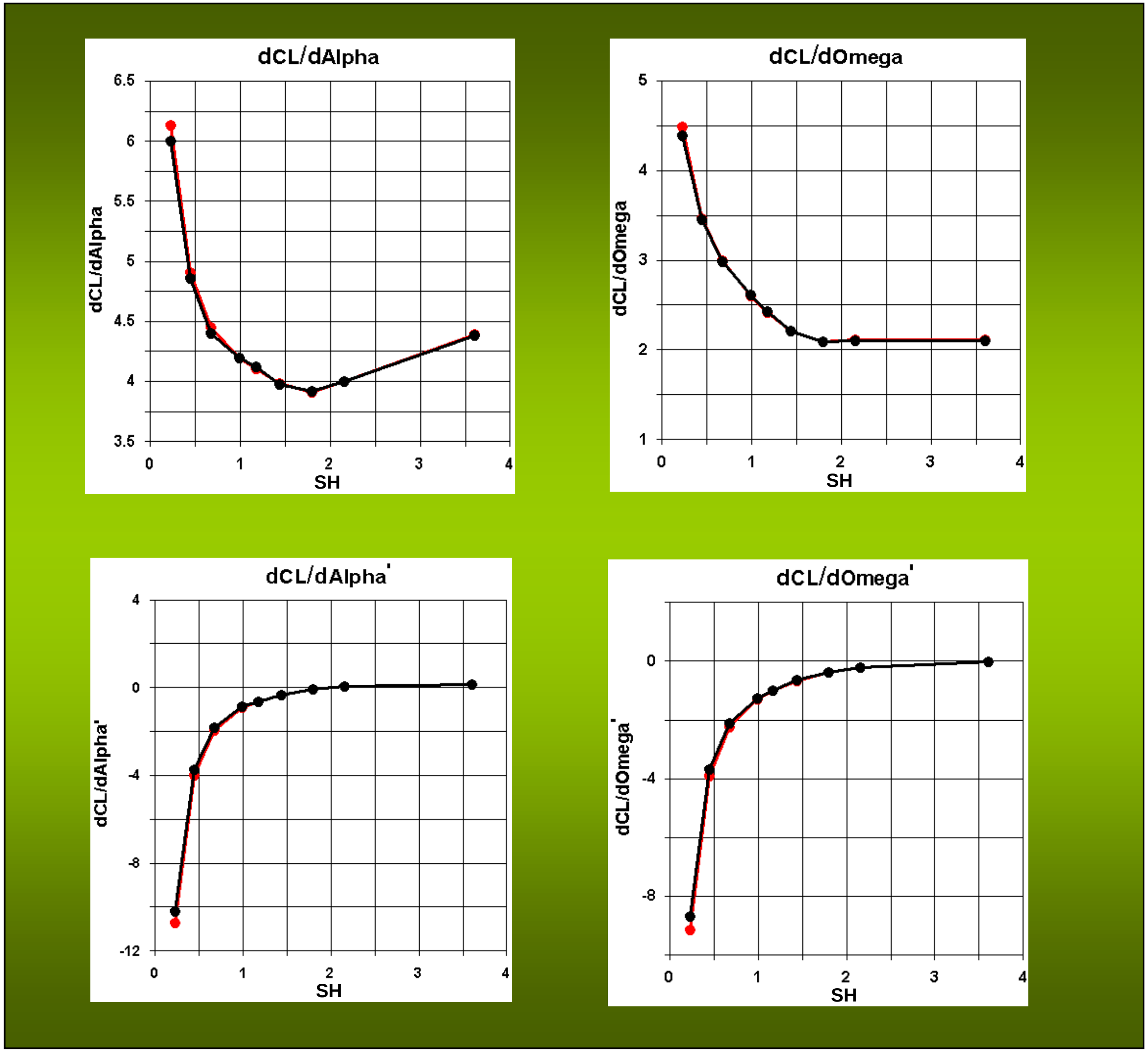




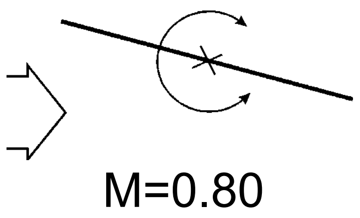
Flat Plate Harmonic Motion : **Lift Derivatives M=0.80**

