Numerical Simulation of Cavitating Flows

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Motivation

- Cavitation is complex process
- Not completely understood
- Hardly to predict
- Testing of existing models and combination with others → Validation
- Estimation of numerical errors

Contents

- Cavitation modelling
  - Two-phase flow approach
  - Mass transfer model
  - Cavitation and cavitation inception
- Test cases
  - Two-dimensional
  - Three-dimensional
- Conclusion and outlook

Cavitation

- Definition

  Rupture of a liquid due to pressure decrease at roughly constant temperature.

- Saturation pressure p_s
- Problem

  Rupture starts at inhomogenities in a liquid, so-called nuclei

- Lack of nuclei might postpone inception
- Integral measure by means of tensile strength Δp_t

$$\Delta p_t = p_S - \frac{2S}{R_B}$$

Cavitation modelling

- Large density differences between liquid and vapour
- Volume-of-Fluid method → r_v , r_l
- Two-phase flow with source term Γ_{lv}

$$\frac{\partial}{\partial t}\left(r_V \rho\right)+\frac{\partial}{\partial x_i}\left(r_V \rho u_i\right)=\Gamma_{lv}$$

- Homogenic description → number of equations

$$\vec{u}_v = \vec{u}_l$$

Cavitation modelling

- Rayleigh-Plesset mass transfer model

$$\Gamma_{lv} = F_{evap} \frac{3 r_{nuc} (1 - r_v) \rho_v}{R_B} \sqrt{\frac{2}{3} \frac{|p_s - p_B|}{\rho_l}} \cdot sgn(p_s - p_B)$$

$$\Gamma_{lv} = F_{cond} \frac{3 r_v \rho_v}{R_B} \sqrt{\frac{2}{3} \frac{|p_s - p_B|}{\rho_l}} \cdot sgn(p_s - p_B)$$

- $F_{evap} = 50$, $F_{cond} = 0.01$
- $r_{nuc} = 5 \times 10^{-4}$, $R_B = 2 \times 10^{-6}$ m

Turbulence modelling

- RANS, URANS
- SST model, eddy viscosity model

$$\mu_t = \rho \frac{C\,k}{f(\omega)}$$

- Blending via F_1 function in ω–equation between
  - $F_1=0$ → k-ε model, free stream
  - $F_1=1$ → k-ω model, near walls
- Curvature correction to the SST model

$$P_k = f_r \cdot \widetilde{P}_k\,; \quad f_r = 0 \ldots 1.25$$

Numerical errors

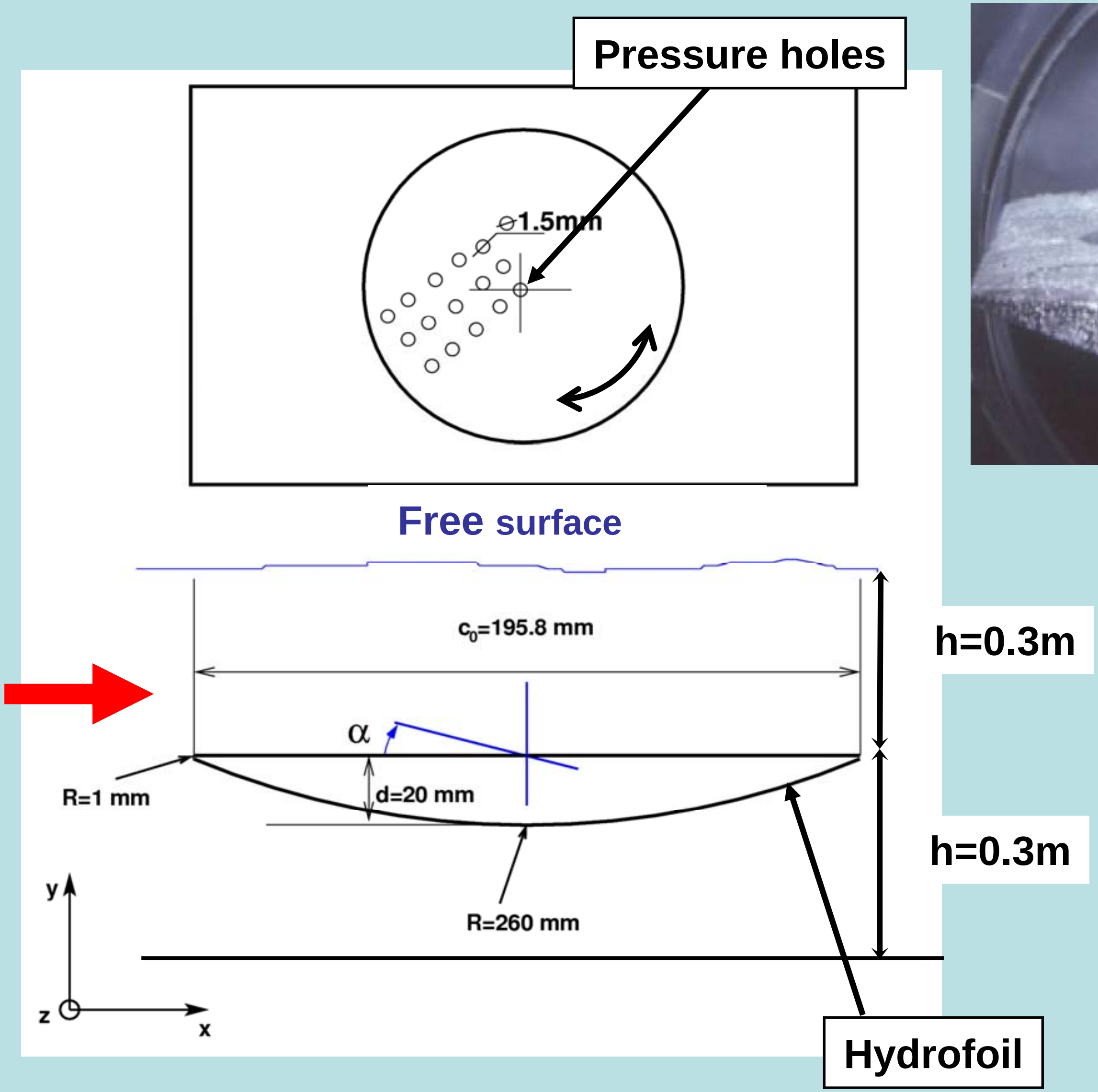
- Errors regarding
  - Spatial discretisation
  - Time discretisation
  - Iteration number
- Time step studies
- Grid studies
- Abort at different residual norms

Symbol definitions

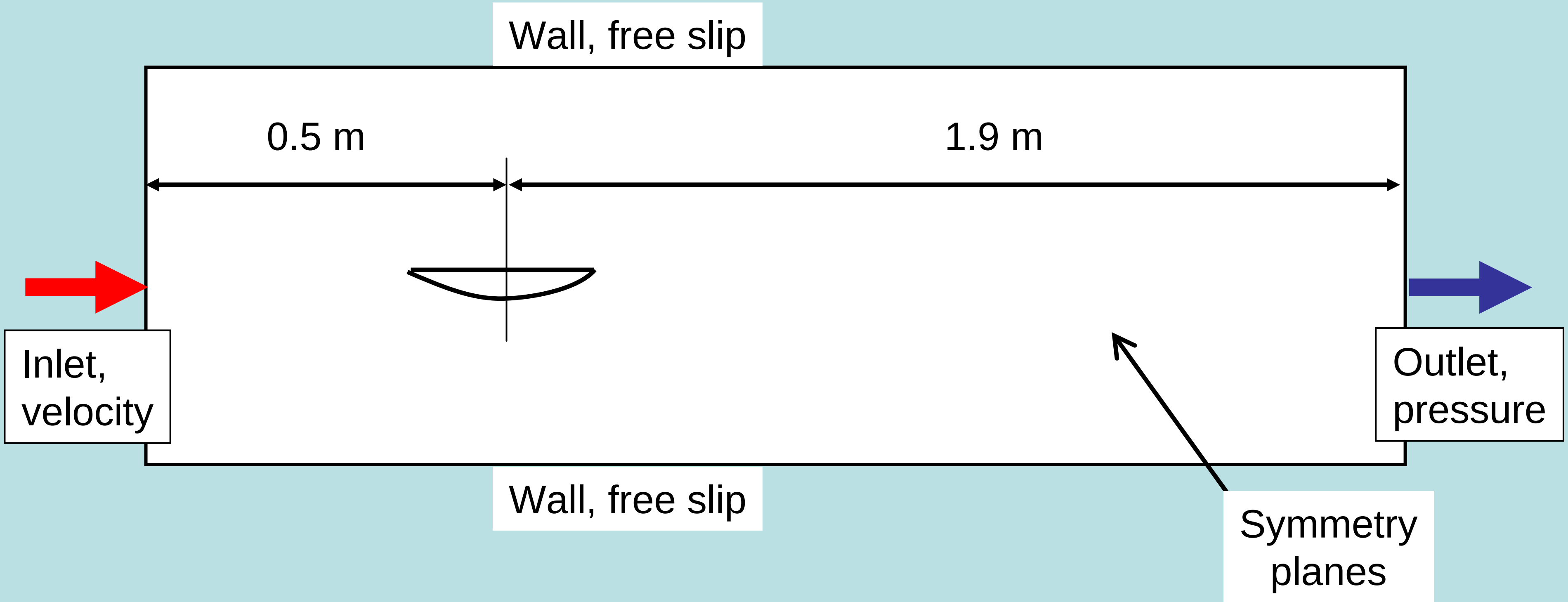
- Gas holdup $$G = \int_{(v)} r_G \cdot dV$$
- Lift coefficient $$c_L = \frac{2 \cdot F_L}{\rho_f \cdot u_\infty^2 \cdot A_P}$$
- Pressure coefficient $$c_p = \frac{2 \cdot p_{stat}}{\rho_f \cdot u_\infty^2}$$
- Cavitation number $$\sigma = \frac{2 \cdot (p - p_s)}{\rho_f \cdot u_\infty^2}$$

p_s	Saturation pressure	A_P	Hydrofoil surface
p_{stat}	Static pressure	F_L	Lift force
u_∞	Inlet velocity	r_v	Vapour volume fraction
ρ_f	Density - water	r_l	Water volume fraction

