Simulation strömungsinduzierter Schwingungen eines rechteckigen Körpers

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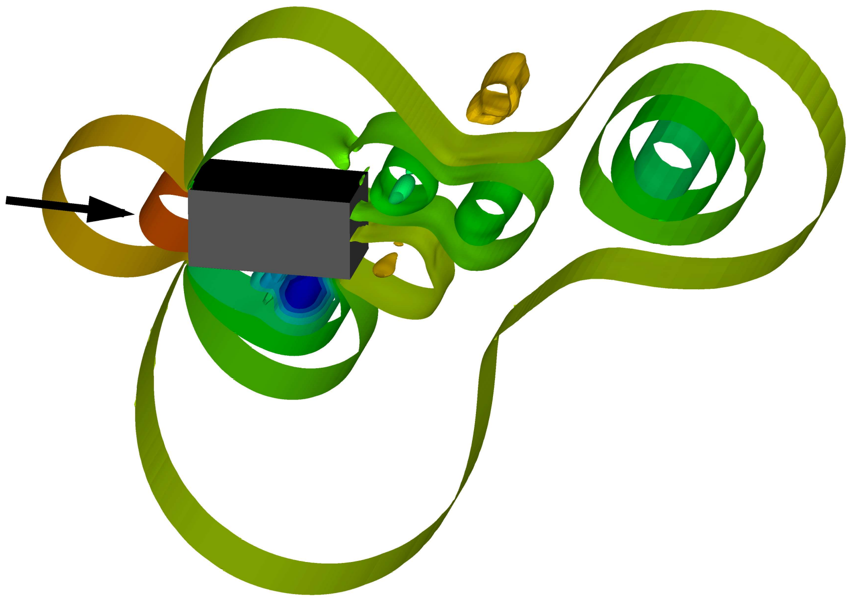
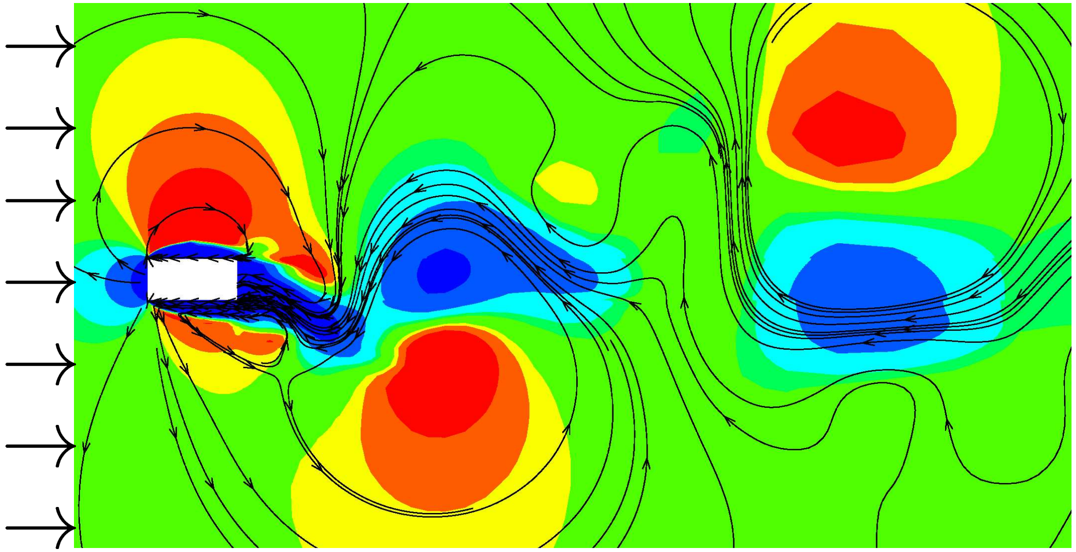


- Einleitung und Ziel der Simulationen
  - Beschreibung der physikalischen Vorgänge
  - Berechnung der Resonanz–Strömungsgeschwindigkeit mit validierten Methoden
  - Identifikation der (numerischen) Einflußparameter
  - Bewertung des URANS–Ansatzes (Experimentelle Daten)
- Wie wurde das erreicht? (Methode)
  - Simples Model, 2D/3D, URANS, DES (standard), explizite Kopplung
- Was wurde bis jetzt erreicht? (Ergebnisse)
  - Unbewegt 2D/3D, URANS, DES
  - Schwingend 2D, URANS
  - Vergleich mit Experimenten
- Zusammenfassung, Schlussfolgerungen und Ausblick
- Erste neue Ergebnisse, DES (Zwei–Gleichungs–Modell)