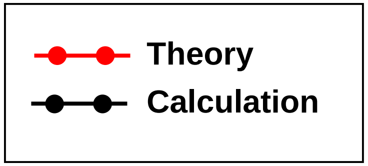


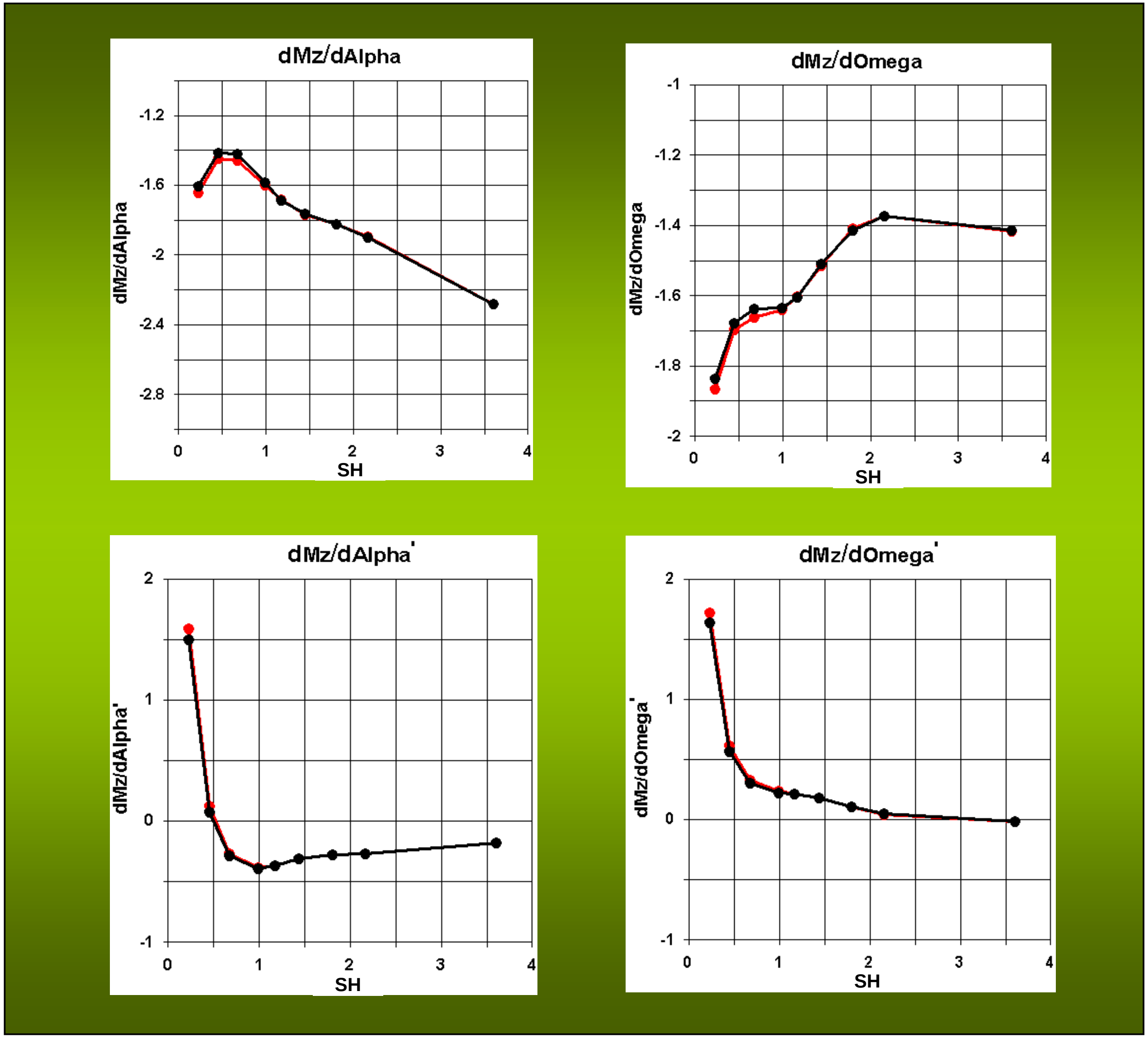
- Theory
- Calculation



Flat Plate Harmonic Motion : **Pitching Moment Derivatives M=0.80**

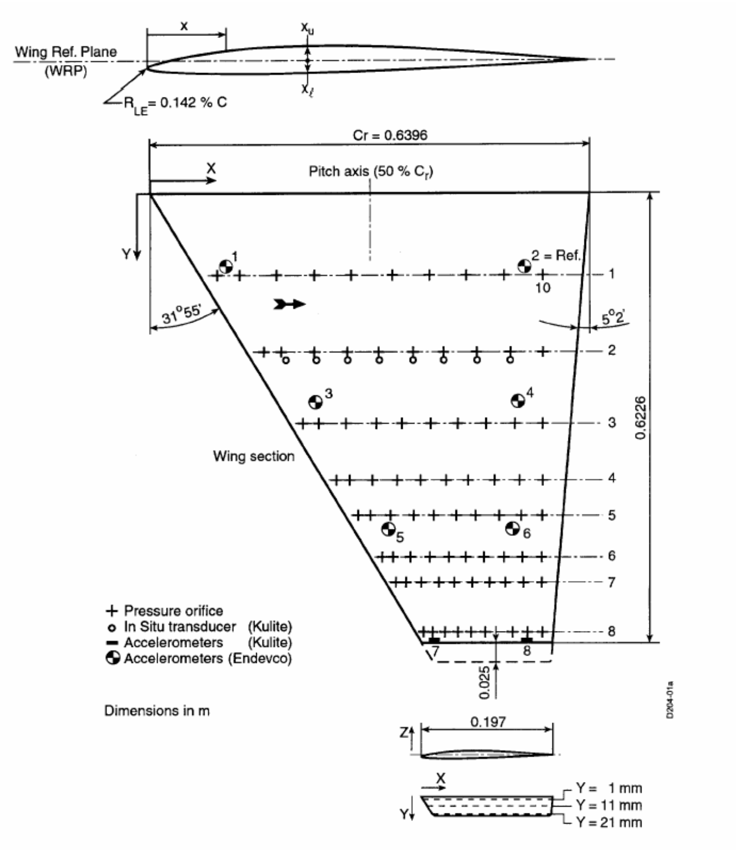




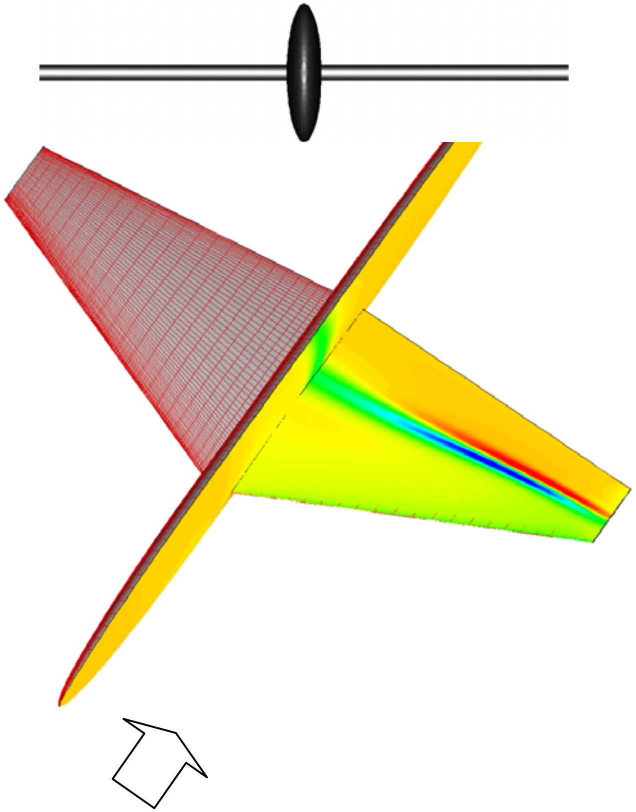


NLR F5 WING test : **Pitching Oscillations.**

Tested Wing Configuration



Calculated Configuration

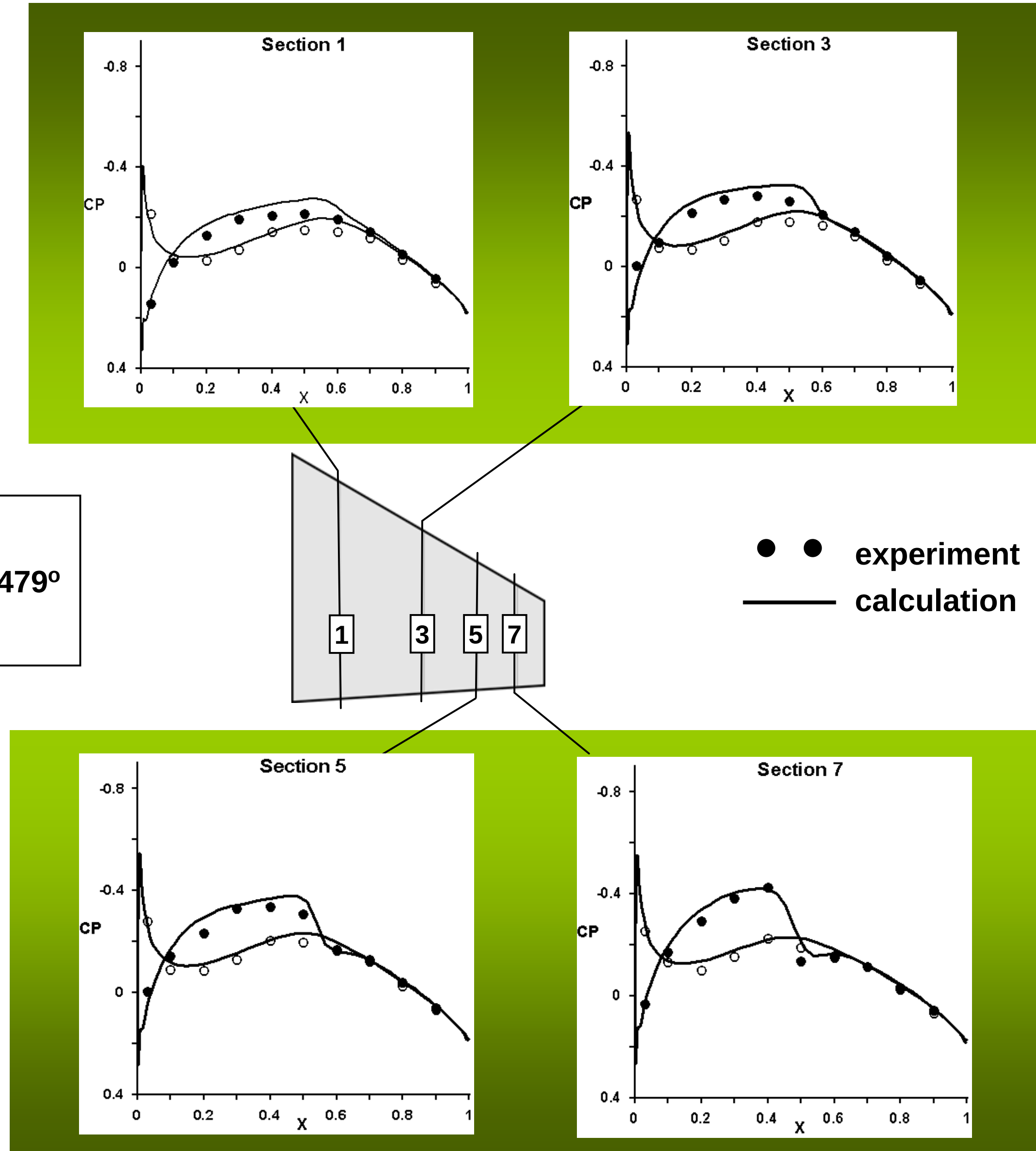


F5 wing test : **Steady Cp distribution. (Run152, M=.9, Al=0.5)**

F5 wing test

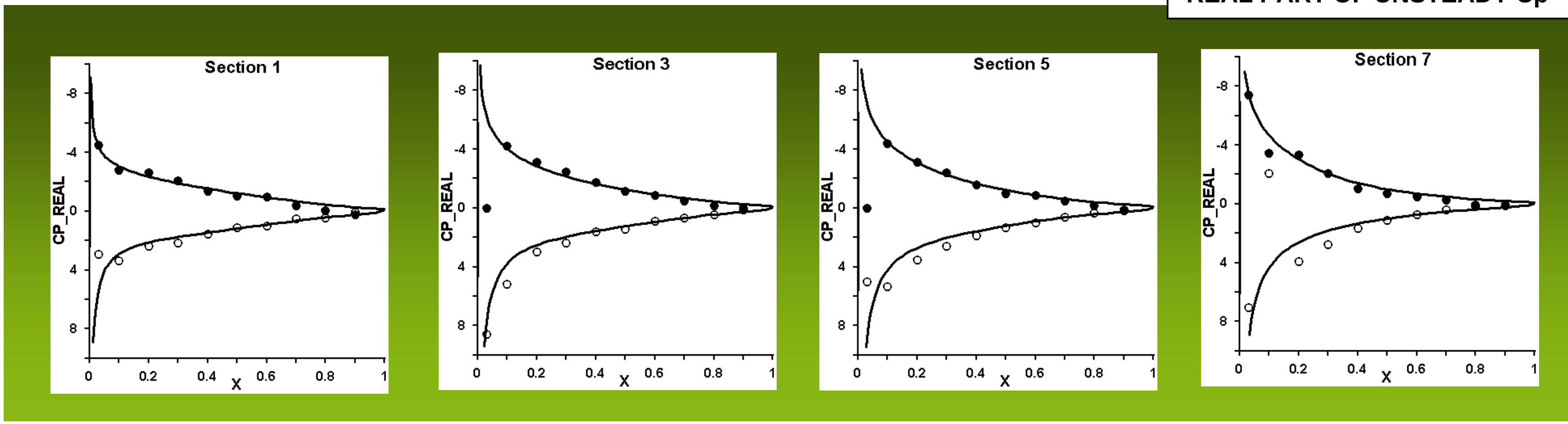
M=0.896, ALPHA=0.479°

Re=5.79*10^6



F5 wing test : **Pitching Oscillations. (Run383, M=0.60, h=40 Hz).**

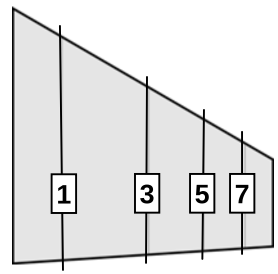
REAL PART OF UNSTEADY Cp



F5 wing test

M=0.597, ALPHA=0.º Re=4.57*10^6

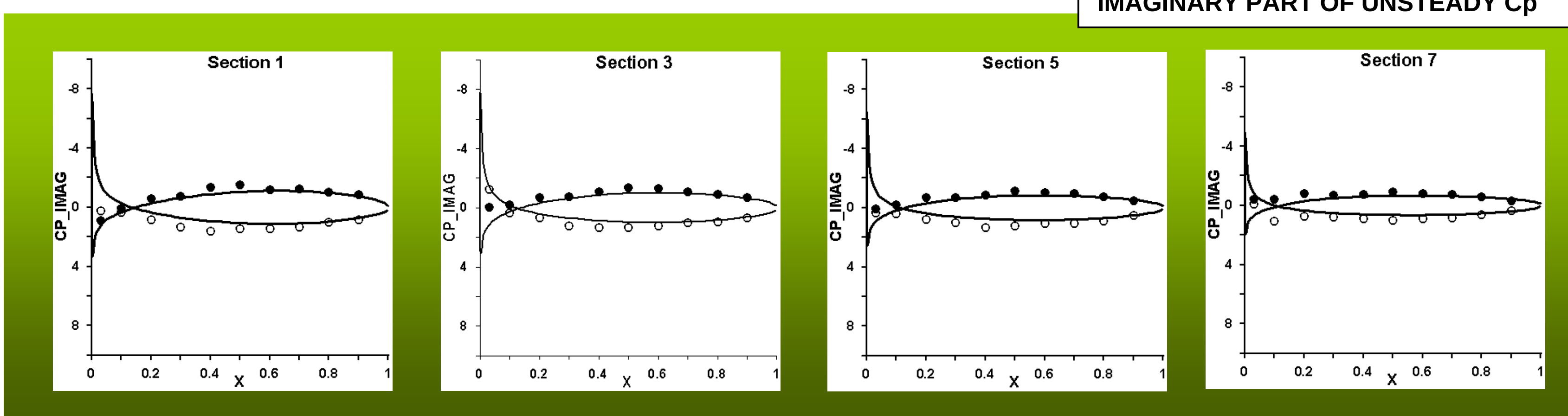
K=0.399 (40 Hz)



● ● **experiment**
○ ○

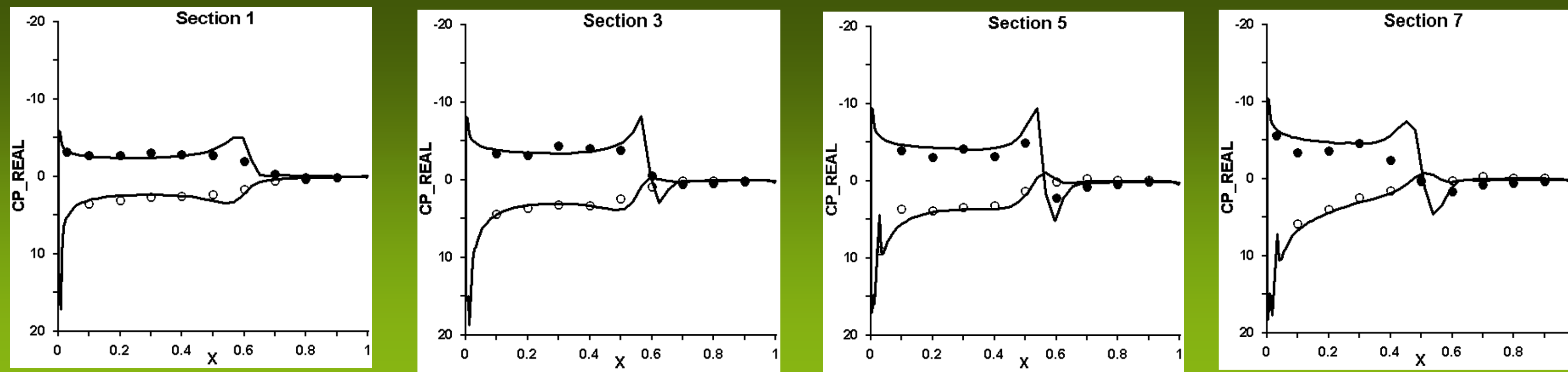
calculation

IMAGINARY PART OF UNSTEADY Cp



F5 wing test : **Pitching Oscillations. (Run369, M=0.90, h=20 Hz).**

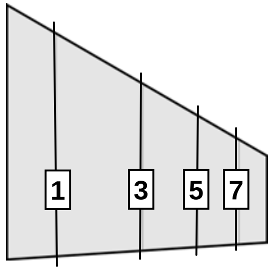
REAL PART OF UNSTEADY Cp



F5 wing test

M=0.899, ALPHA=0.º Re=5.73*10⁶

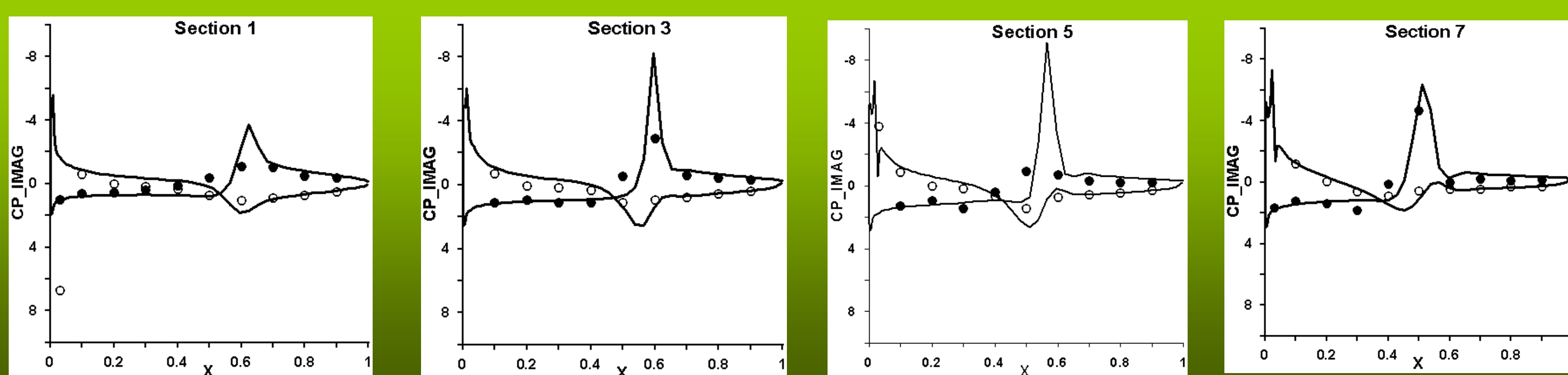
K=0.137 (20 Hz)