Two-dimensional test case



Boundary conditions



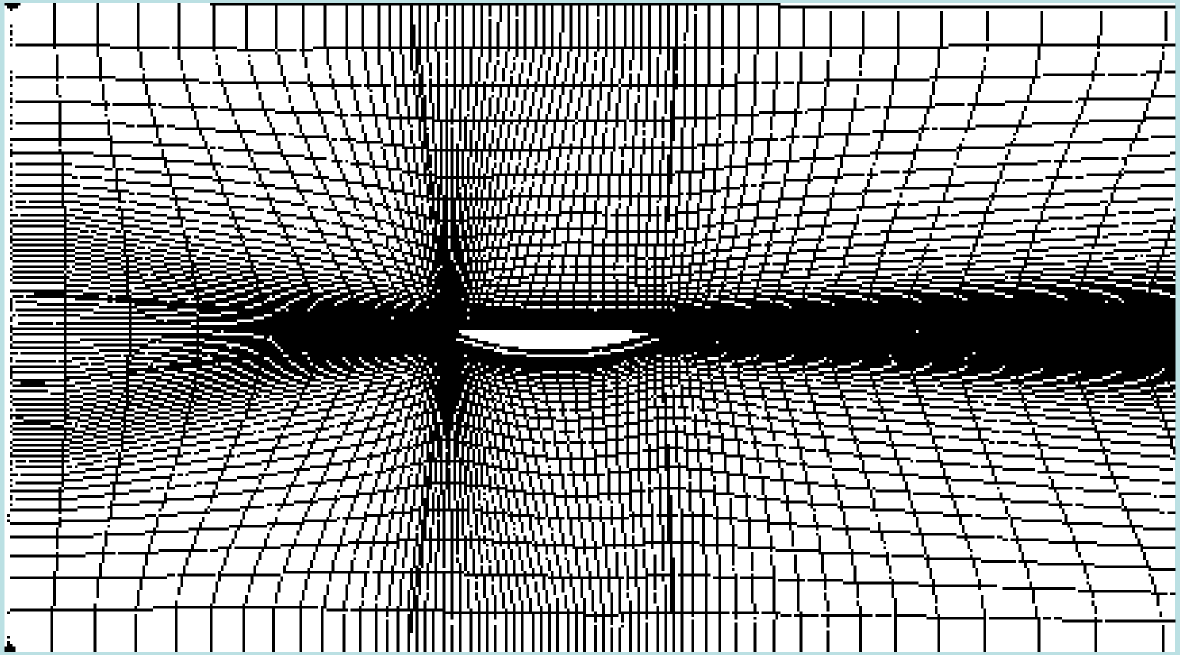
- Pressure boundary condition

$$p_{out} = \sigma \cdot \rho/_2 \, u_\infty^2 - p_s$$

Test Case Summary

- Spatial discretisation
  - HighResolution scheme, hybrid scheme
- Time discretisation
  - 2^{nd} order Backward Euler
- Saturation pressure p_s=3240 [Pa]
- Standard SST turbulence model
- Outlet: Pressure boundary condition via σ
- Inlet: u_∞=10 m/s, Re$\approx 2\times 10^6$

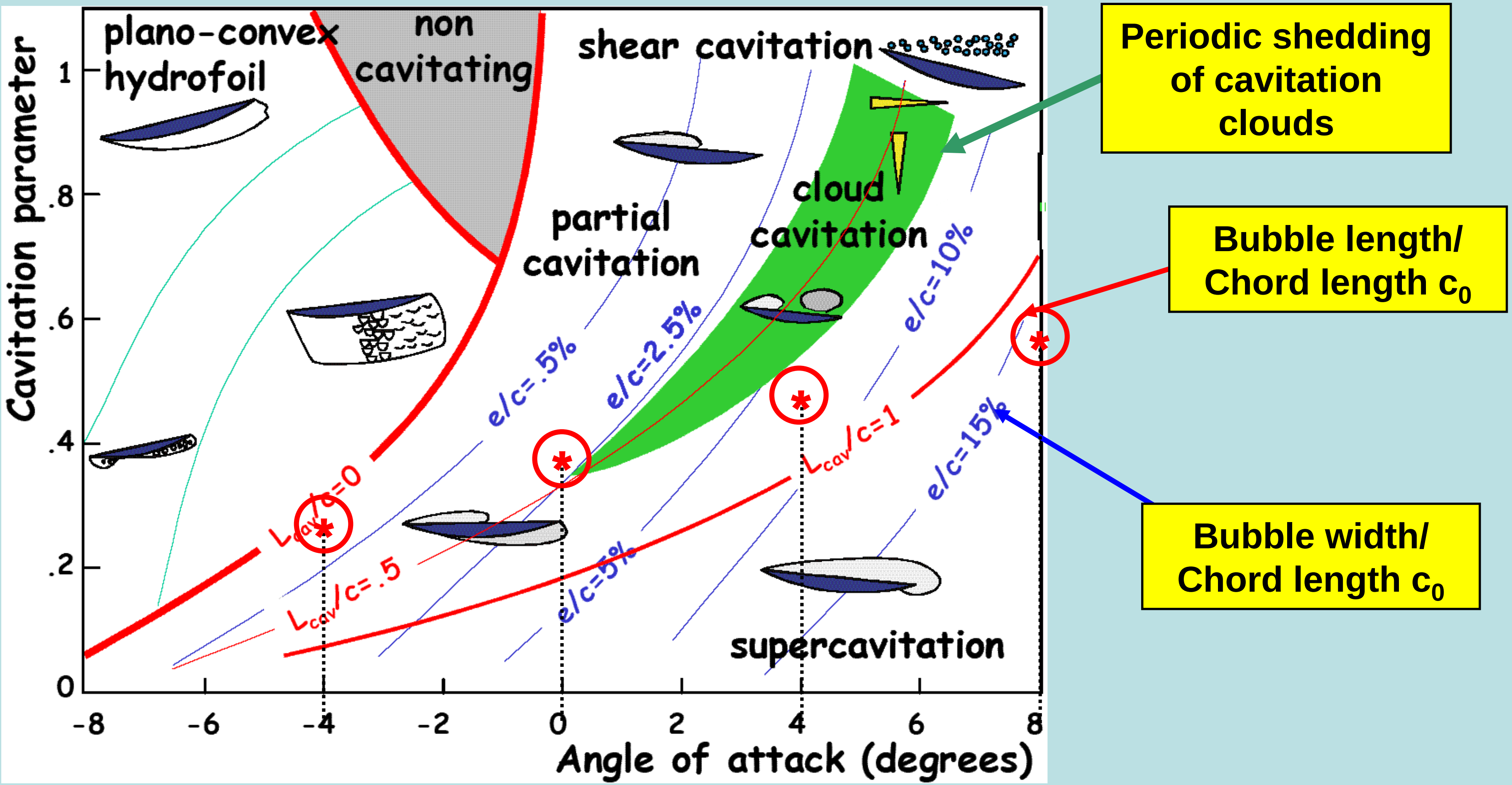
Grids



Grid	(1)	(2)	(3)	(4)
Node number	14 306	56 452	224 264	893 986
Element number	6 960	27 840	111 360	445 440
Min. grid angle [°]	40	41	38	43
First layer width y [μm]	20	10	5	2,5
Average layer width y^+	8	4	2	1