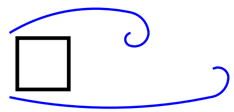
- Geometry of bluff body

  $L/H = 2$

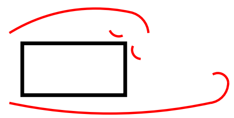
- High Reynolds number

  $Re = UH/\nu = 1 \cdot 10^4 \ldots 6 \cdot 10^4$

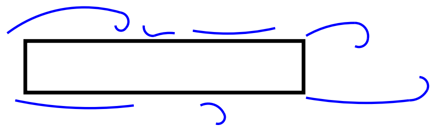
$\Rightarrow$ Vortex street



$\frac{L}{H} < 2$



$\frac{L}{H} \approx 2$



$\frac{L}{H} > 2$

Two dominant frequencies:

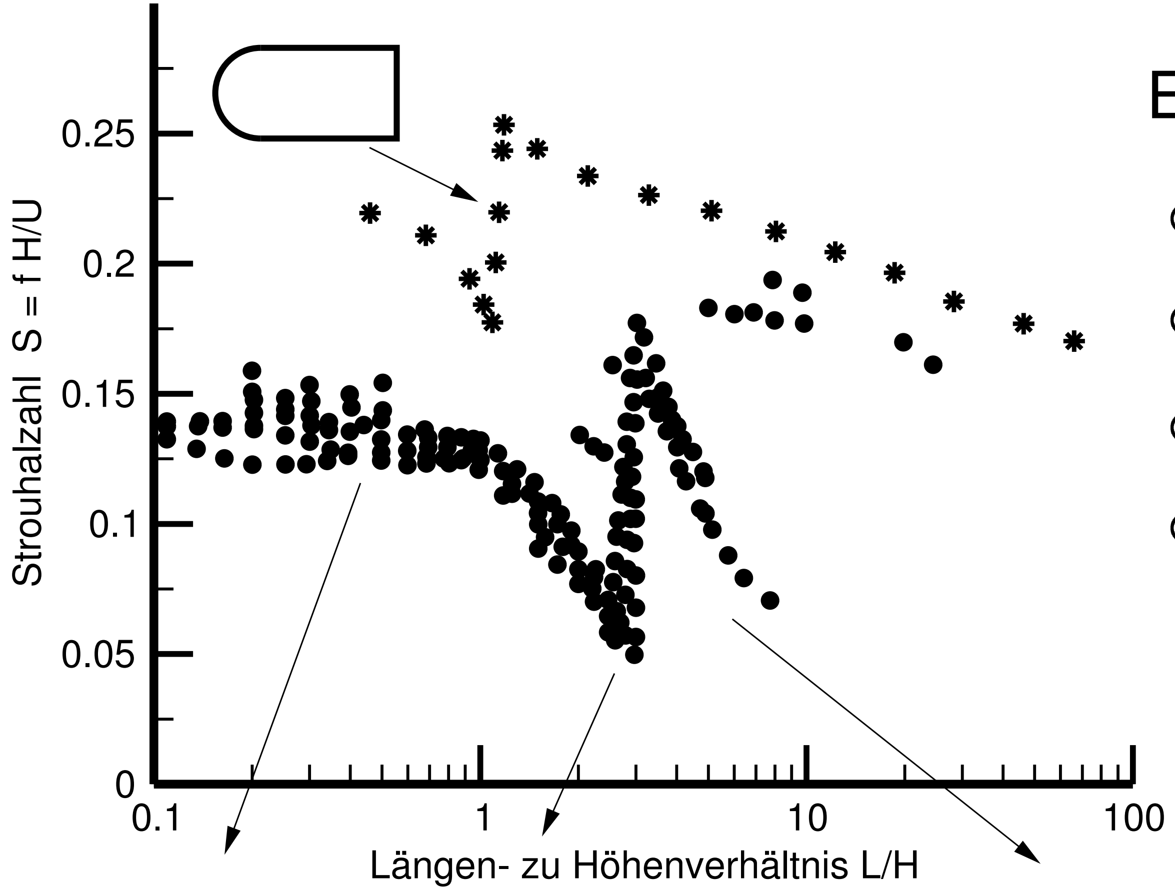
- Vortex shedding, f_S ($\frac{L}{H} < 2$)