experiment

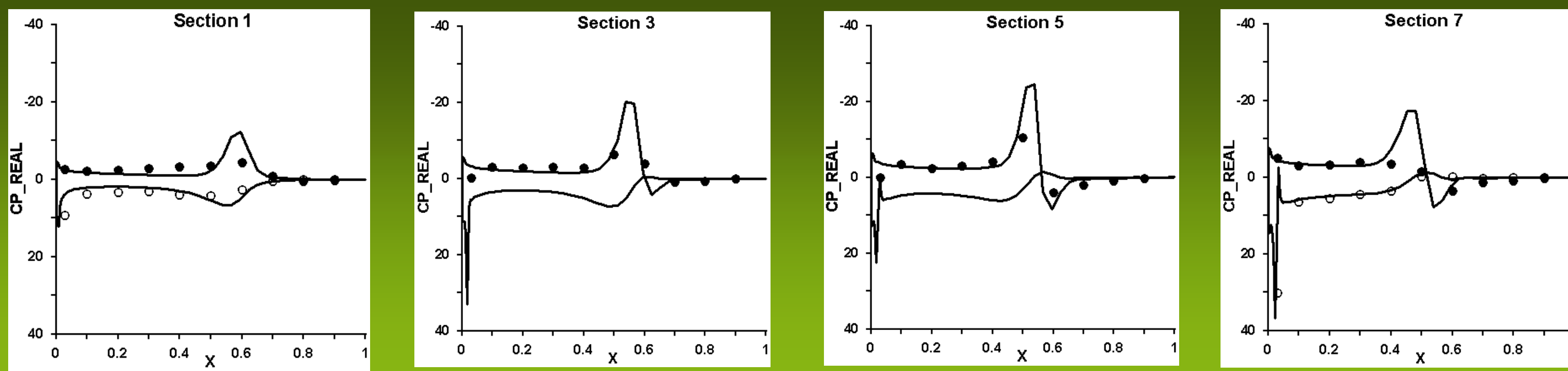
calculation

IMAGINARY PART OF UNSTEADY Cp



F5 wing test : **Pitching Oscillations. (Run370, M=0.90, h=40 Hz).**

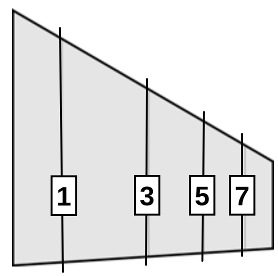
REAL PART OF UNSTEADY Cp



F5 wing test

M=0.896, ALPHA=0.º Re=5.73*10^6

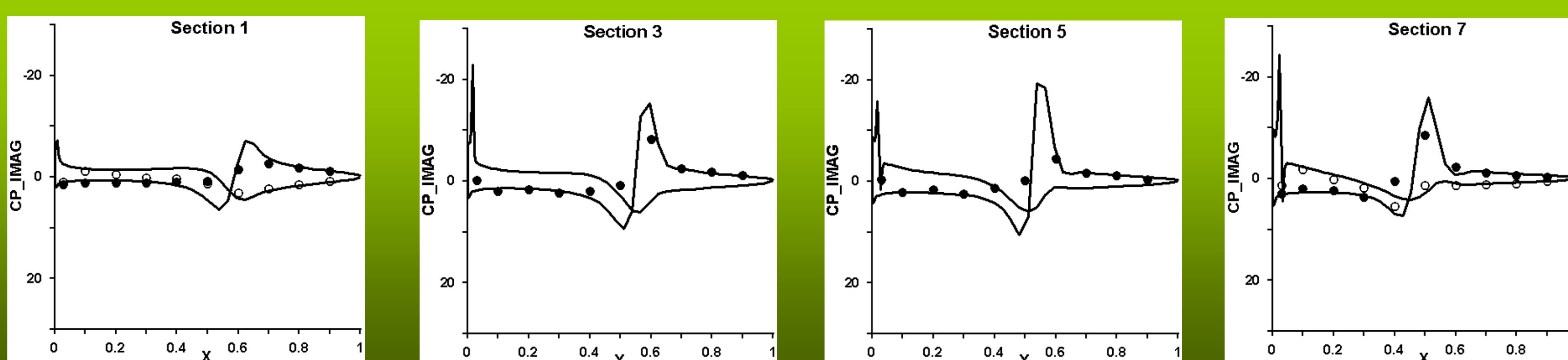
K=0.275 (40 Hz)



●● ○○ **experiment**

—— **calculation**

IMAGINARY PART OF UNSTEADY Cp

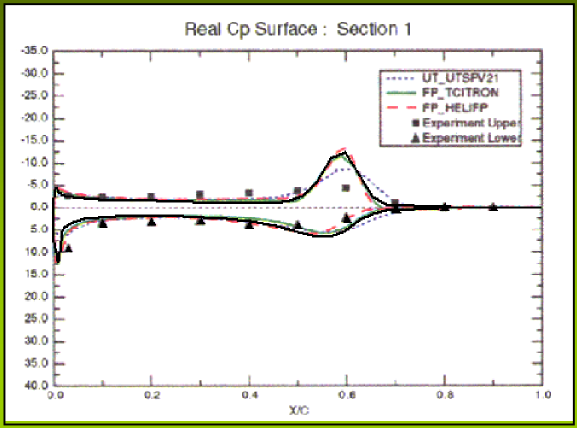


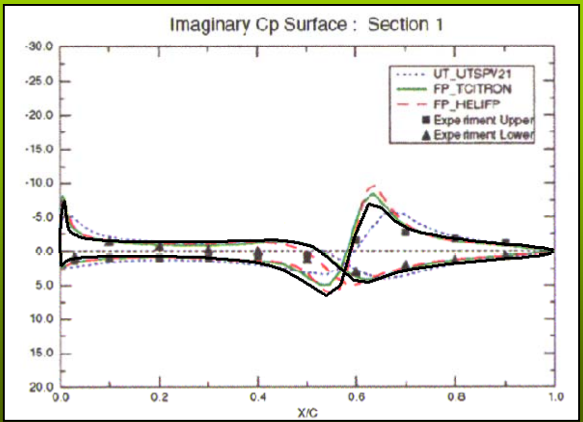
F5 wing test : **Pitching Oscillations. (Run370, M=0.90, h=40 Hz).**

Code comparison for UTSP and Full Potential codes: UTSPV21, TCITRON, HLIFP

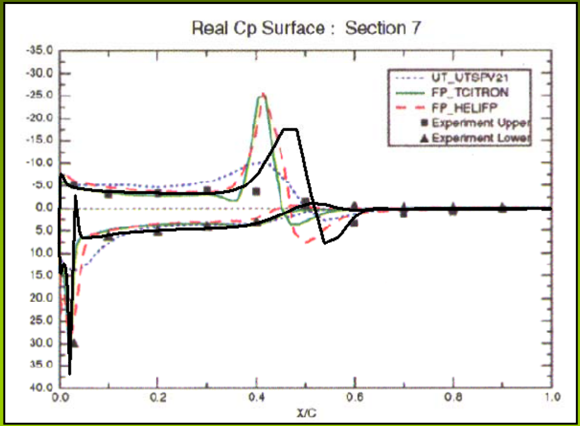
- ··········· **UTSPV21 (BAe)**
- —— **TCITRON (Das. Av.)**
- – – – **HELIFP (CIRA)**
- —— **current calculation**
- ■ ▲ **experiment**

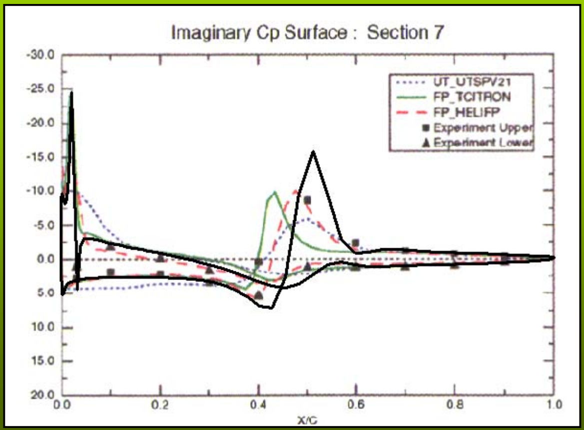
Section 1





Section 7



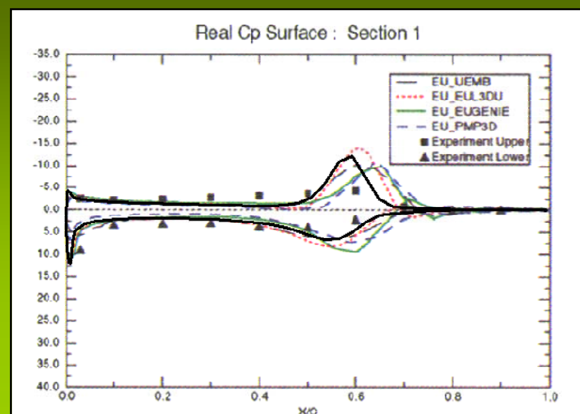


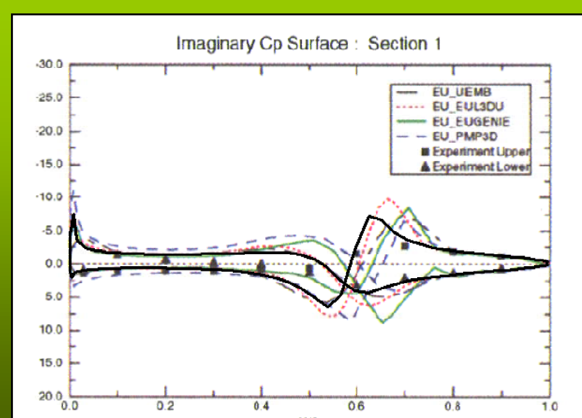
F5 wing test : **Pitching Oscillations. (Run370, M=0.90, h=40 Hz).**

Code comparison for EULER codes: UEMB, EUL3DU, EUGENIE, PMP3D

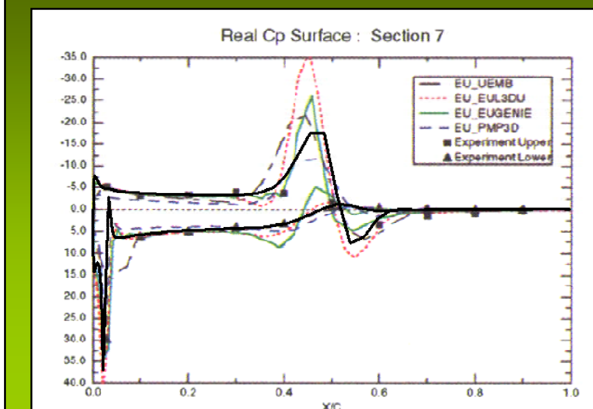
- UEMB (BAe)
- EUL3DU (INTA)
- EUGENIE (Dass. Av.)
- PMP3D (Glasgow Un.)
- current calculation
- experiment