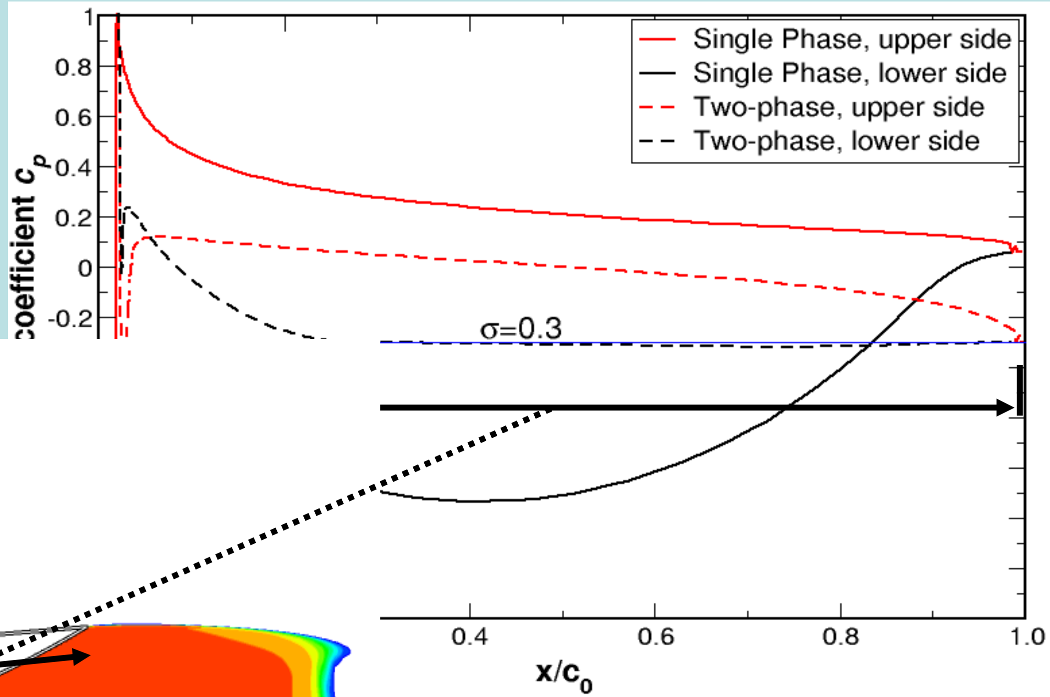
Experimental data

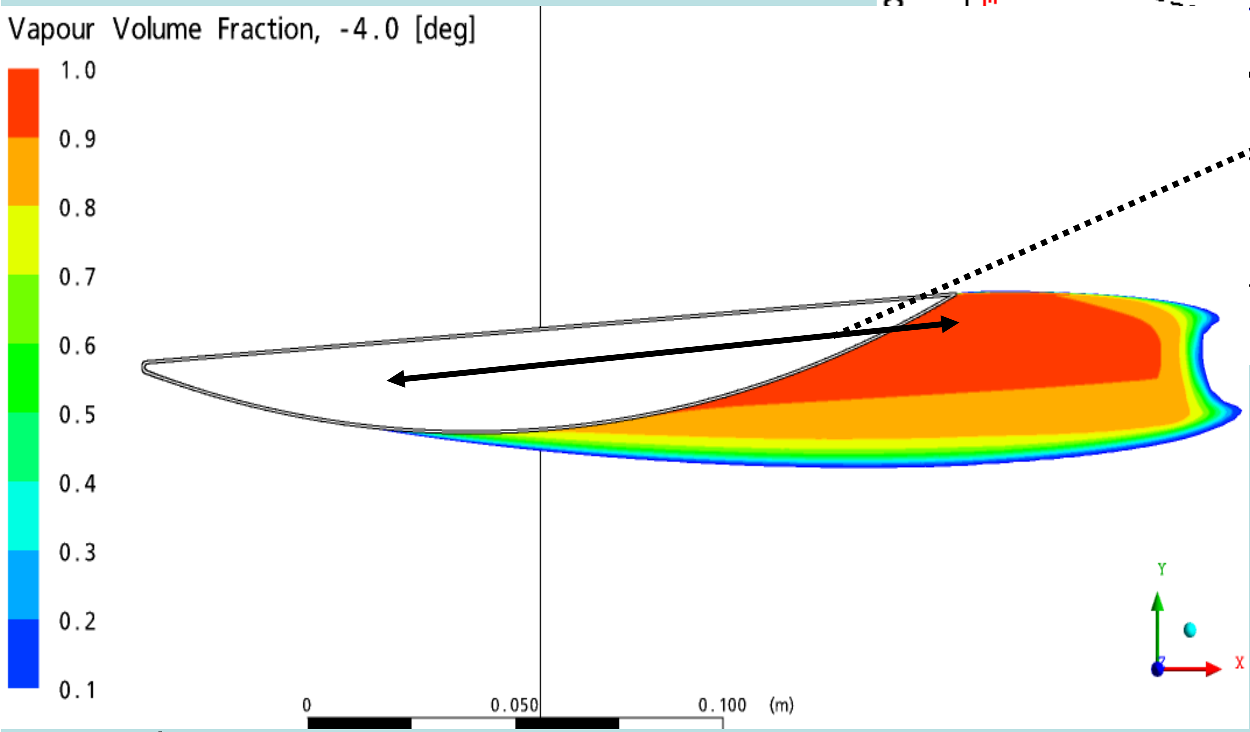
- Flow patterns in experiment



Case study, $\alpha = -4°$

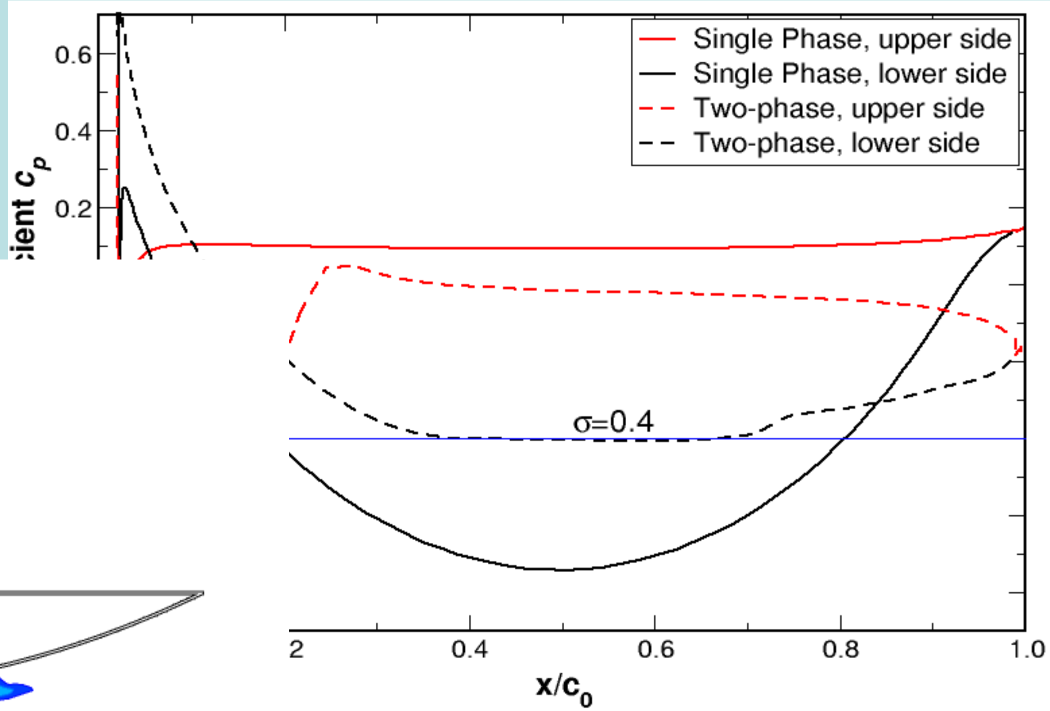
- Pressure coefficient/ Vapour volume fraction
  - Medium (3) grid

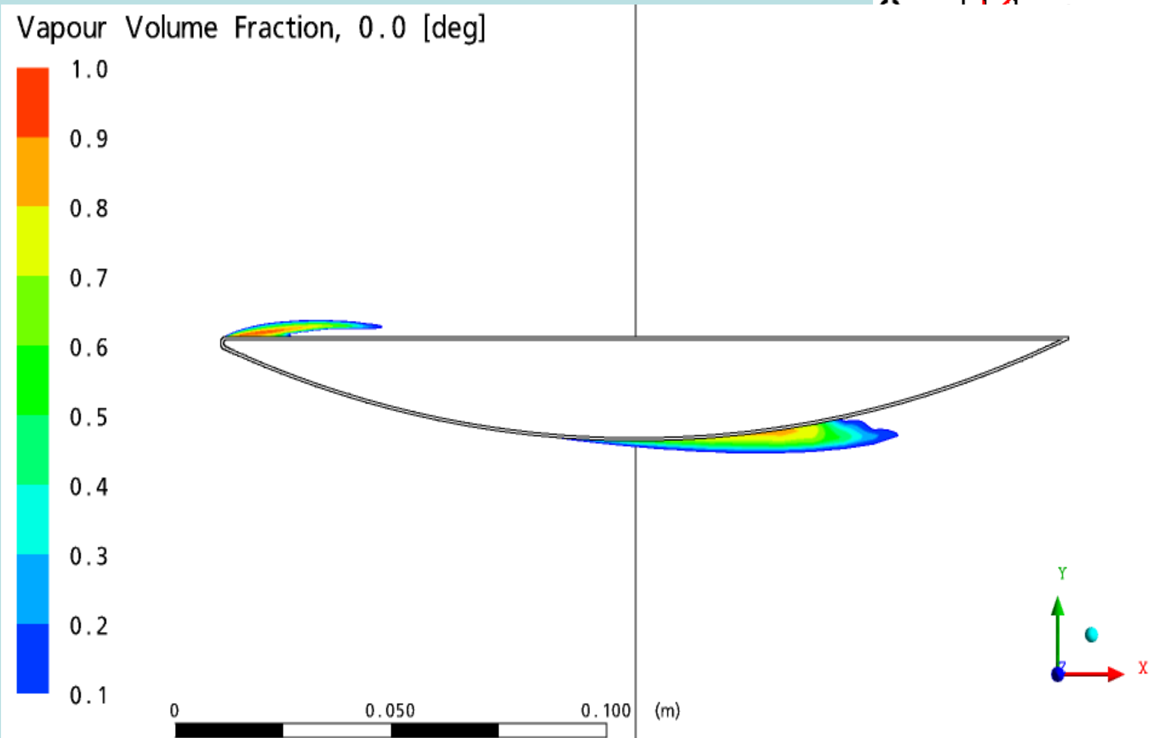




Case study, α=0°

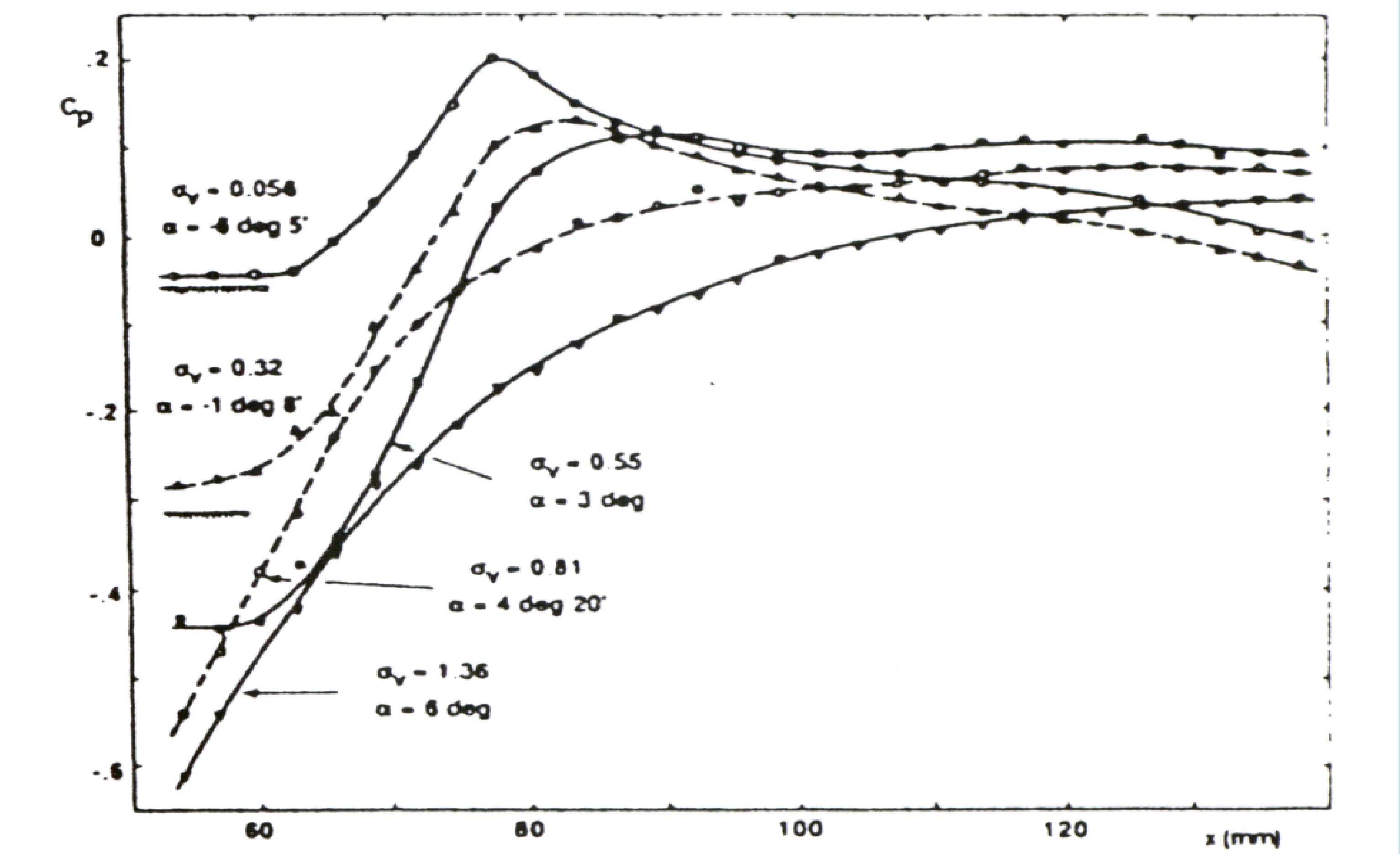
- Pressure coefficient/ Vapour volume fraction