  $St_S = f_S H/U$

- Vortex impingement, $f_I > f_S$

  $St_I = f_I H/U > St_S$

can cause resonance of free body



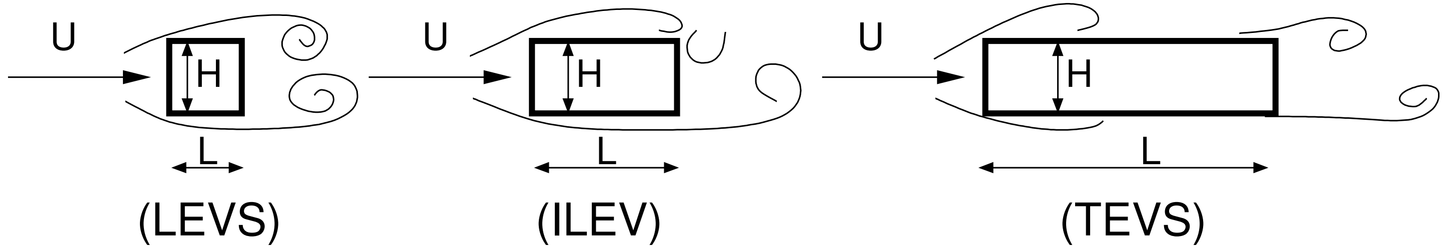
Experimentelle Daten

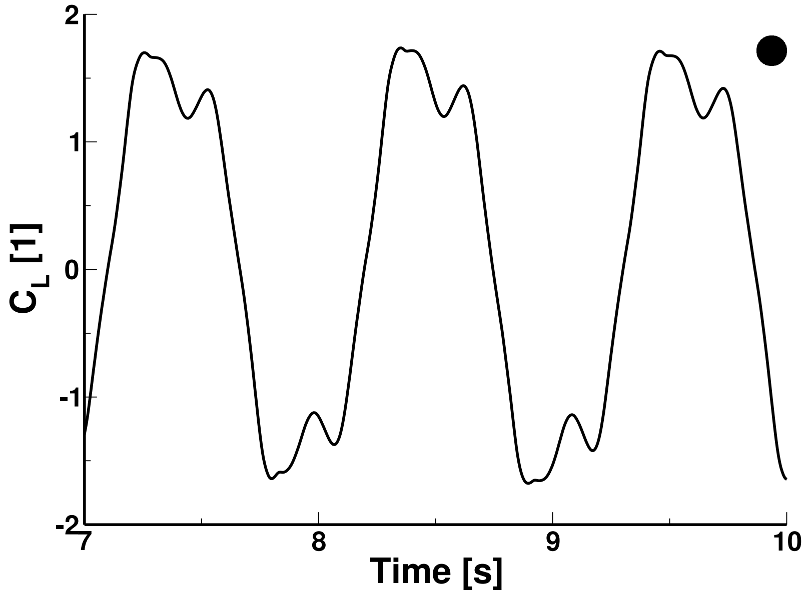
- Unbewegte Körper
- Re–Zahlen $\mathcal{O}(10^4 - 10^5)$
- LEVS und TEVS
- Indifferenter Zustand bei