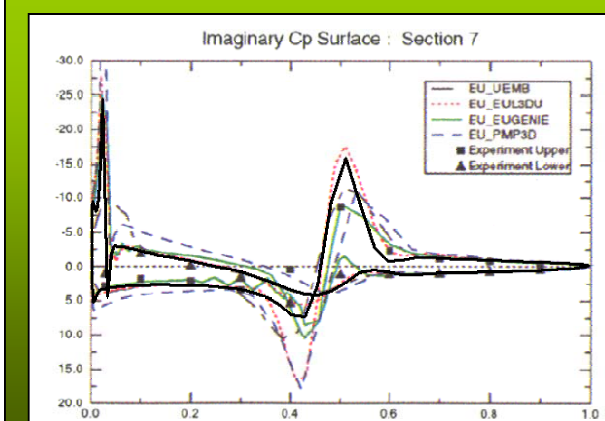
Section 1





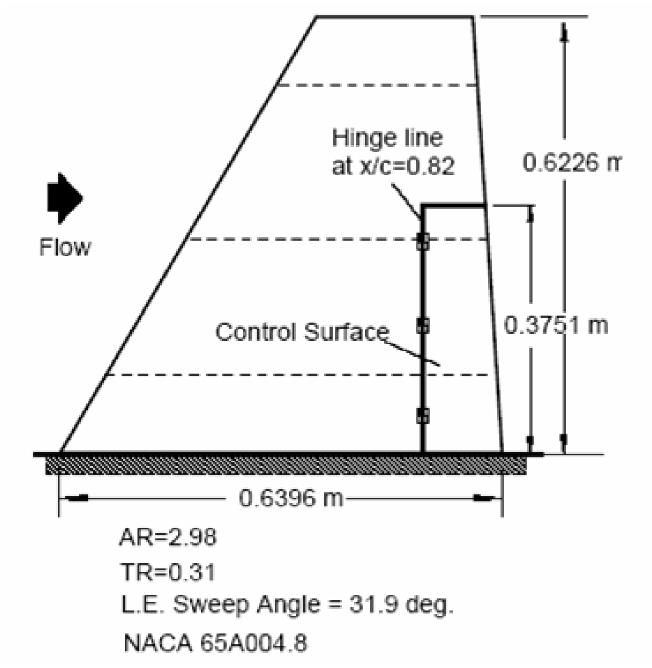
Section 7



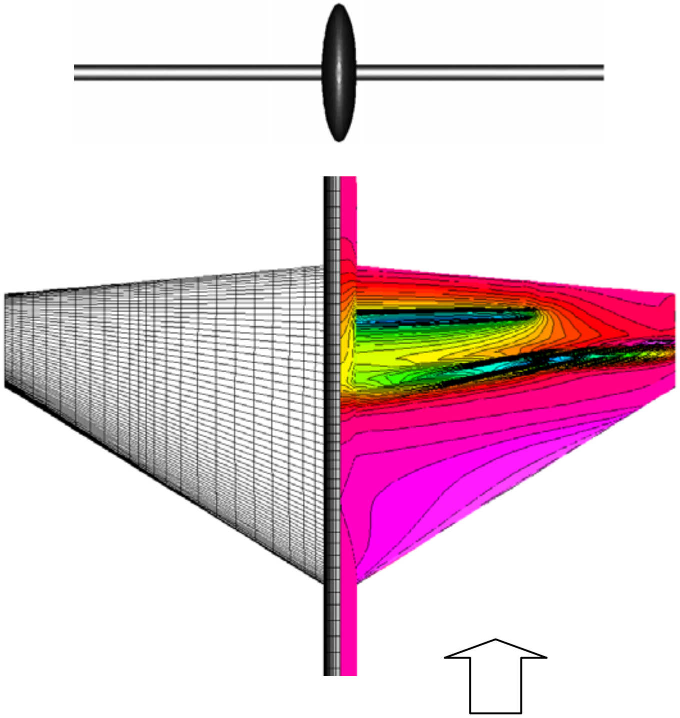


NLR F5 WING test : **Trailing Edge Control Surface Oscillations.**

Tested Wing Configuration



Calculated Configuration

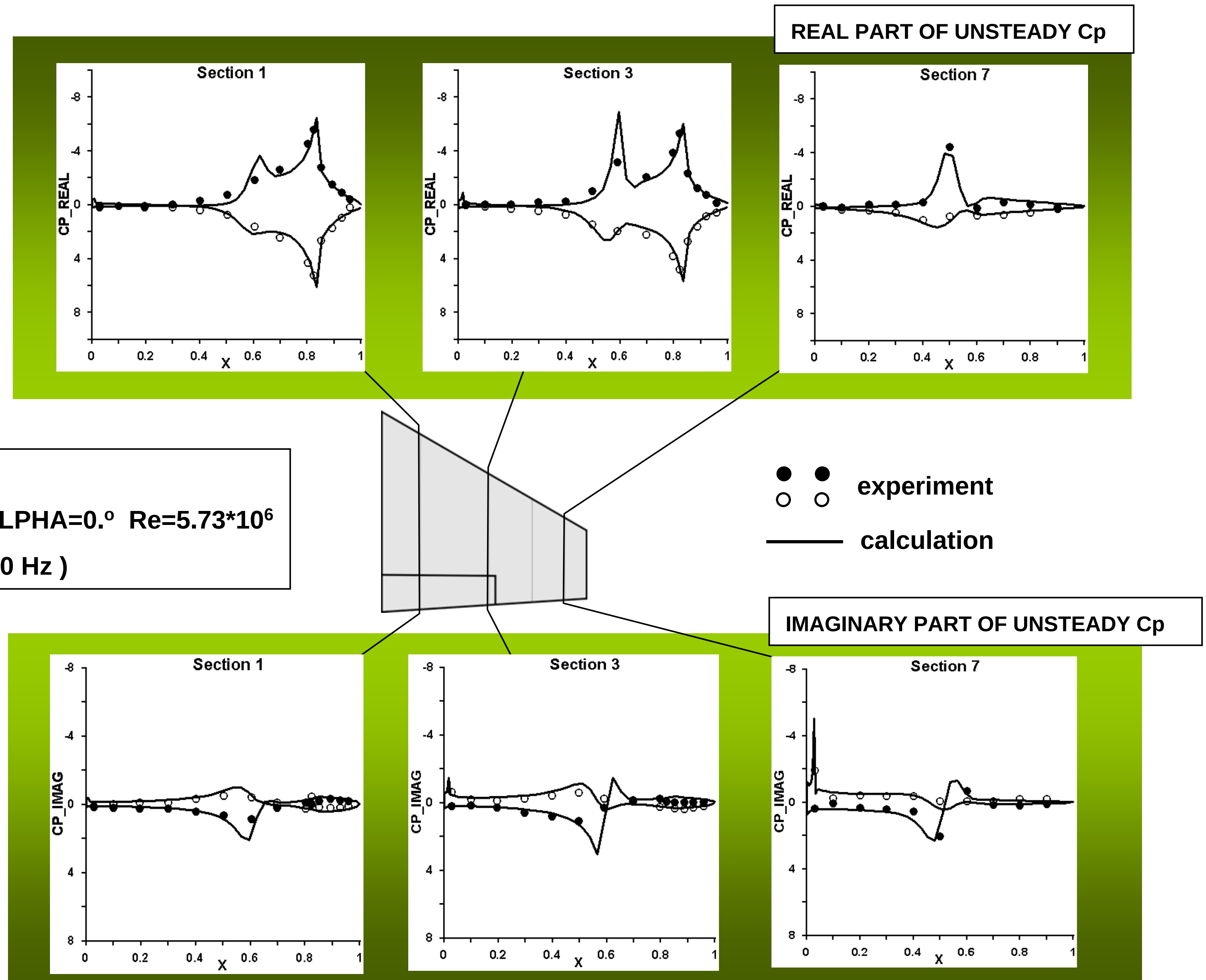


F5 wing test : **Trailing Edge Control Surface Oscillations (20 Hz).**

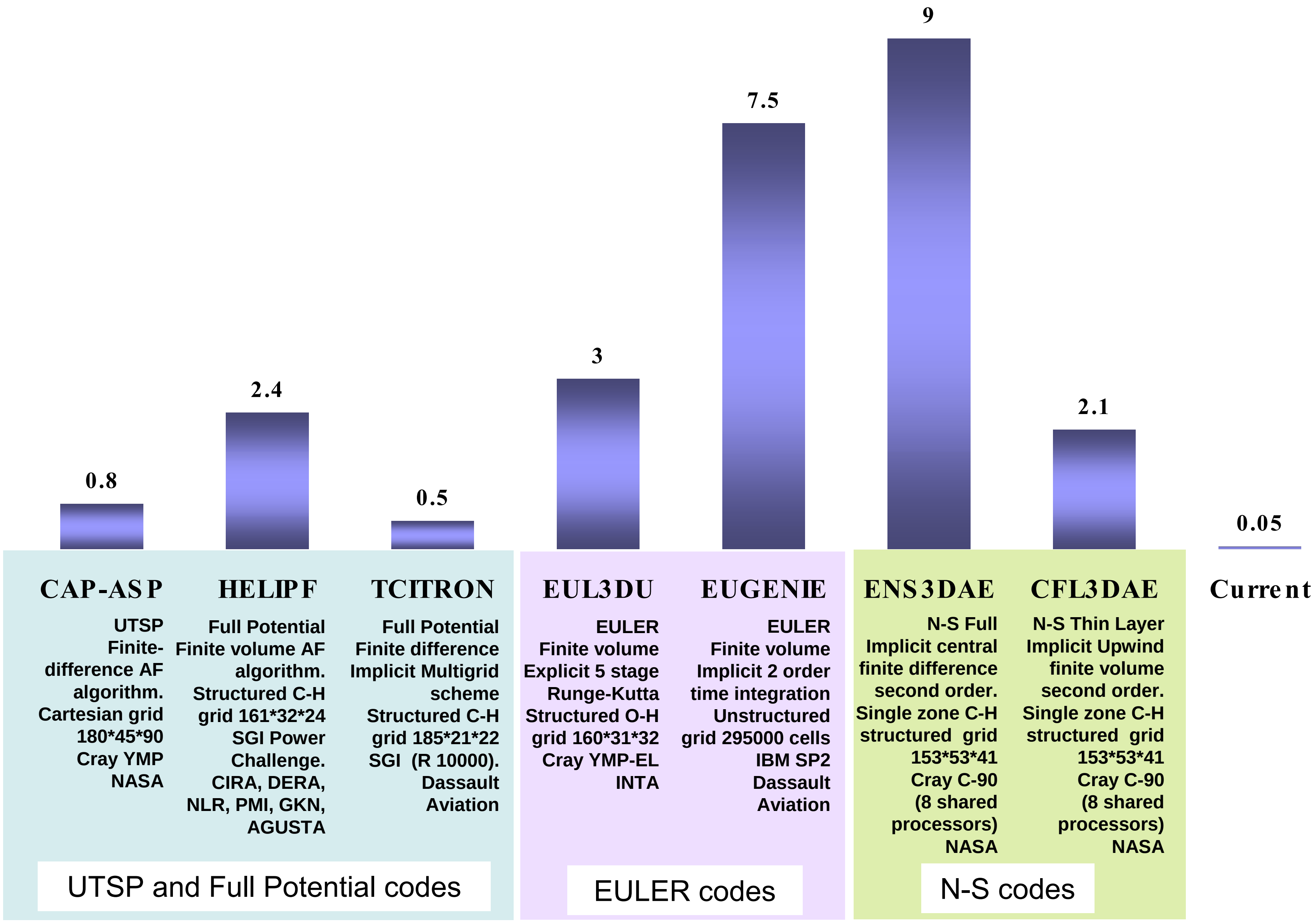
F5 wing test

M=0.899, ALPHA=0.º Re=5.73*10^6

K=0.139 (20 Hz)

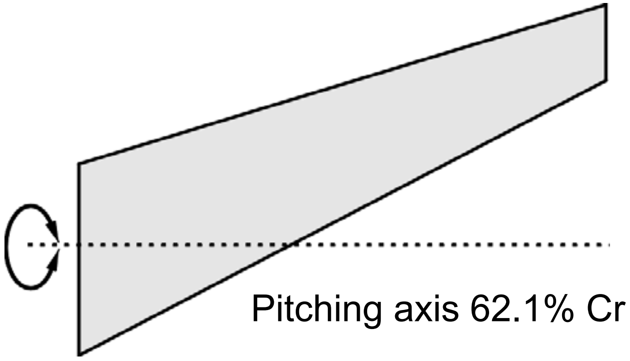


CPU time (in hours) for oscillating wing problem. Comparison of the different codes (from RTO-TR-26)