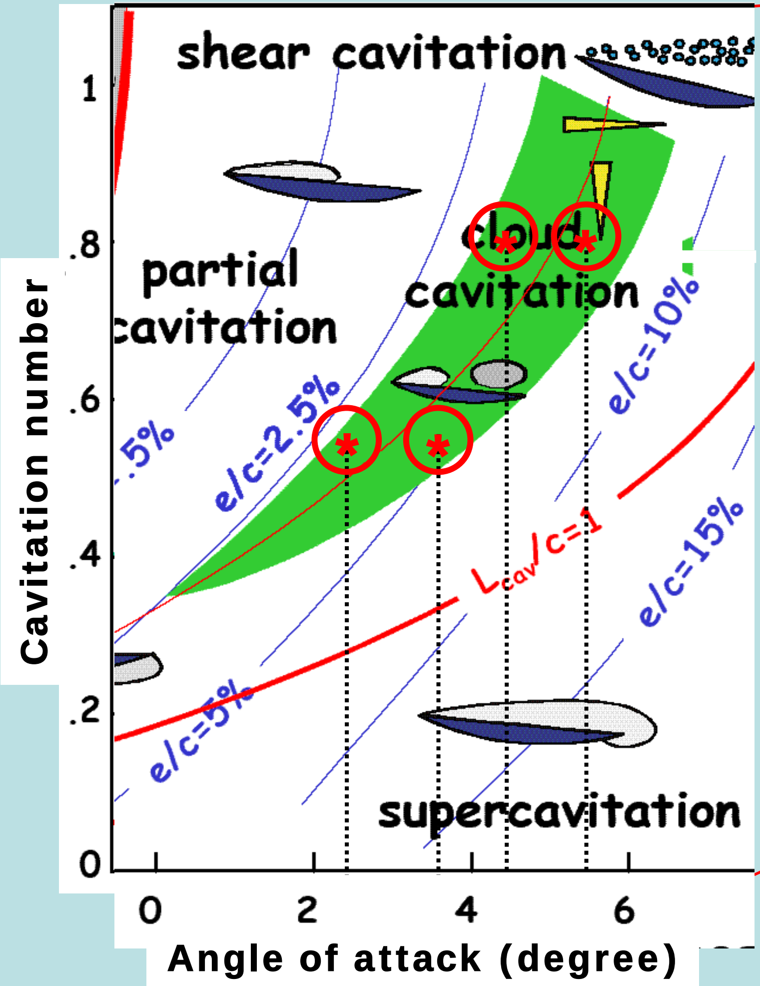
Experimental data (2)

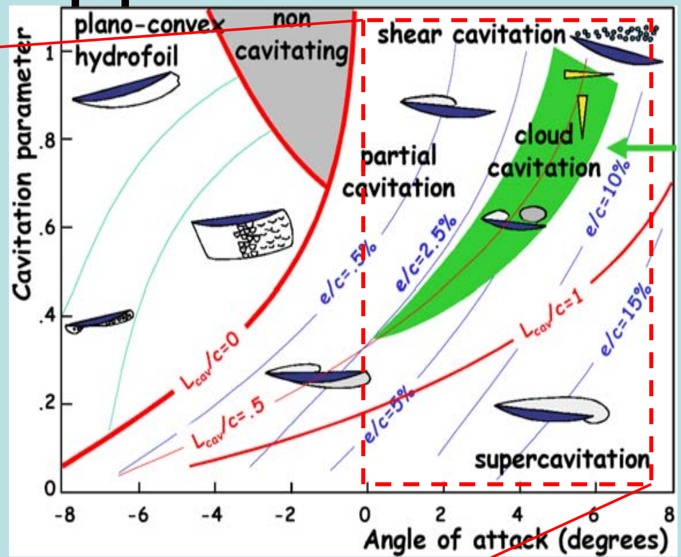
- Experiments Le et al. (1993)
  - Pressure distributions



Validation

- Pressure distribution on upper side:



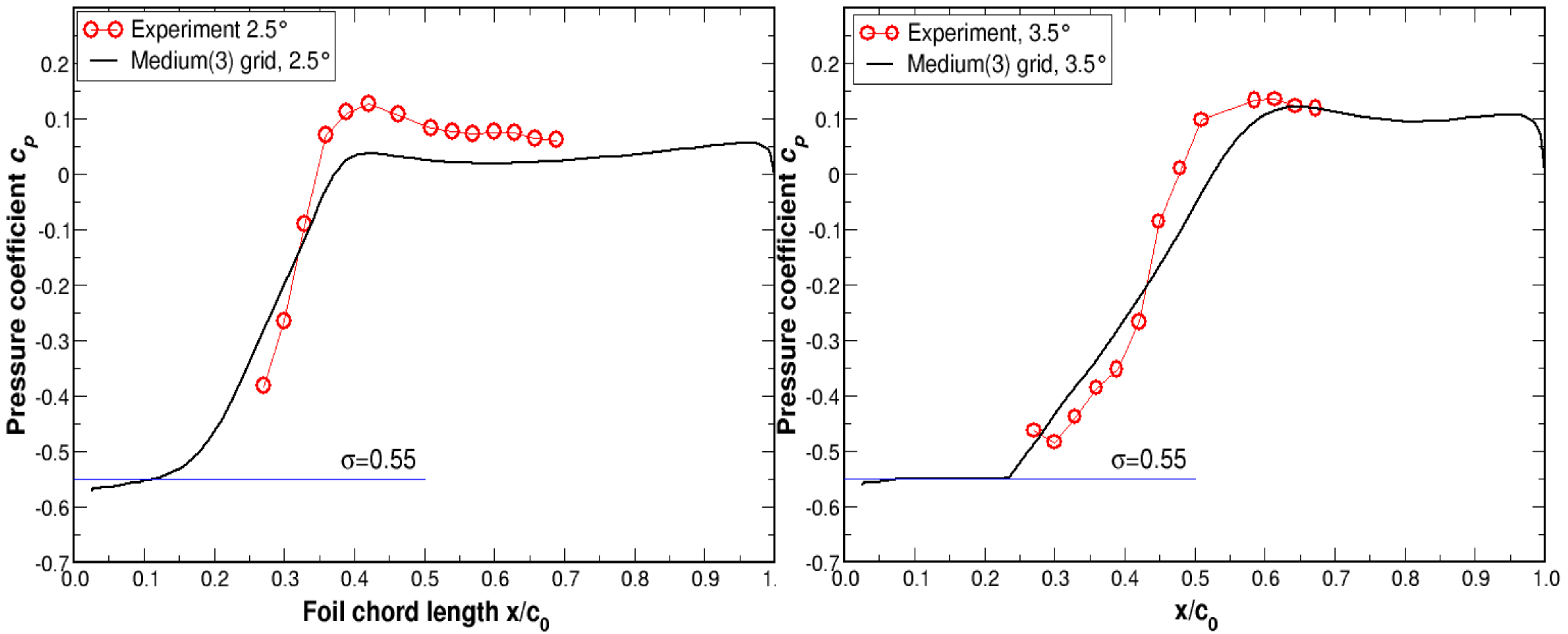


⇒

Angle [°]	Cavitation number
2.5	0.55
3.5	0.55
4.17	0.81
5.17	0.81

Pressure distribution

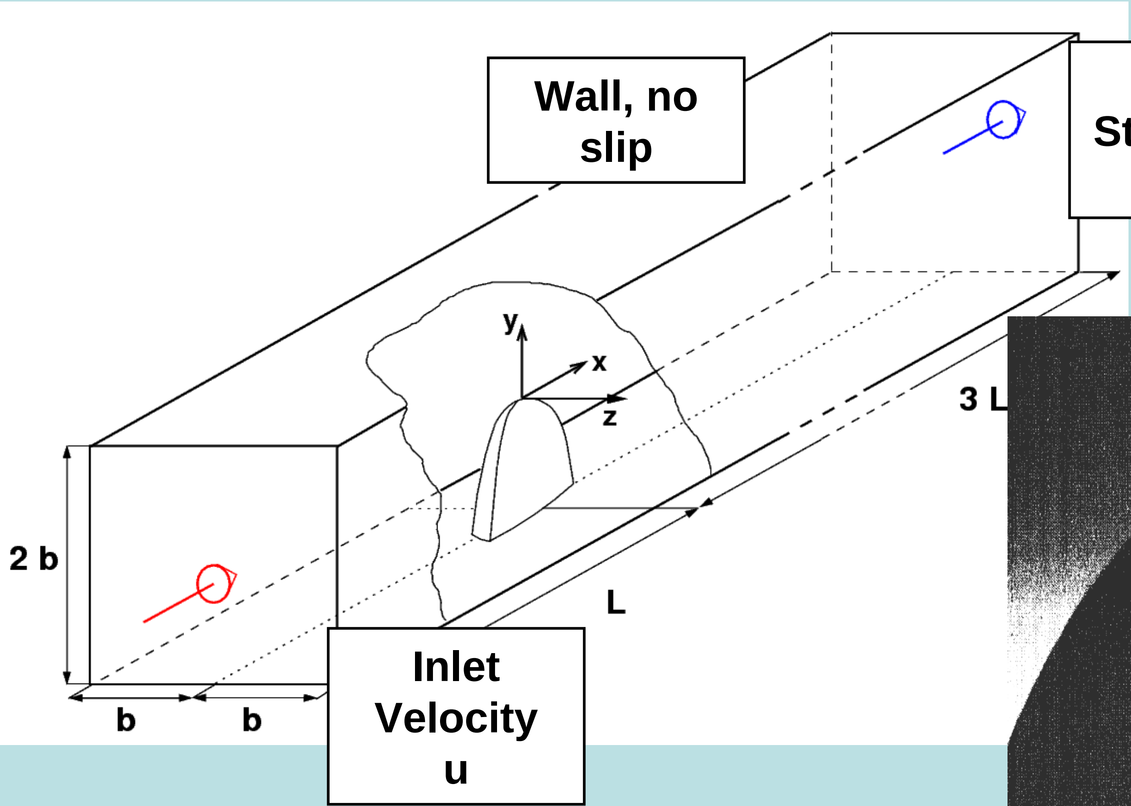
- Angle of attack: $\alpha = 2.5°$ and $3.5°$

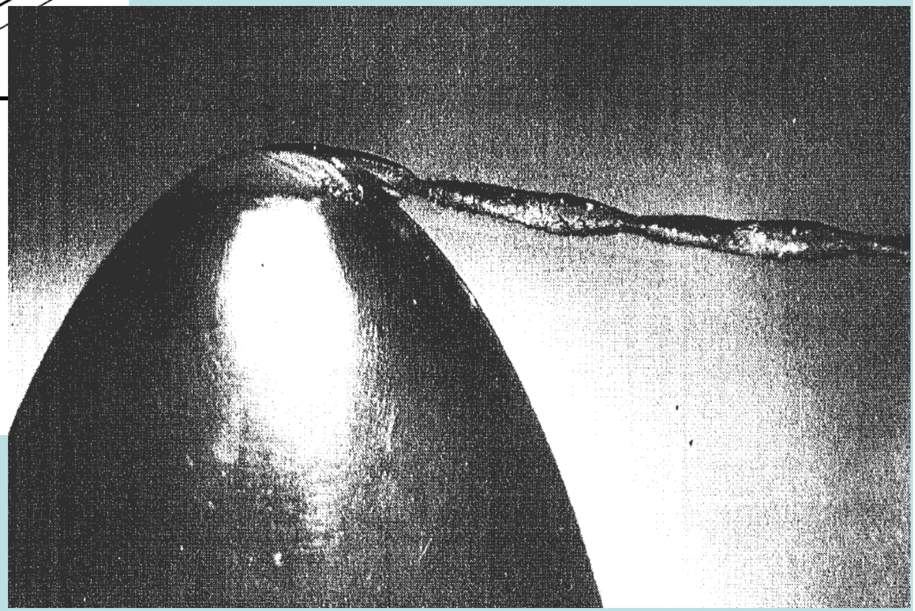


- URANS-Simulations, time averaged

Threedimensional test case

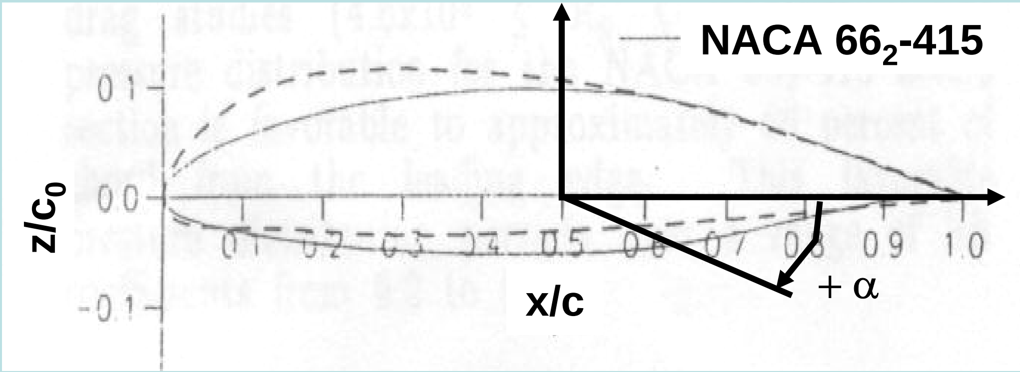
- Water test channel at SAFL (St. Anthony Falls Laboratory, Minnesota, U.S.A.)

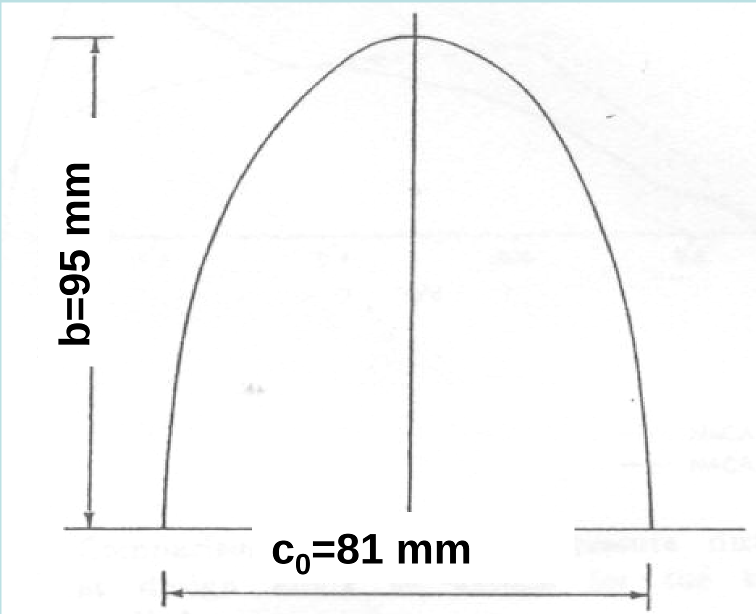




Geometry

- NACA 66_2-415 profile





α...Angle of attack

c_0...Chord length

b...half span

Test case setup

- Spatial discretisation
  - HighResolution scheme for momentum
  - 1st order/ HighResolution for turbulence
- Time discretisation
  - 2nd order Backward Euler
- Single phase calculations, inception
- SST-model/ SST with curvature correction
- Inlet: u_∞=5.73...12.13 m/s, Re=5.2×10^5...1.1×10^6
- Outlet: Pressure boundary condition via σ

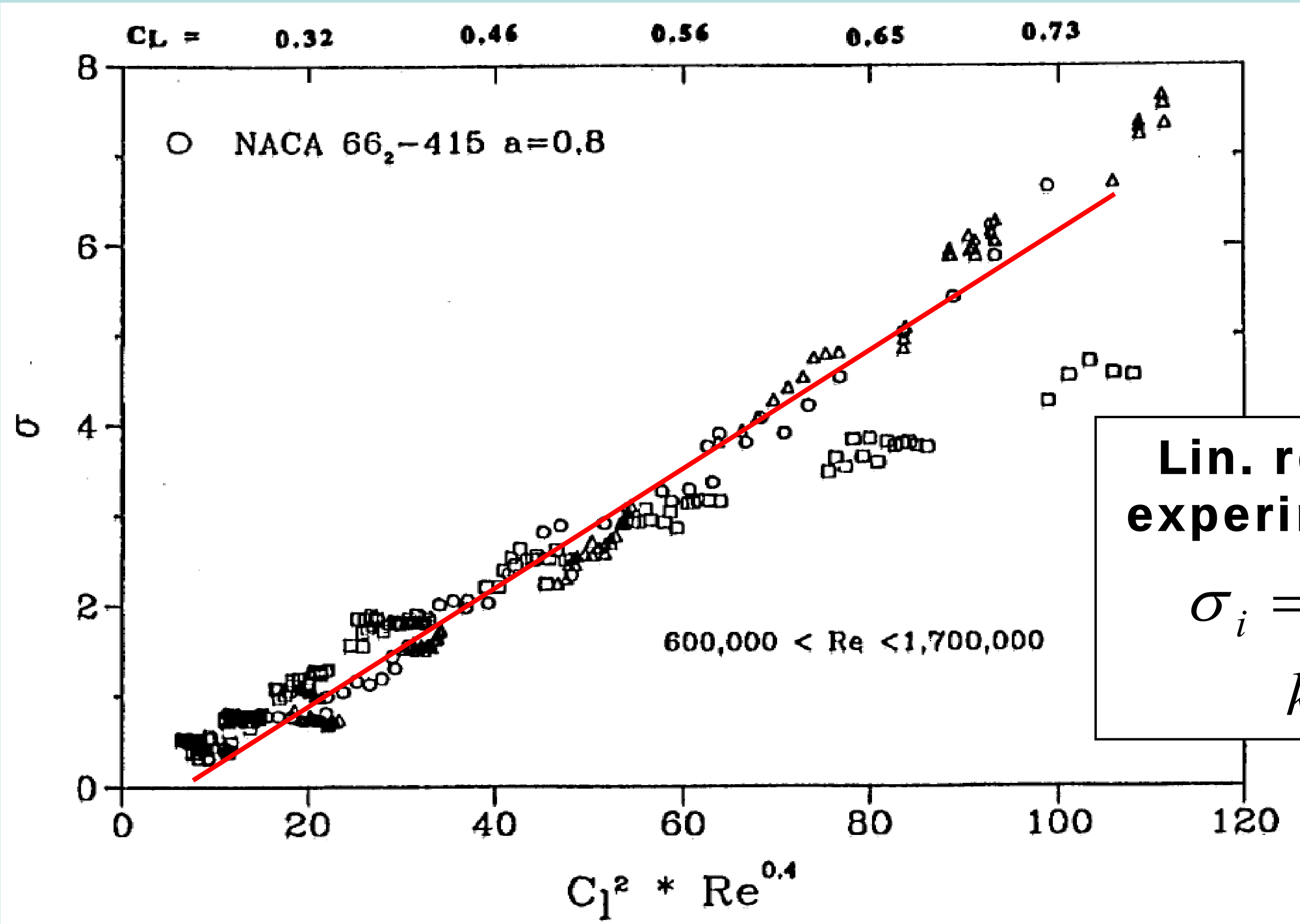
Gitternetze

- Skalierfaktor $4^{1/3}$ in jeder Raumrichtung

Grid	Grob (1)	Mittel (2)	Fein (3)
Knotenanzahl	358 519	1 394 862	5 442 459
Elementanzahl	341 596	1 352 603	5 337 217
Wandschichtdicke y [μm]	30	15	7,5
Durchschnittl. Dicke y^+	14,3	7,1	3,6