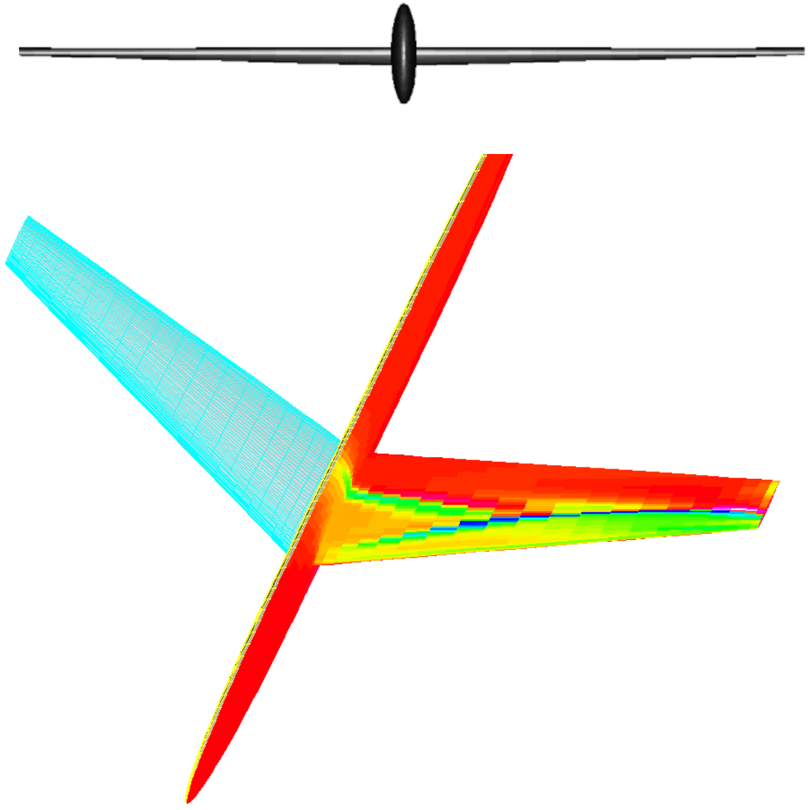


LANN Wing test : **Pitching Oscillations**

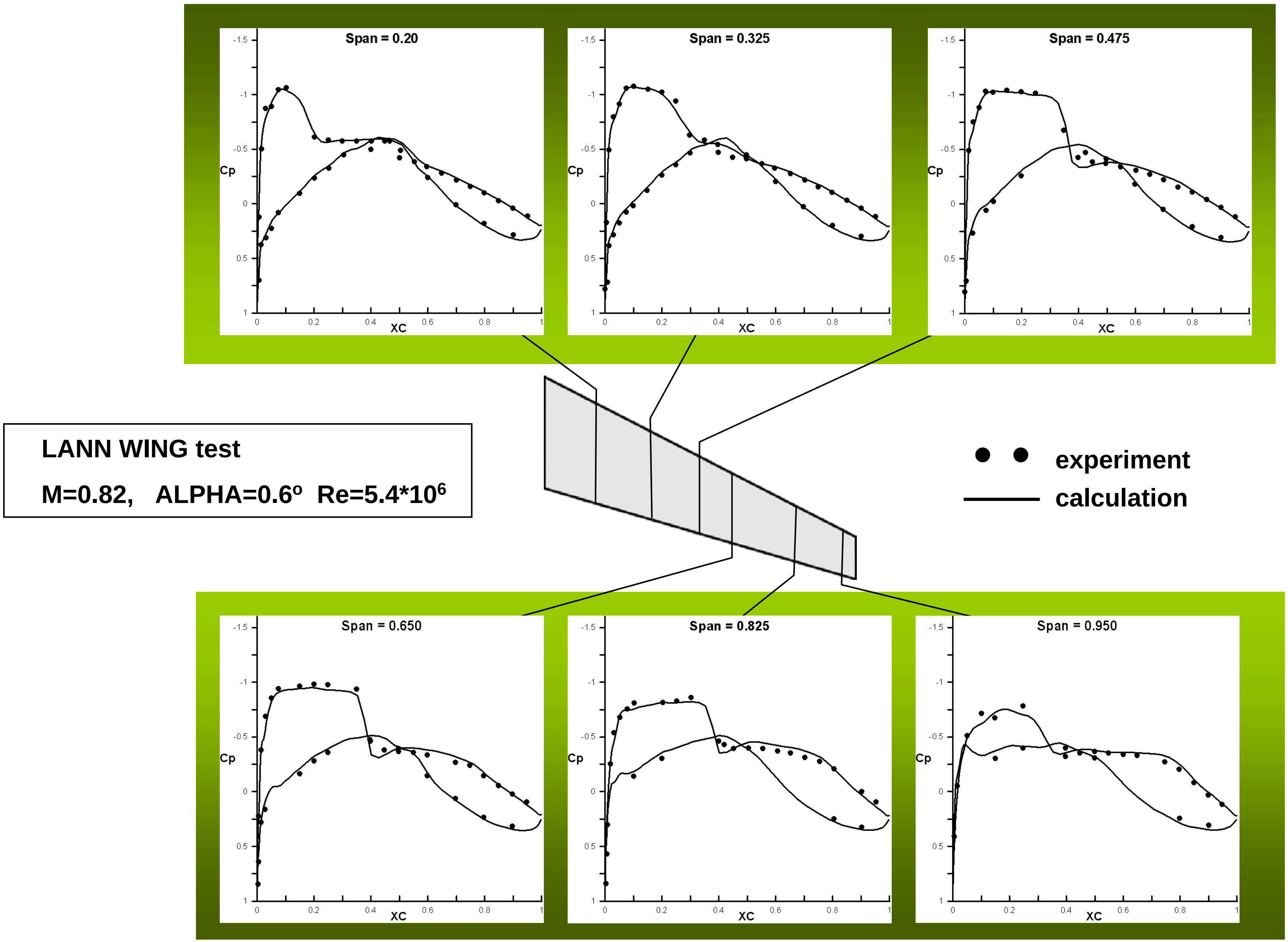
Tested Wing Configuration



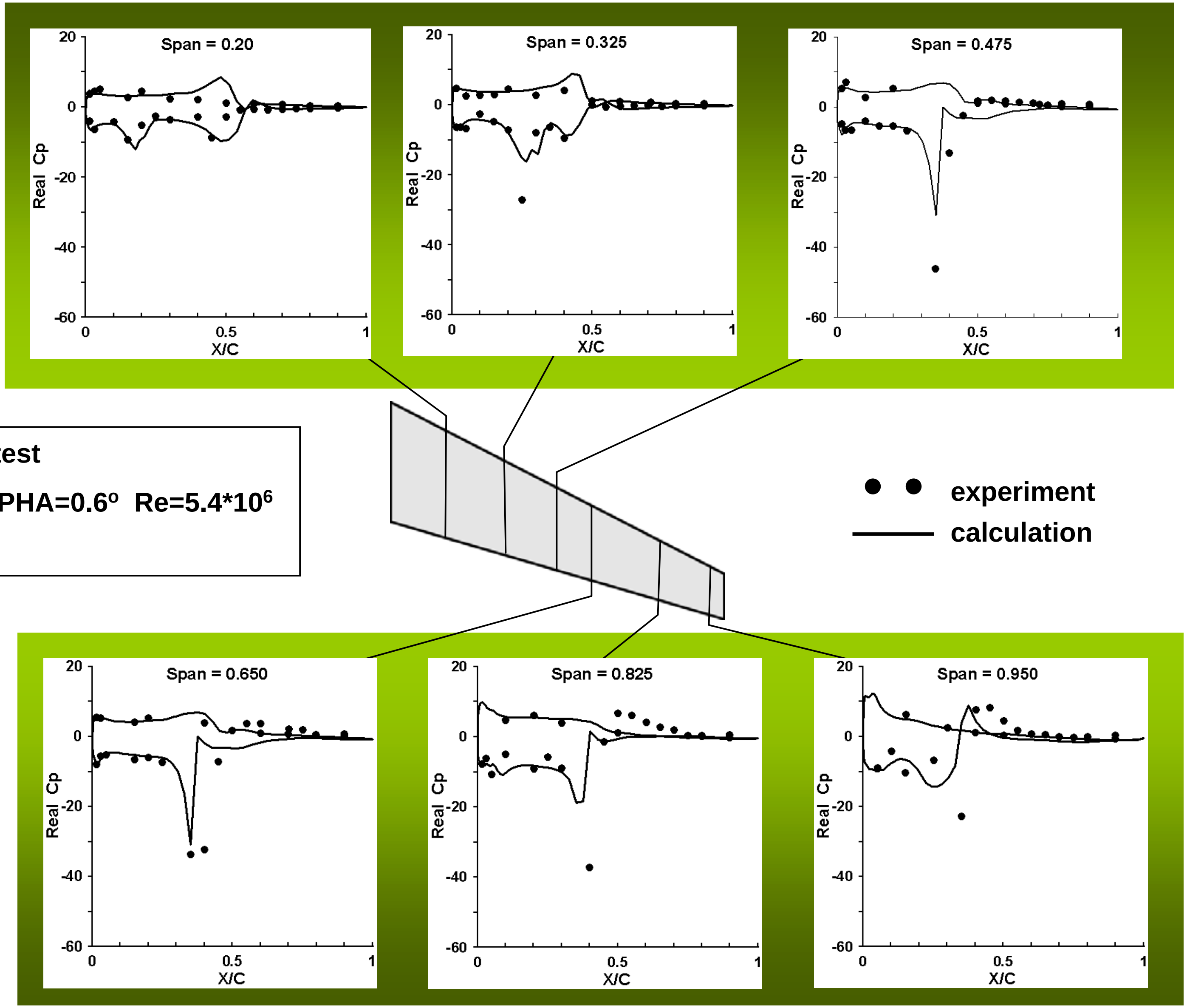
Calculated Configuration



LANN test : **Steady Cp distribution. M=0.82 Alpha=0.6**



LANN test : **Real part of unsteady Cp distribution.**



LANN wing test

M=0.82, ALPHA=0.6º Re=5.4*10⁶

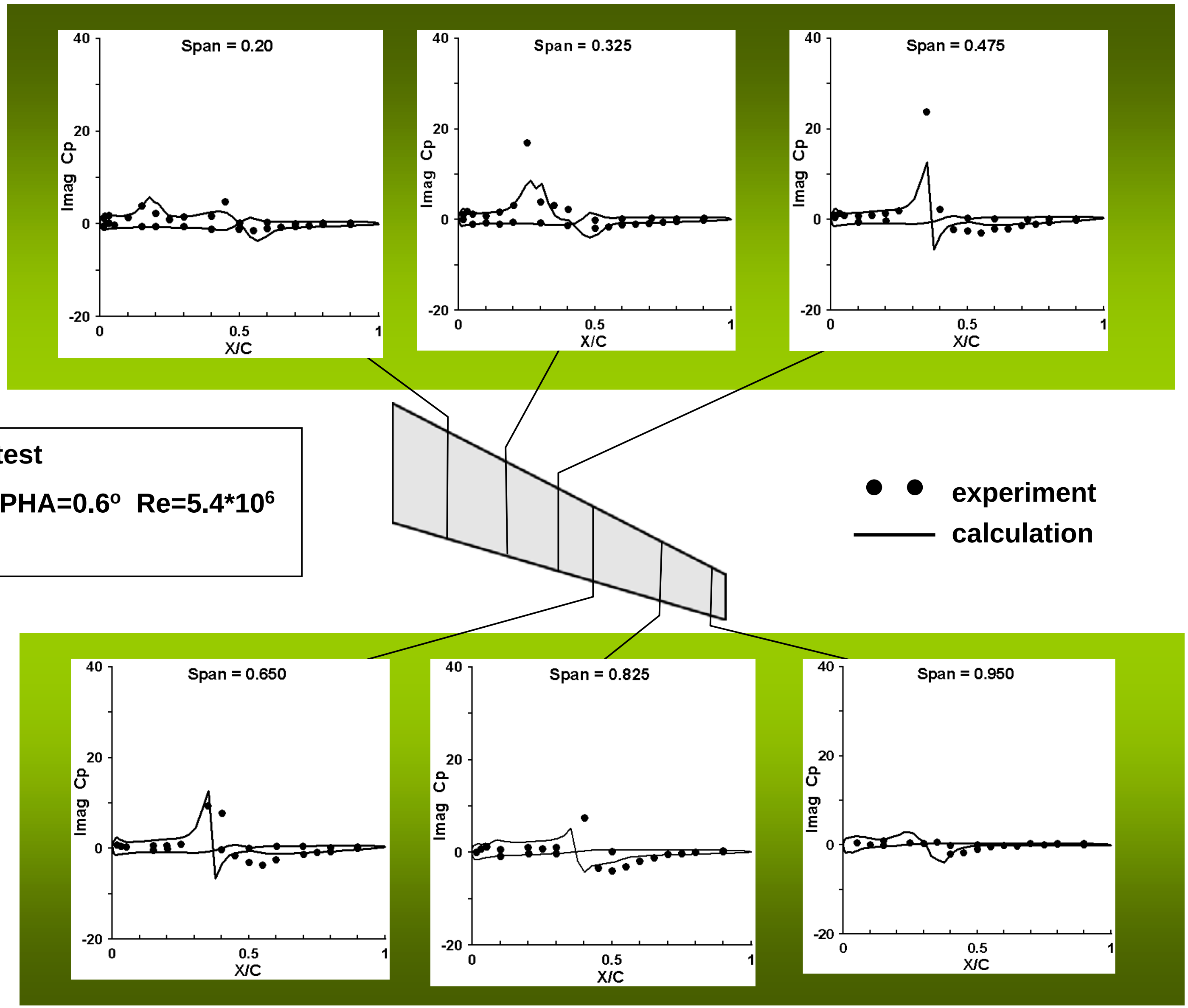
K=0.102

LANN test : **Imaginary part of unsteady Cp distribution.**

LANN wing test

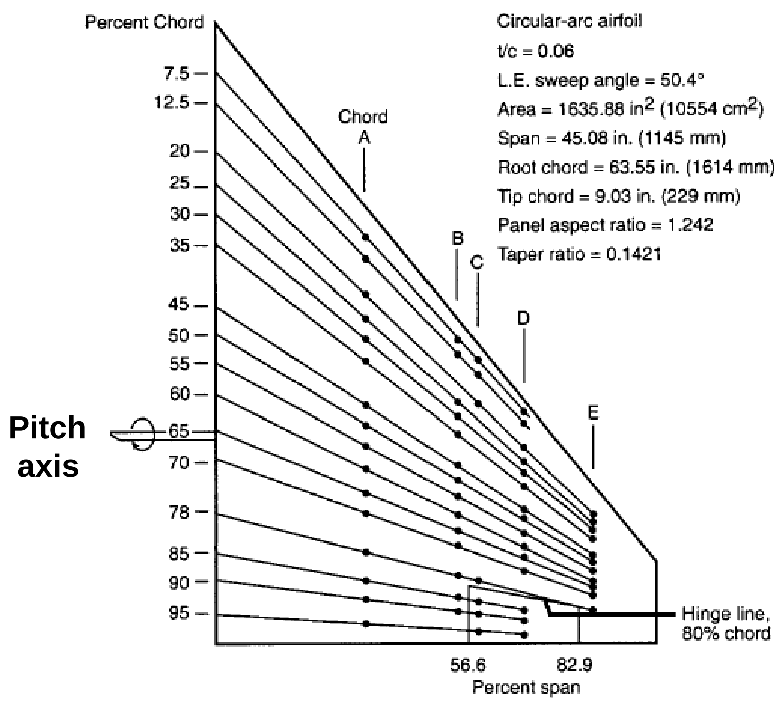
M=0.82, ALPHA=0.6º Re=5.4*10^6

K=0.102

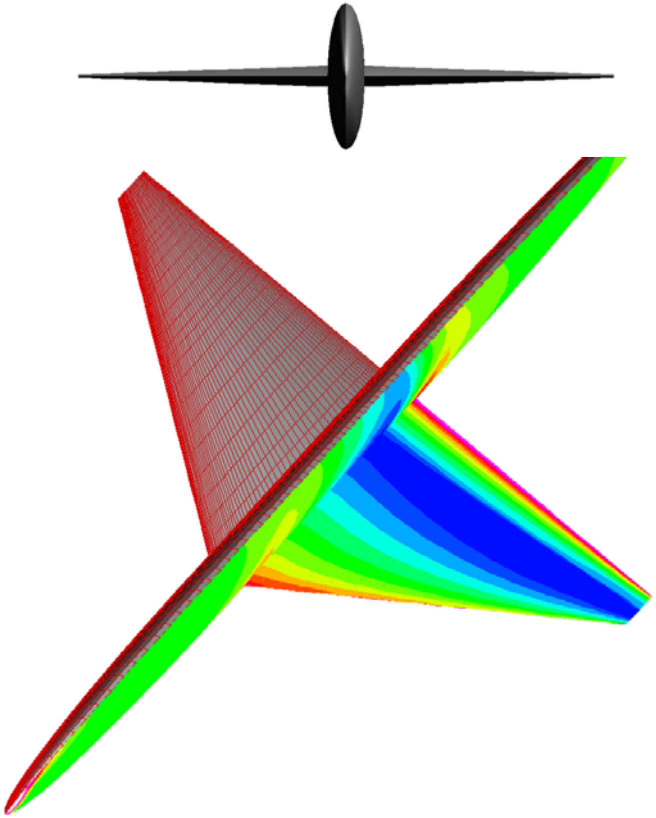


CLIPPED Delta Wing test : **Pitching Oscillations**

Tested Wing Configuration



Calculated Configuration

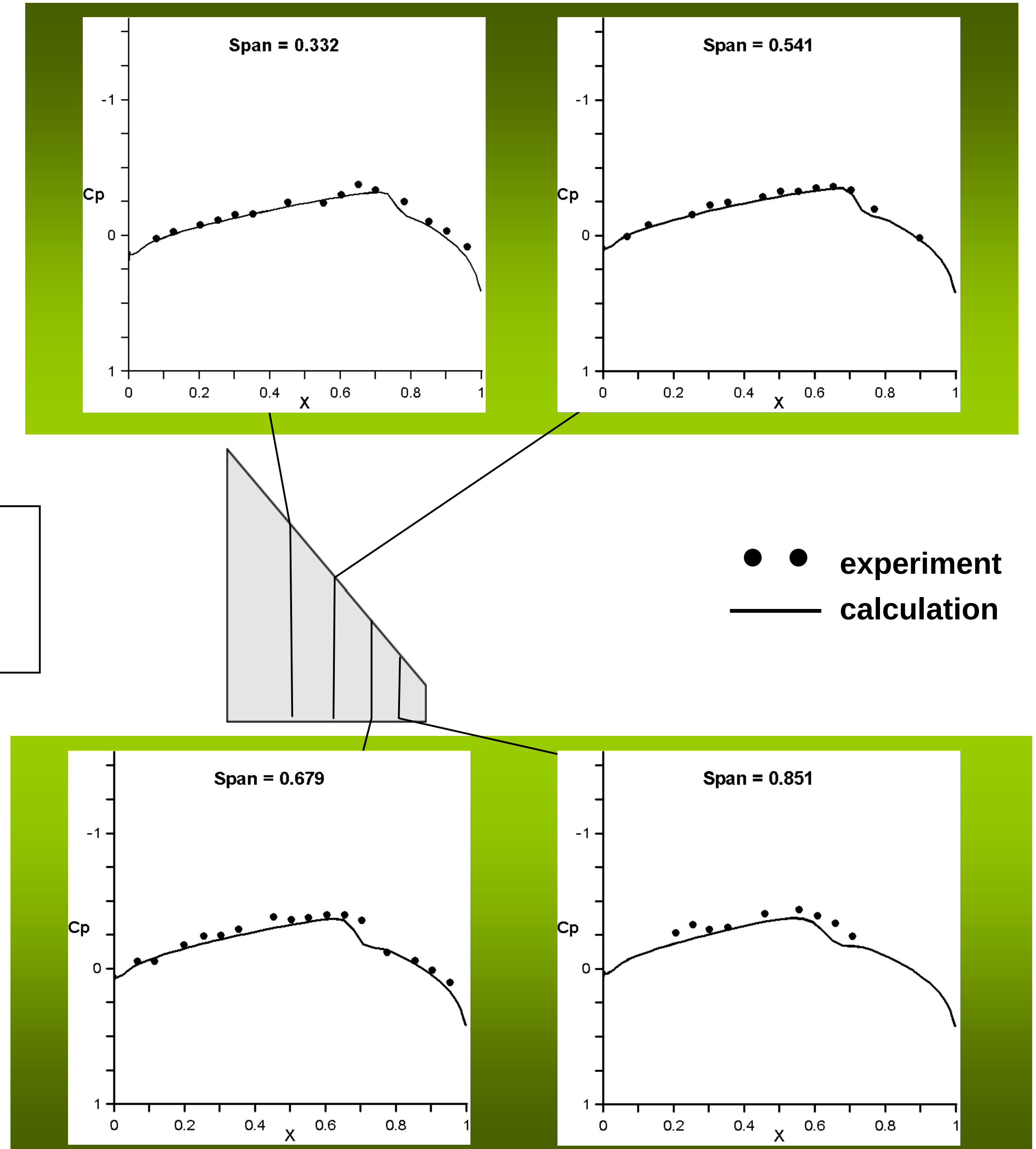


CLIPPED delta wing test : **Steady Cp distribution.**

CLIPPED wing test

M=0.90, ALPHA=0.º

Re=9.8*10^6



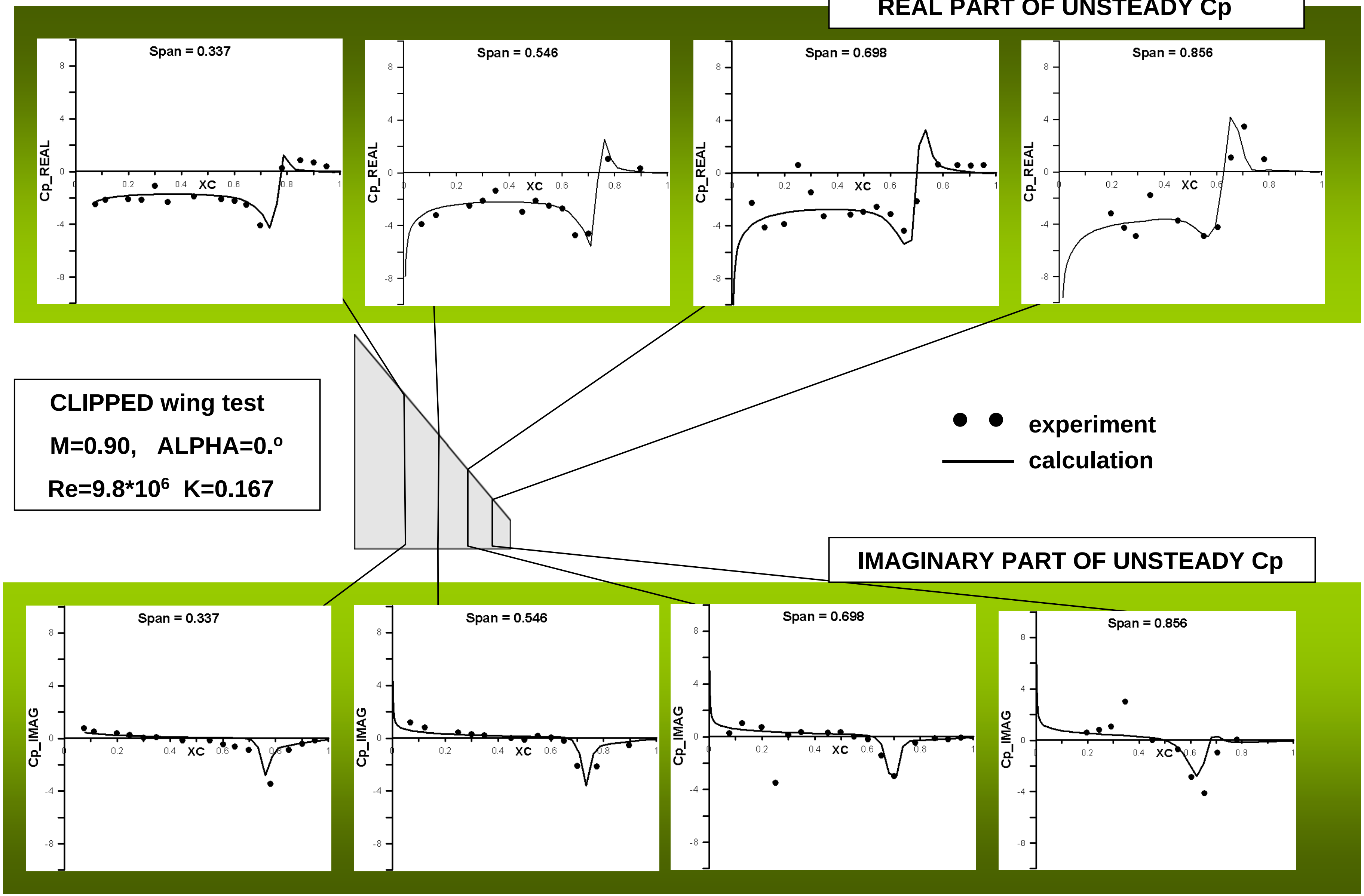
CLIPPED delta wing test : **Unsteady Cp distribution.**