Kavitationseinsatz

- Experimentelle Daten



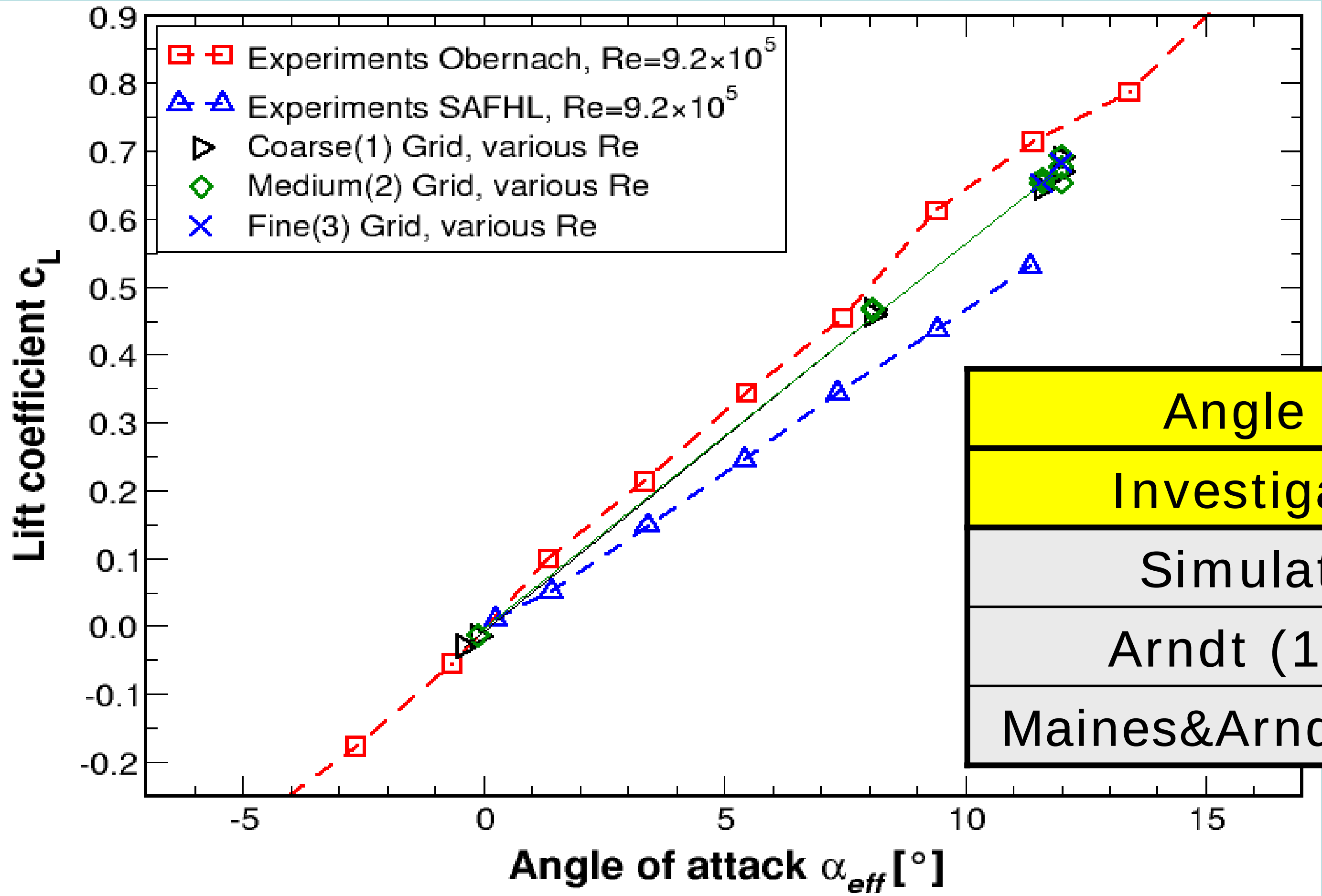
Lin. regression of experimental value:

$$\sigma_i = k \cdot c_L^2 \cdot Re^{0.4}$$

$$k=0.063$$

Lift

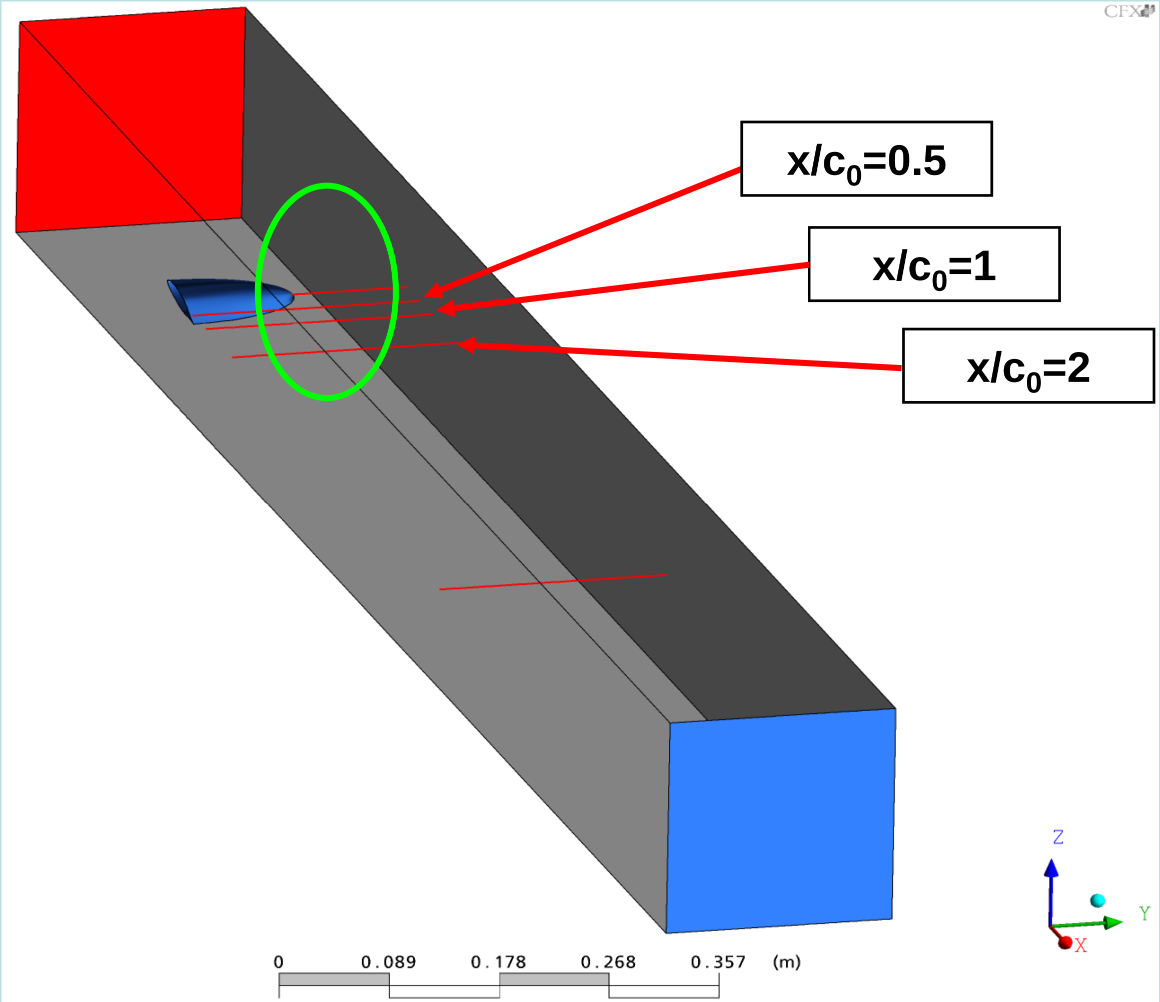
- Lift coefficient – Eff. angle of attack (α-α_0)
- Experiment: Re_c=9.2×10^5



Angle of zero lift	
Investigation	α [°]
Simulation	-2.6
Arndt (1992)	-2.5
Maines&Arndt (1997)	-2.7