REAL PART OF UNSTEADY Cp

CLIPPED wing test

M=0.90, ALPHA=0.º

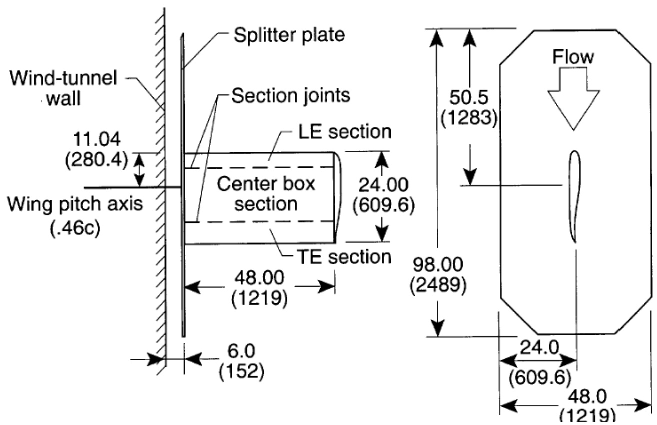
Re=9.8*10^6 K=0.167

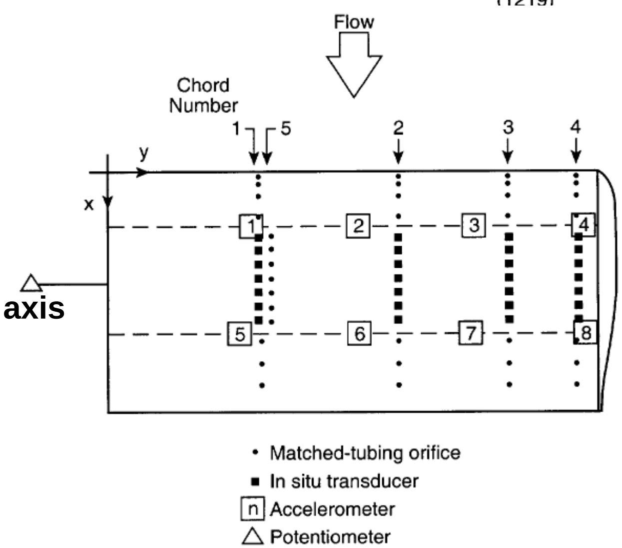


IMAGINARY PART OF UNSTEADY Cp

RSW (Rectangular Supercritical Wing) test : **Pitching Oscillations**

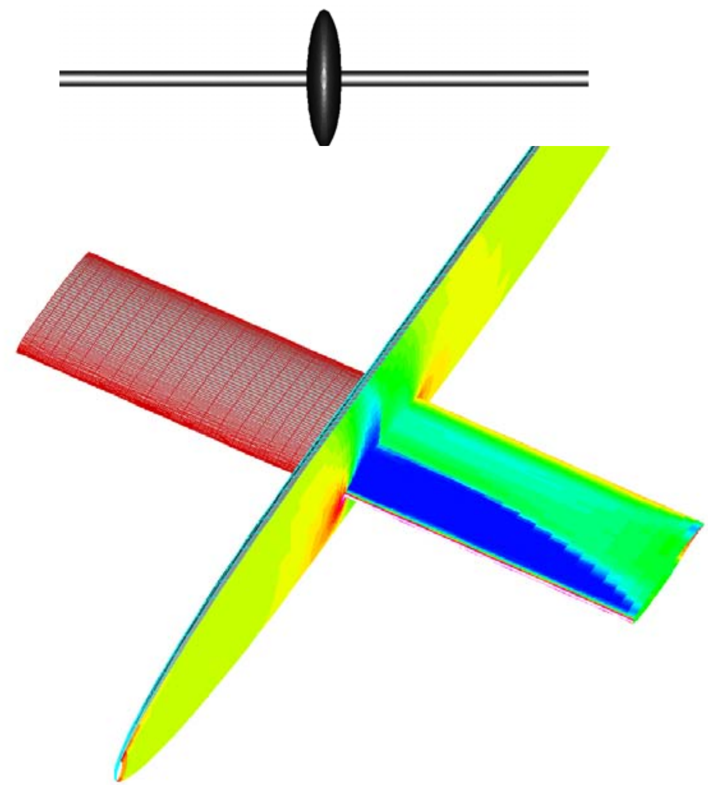
Tested Wing Configuration



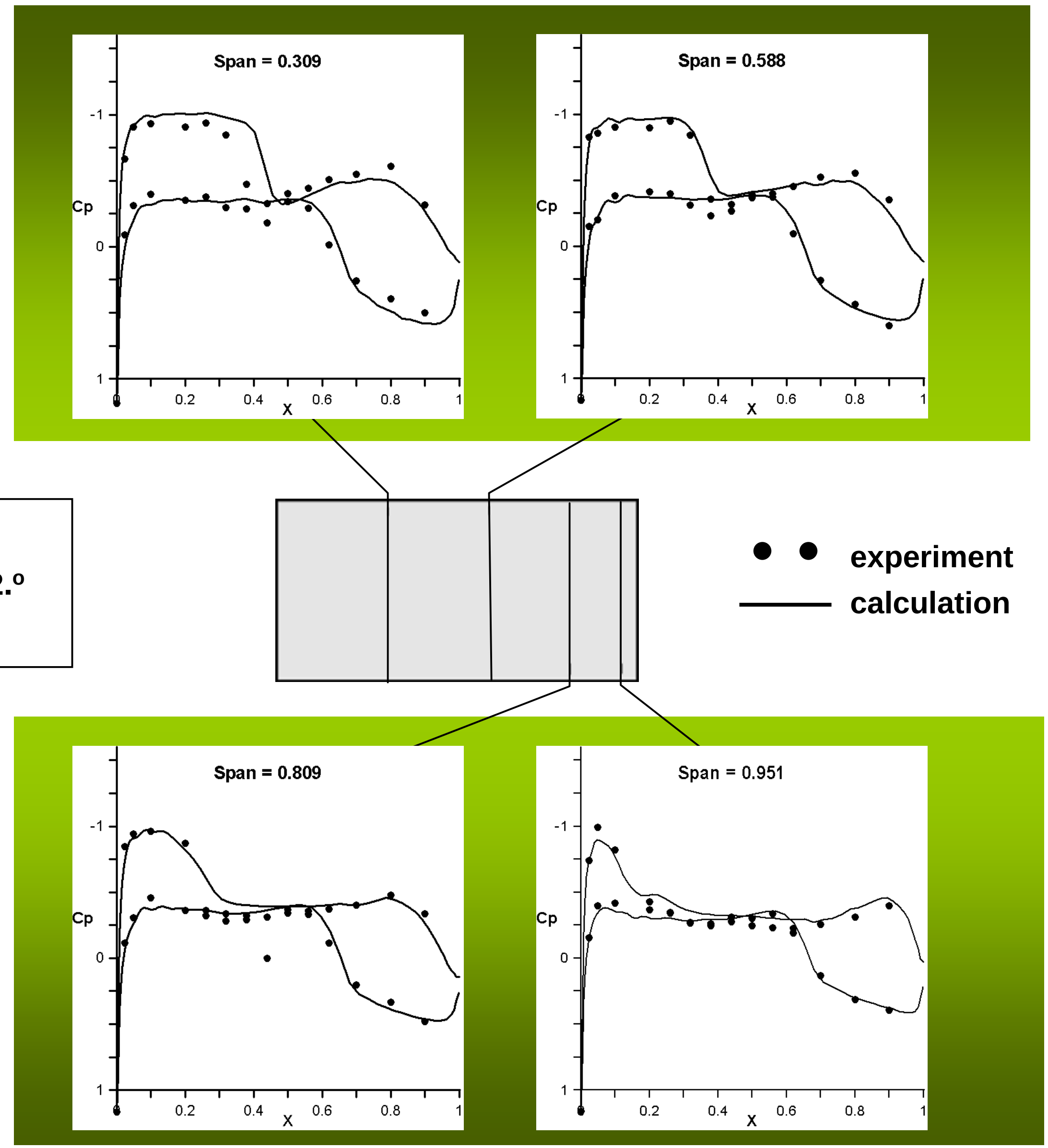


Pitching axis

Calculated Configuration



RSW test : **Steady Cp distribution.**

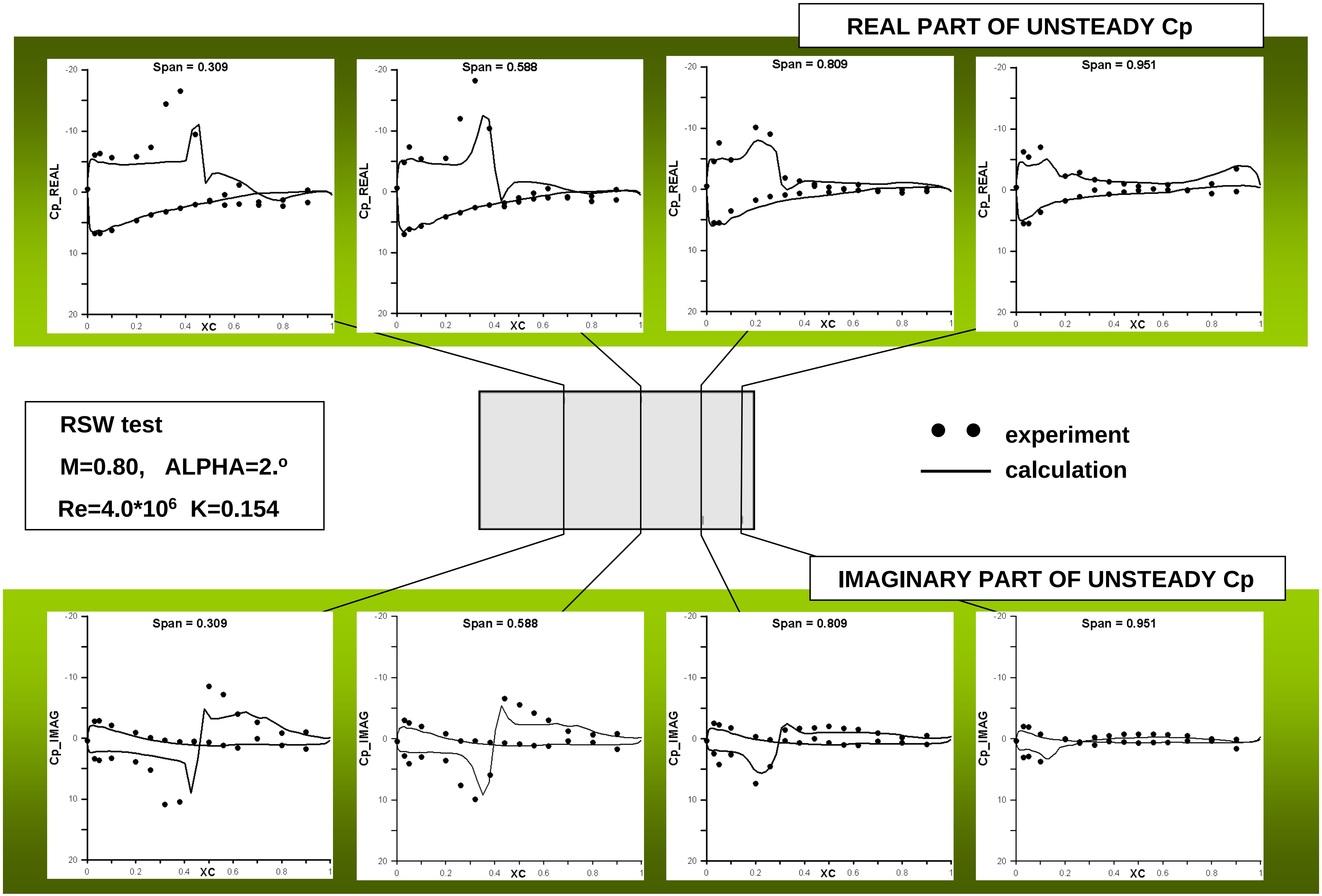


RSW test

M=0.80, ALPHA=2.º

Re=4.0*10⁶

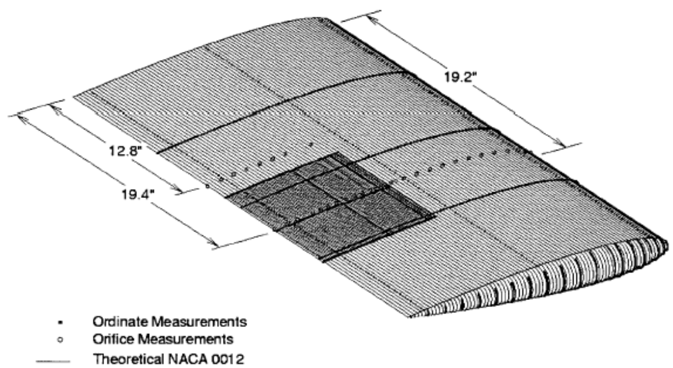
RSW test : **Unsteady Cp distribution.**

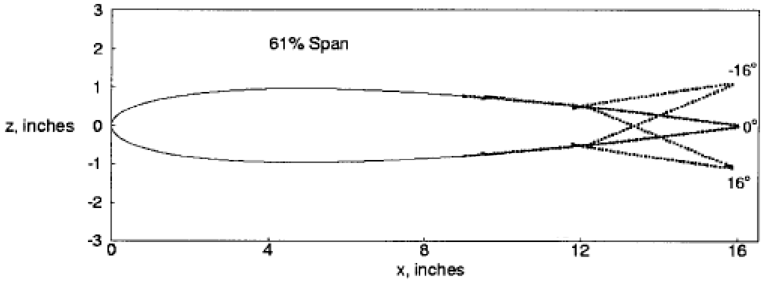


BACT (Benchmark Active Controls Technology) test :

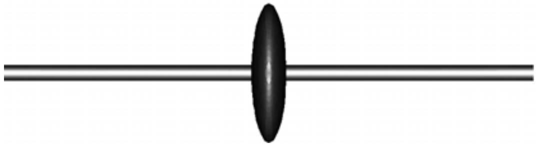
Trailing Edge Control Surface Oscillations.