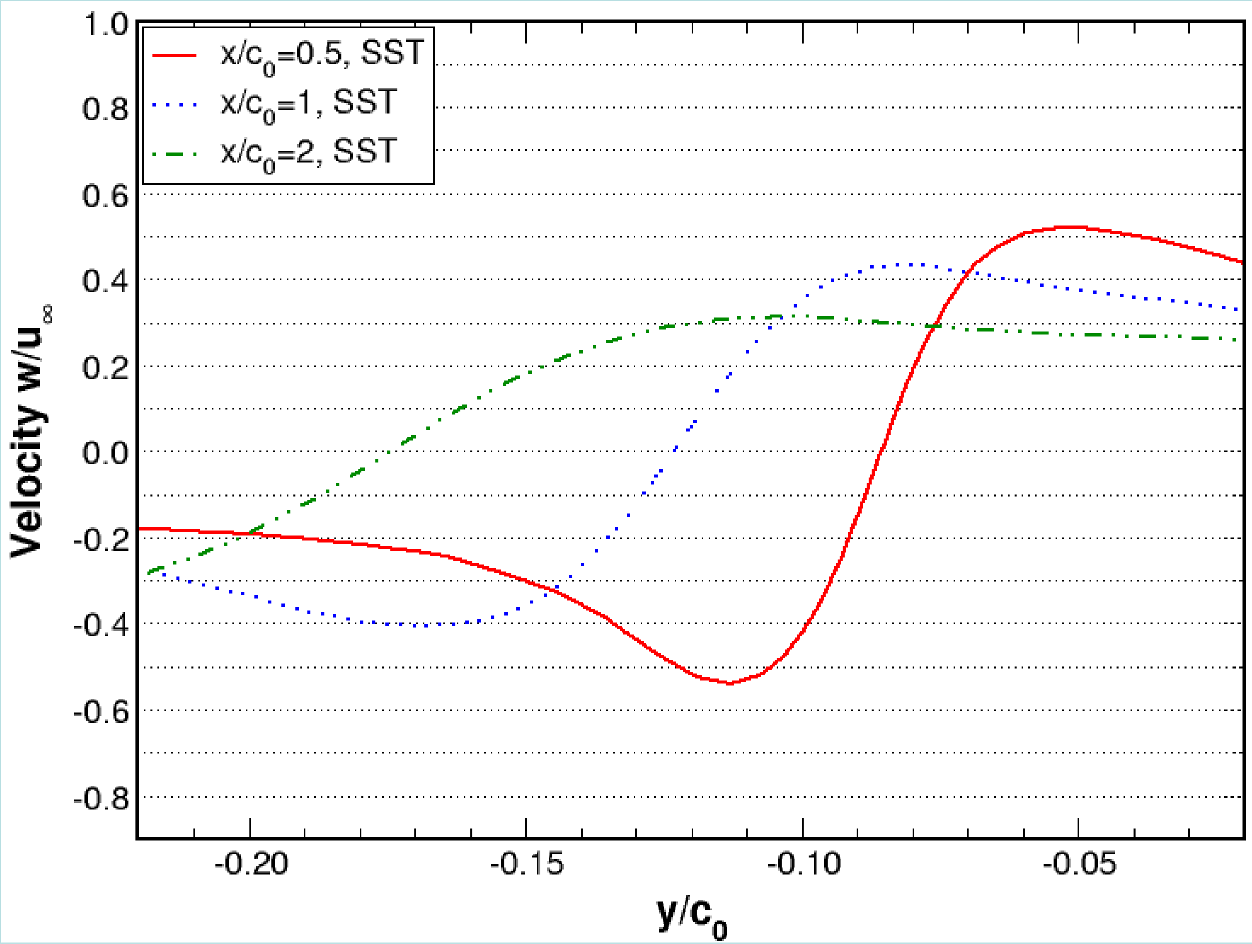
Tip vortex

- Cut planes



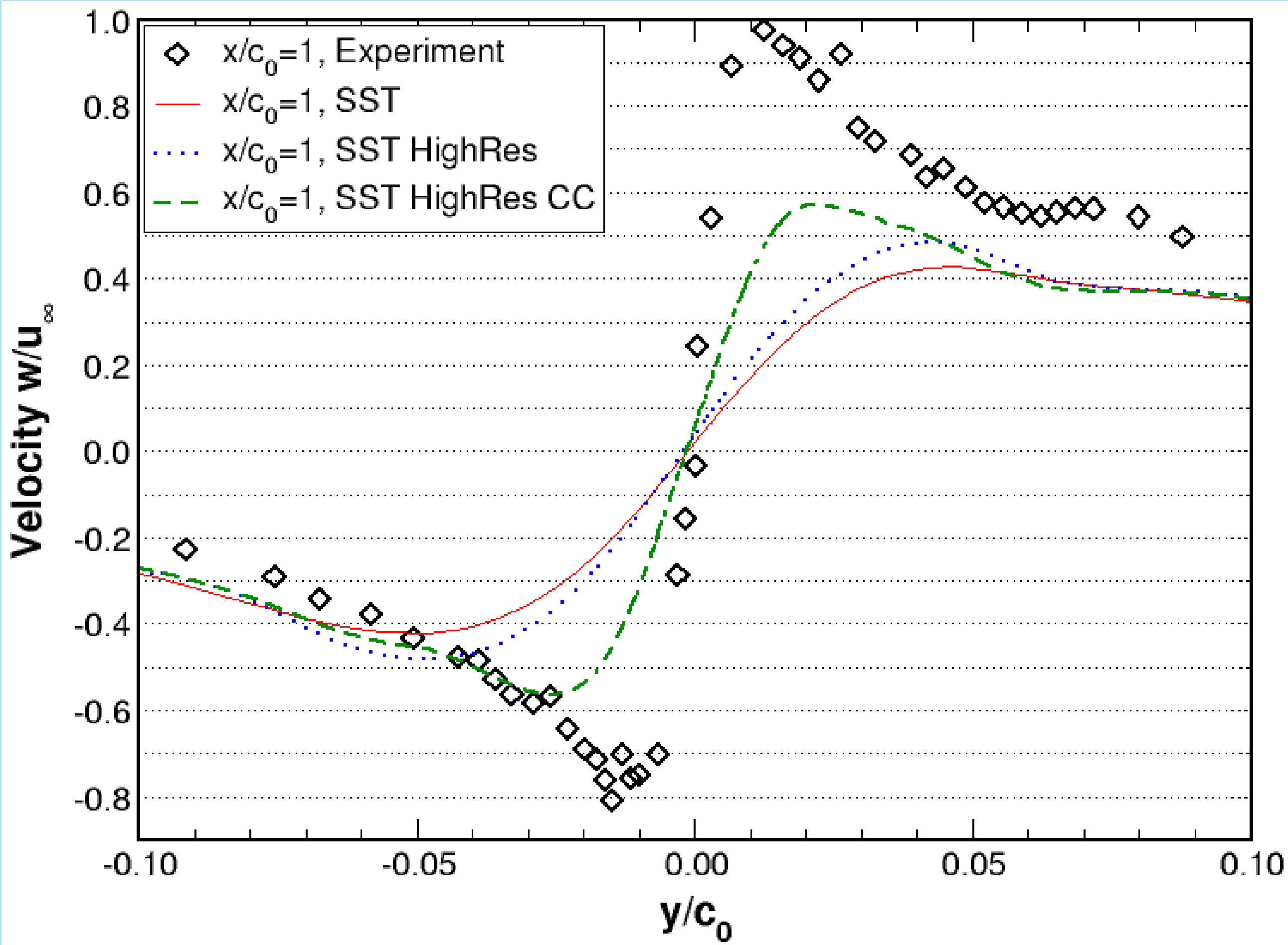
Tip vortex

- Medium(2) grid, α_{eff}=12°, Re=5.2×10^5
- Different cut planes, vortex deflection



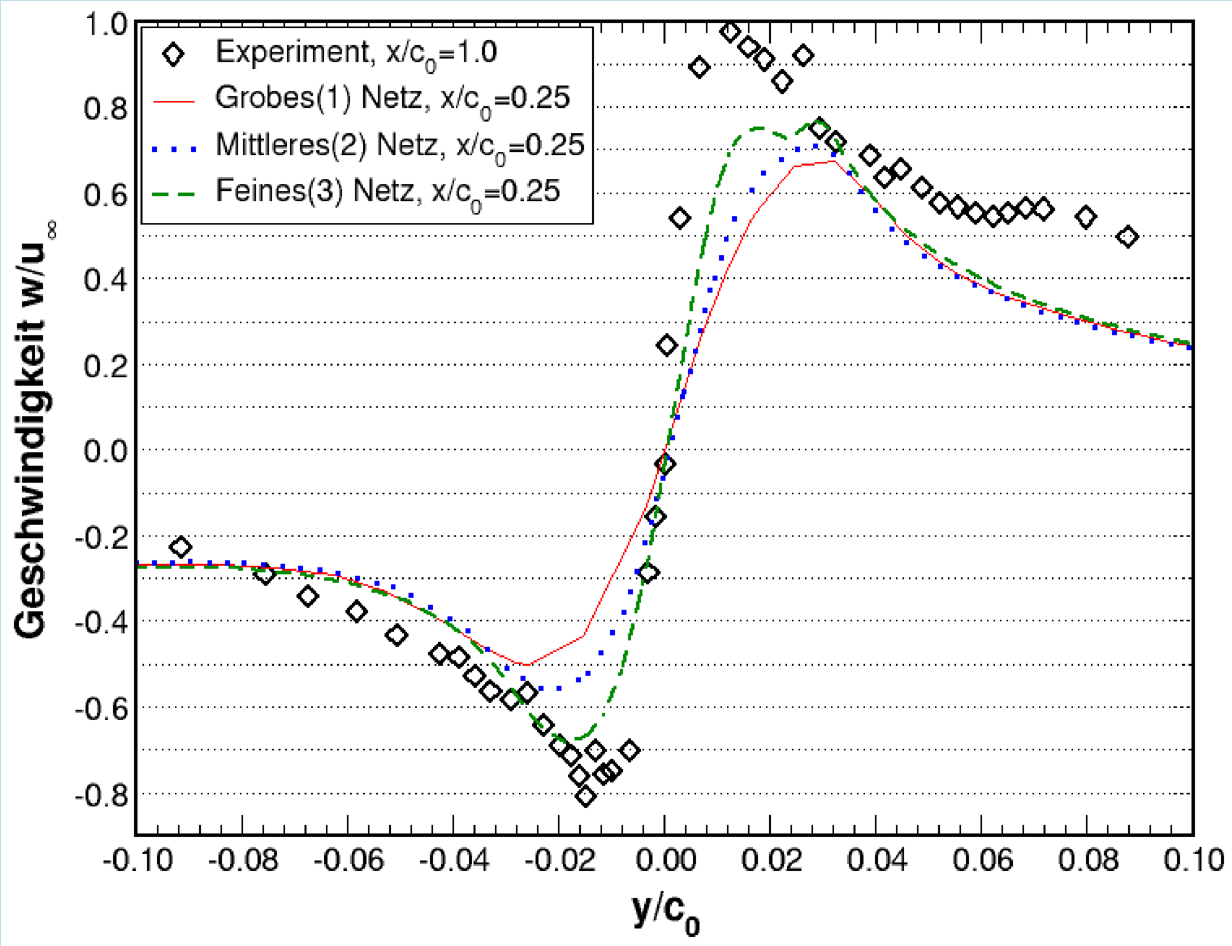
Tip vortex

- Fine(3) grid, α_{eff}=12°, Re=5.2×10^5
- Model comparison



Tip vortex

- All grids, α_{eff}=12°, Re=5.2×10^5
- Small distance to blade tip



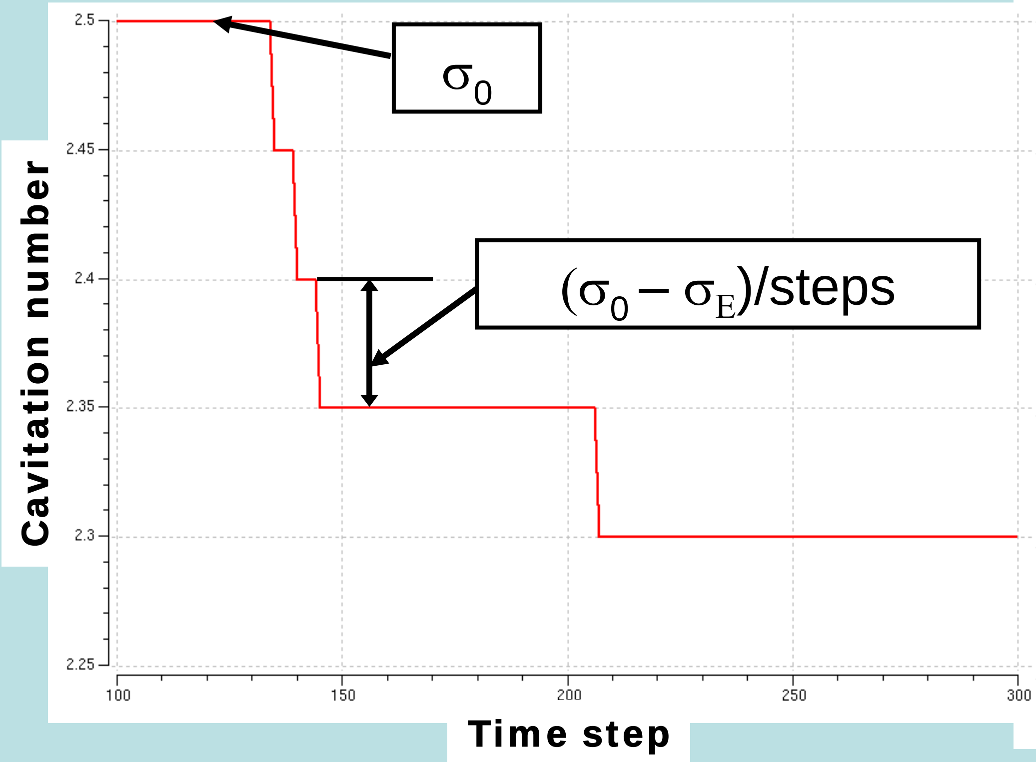
Cavitation inception

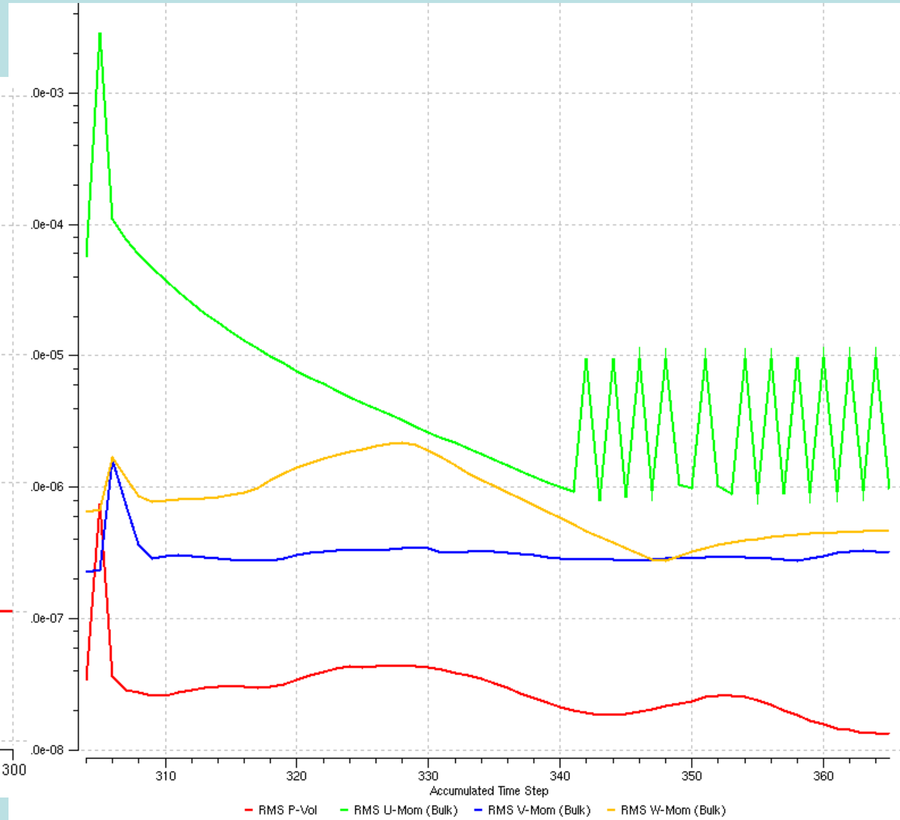
- Decrease of σ according to:

$$\sigma_{actual} = \sigma_0 - \frac{\sigma_0 - \sigma_e}{step\ number} \cdot i$$

evaluated by:

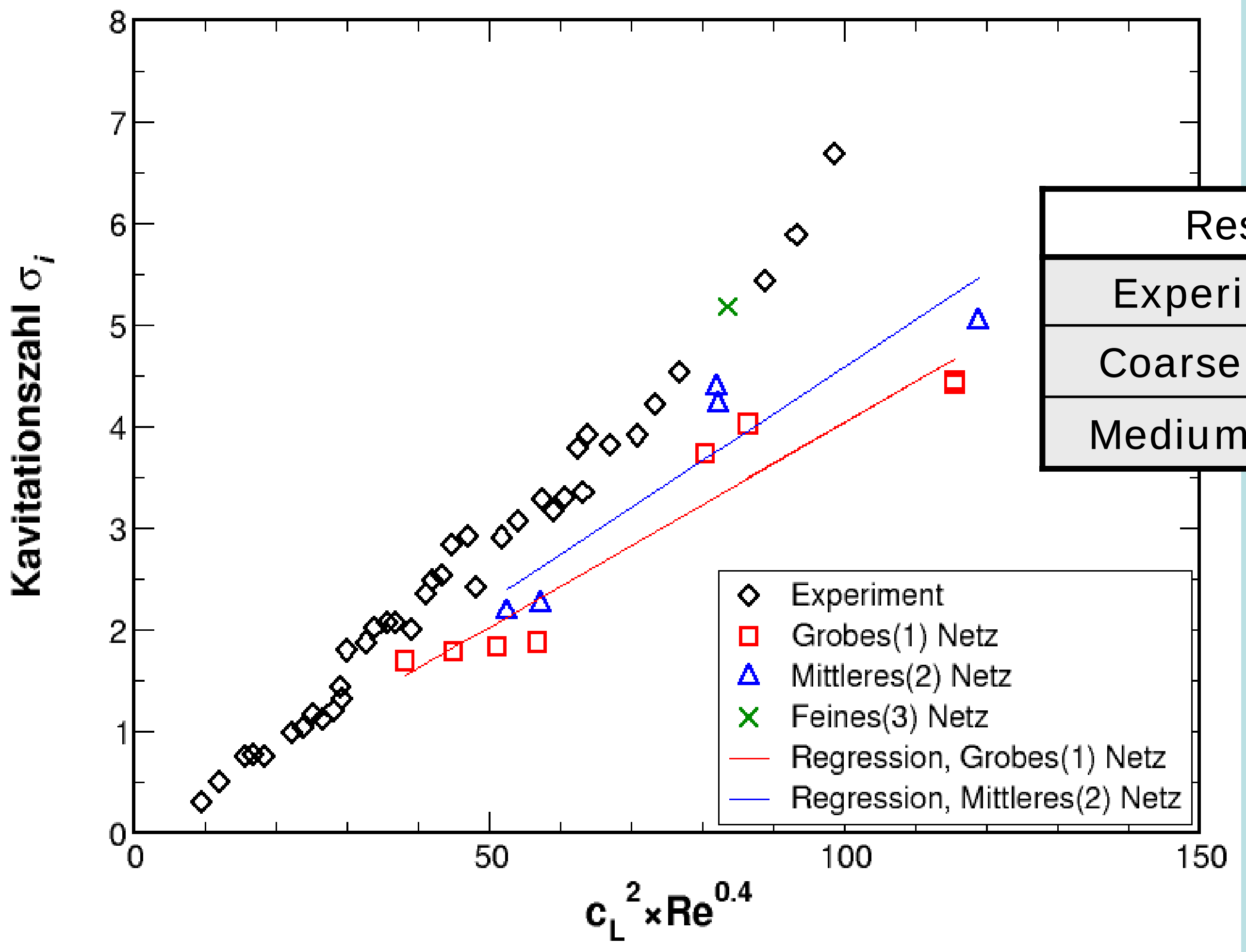
CEL Function





Cavitation Inception

- Results and experimental values



Result	k
Experimental	0.063
Coarse(1) grid	0.040
Medium(2) grid	0.046

Summary

- Two-dimensional test case
  - Phase transition modelled
  - Averaged pressure distributions in good accordance
  - Transient behaviour detected
- Outlook
  - More experimental data
    - Vapour clouds
    - Volume fraction
  - Separation regions on foil surface

Summary

- Threedimensional test case
  - Lift forces evaluated and compared (less grid influence)
  - Trailing vortex examined
  - Cavitation inception with single phase flow
- Outlook
  - Further grid refinement
  - Reynolds stress turbulence model
  - Pressure fluctuations

Thank you very much for your attention.