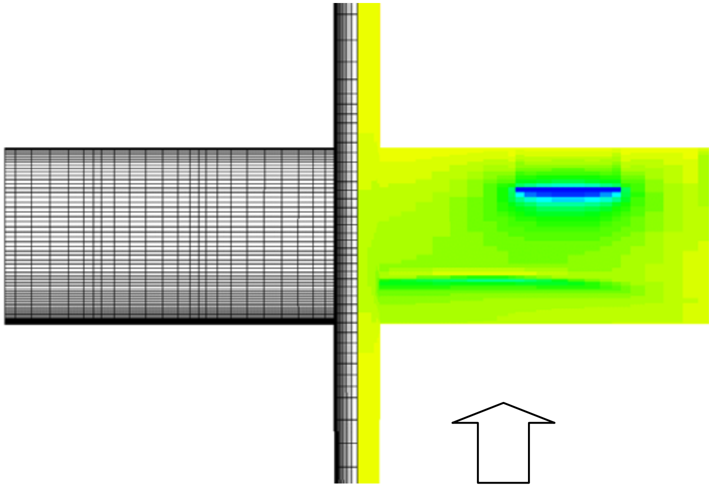
Tested Wing Configuration



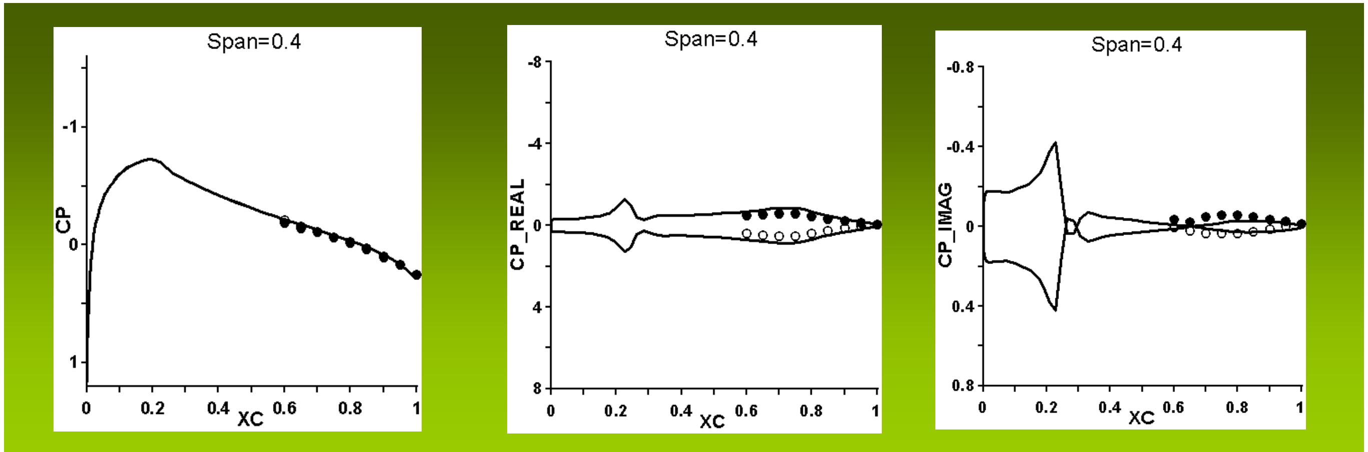


Calculated Configuration





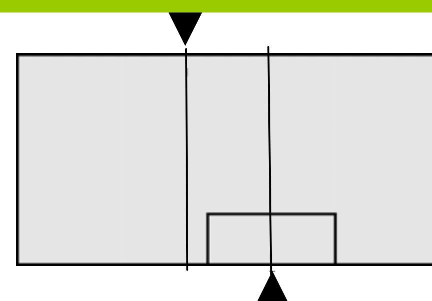
BACT wing test : **Trailing Edge Control Surface Oscillations.**



BACT test

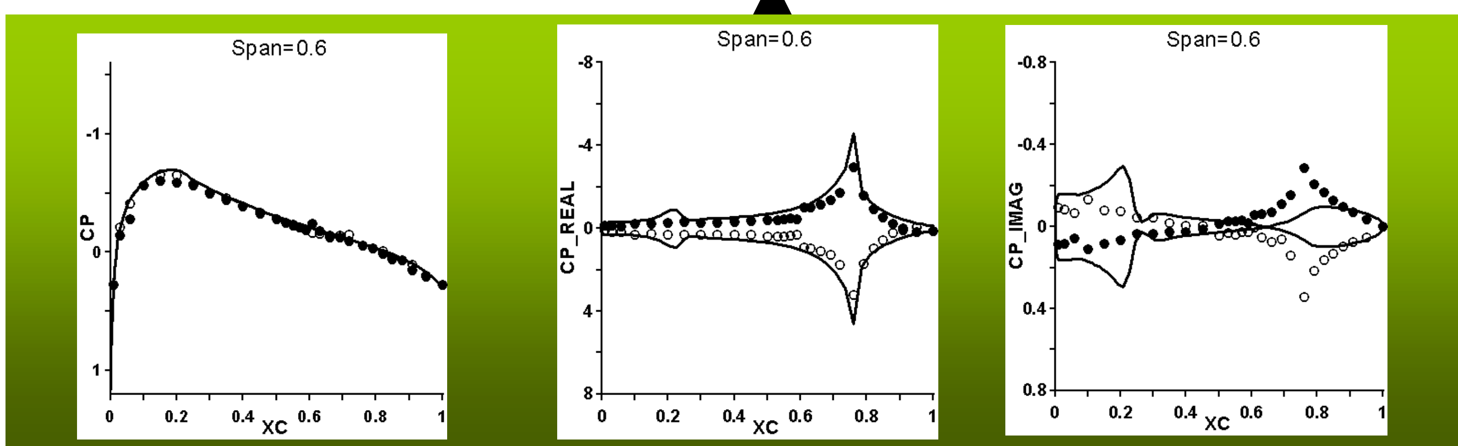
M=0.77, ALPHA=0.º Re=3.96*10^{6}

K=0.0544 (5 Hz)

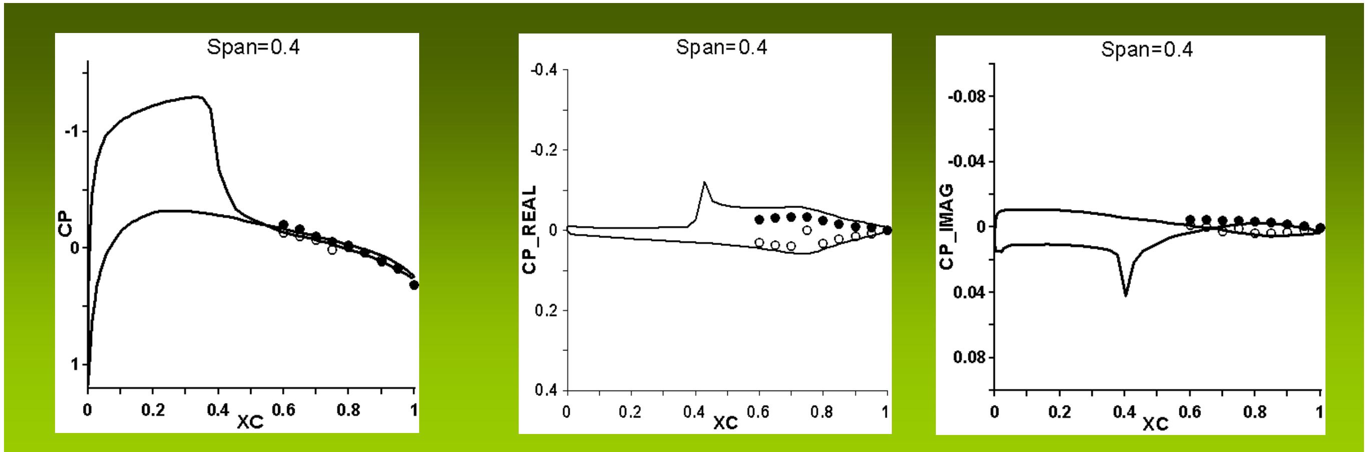


● ● **experiment**
○ ○

—— **calculation**



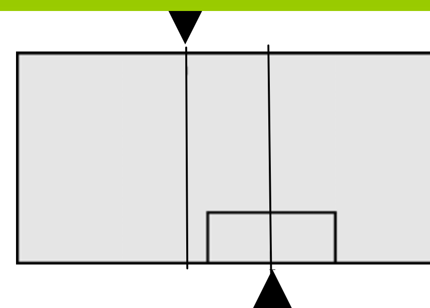
BACT wing test : **Trailing Edge Control Surface Oscillations.**

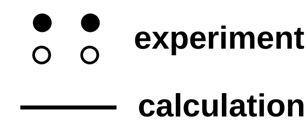


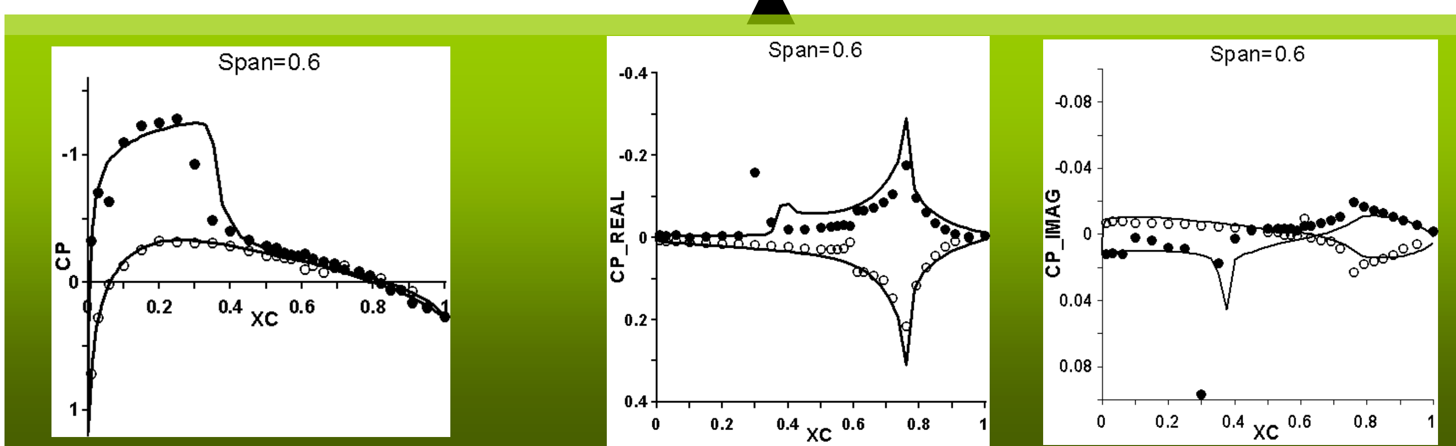
BACT test

M=0.77, ALPHA=4.^{o} Re=3.96*10^6

K=0.1083 (10 Hz)

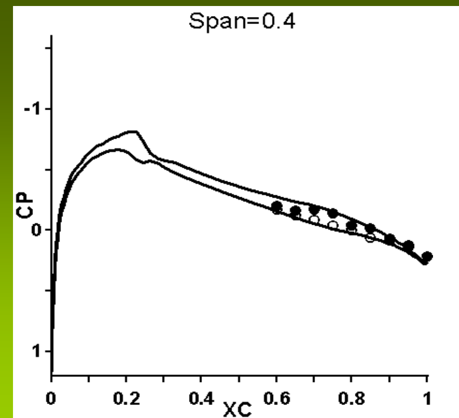


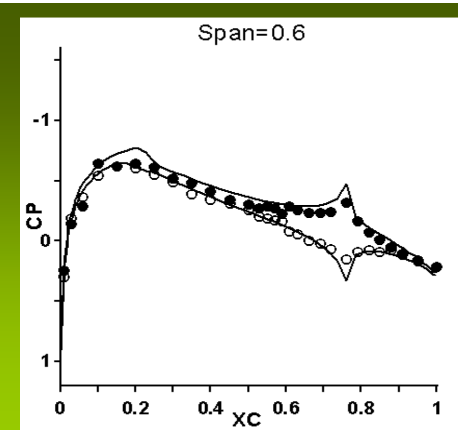




BACT wing test : **Trailing Edge Control Surface Steady Deflection.**

BLWF calculation

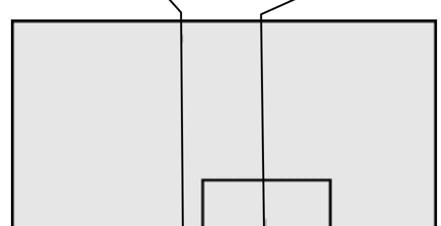




BACT test

M=0.77, ALPHA=0.º Re=3.96*10^{6}

Delta=5.º



experiment

calculation

NASA codes calculation

ENS3DAE (full N-S)
CFL3DAE (thin layer N-S)