  $\mathrm{L}/\mathrm{H} \approx 2 - \mathrm{L}/\mathrm{H} \approx 5$

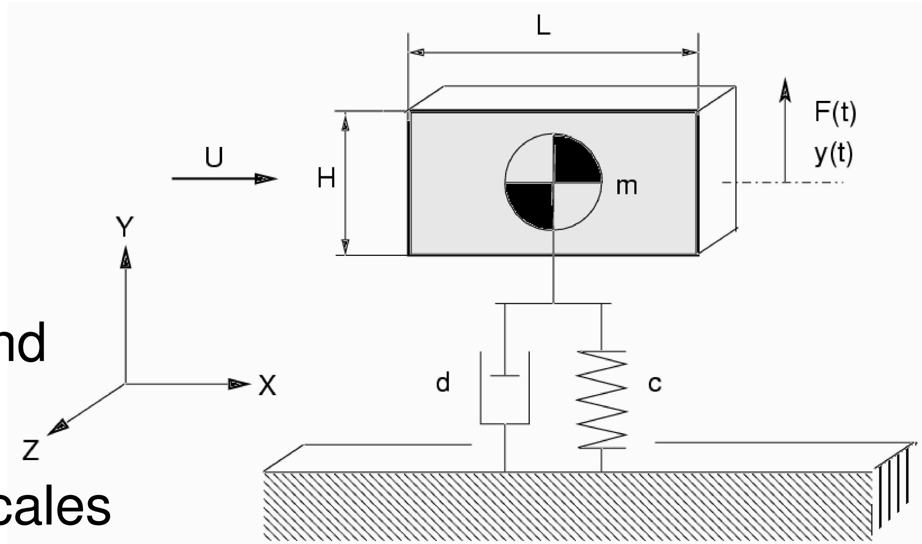
  Sprünge in S

  ILEV





- Compute two dominant frequencies and corresponding amplitudes
  - Vortex shedding
  - Leading–edge vortices
    impinging on the trailing edge ($\frac{L}{H} \approx 2$)



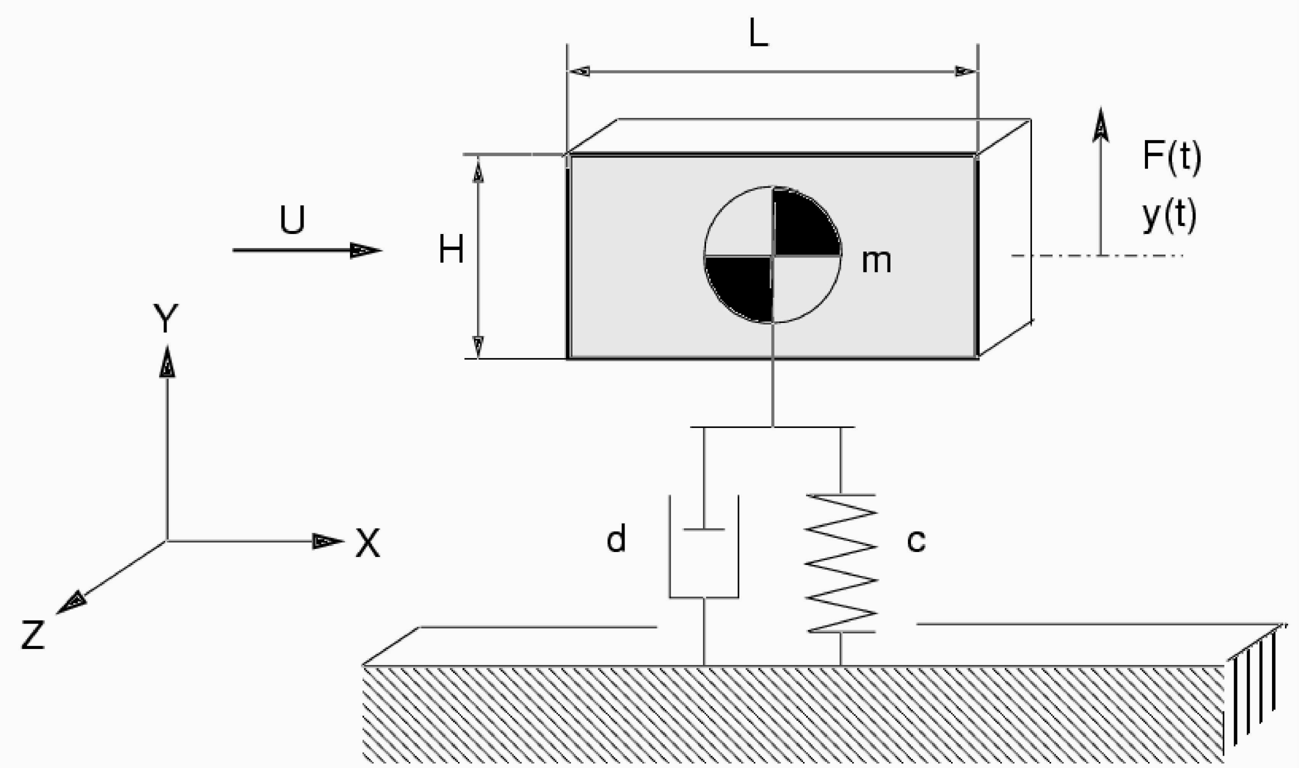
- Unsteady RANS
  - simple geometry, but complex flow and wide range of time and length scales
  - overlapping modeled and resolved scales
  - (standard) EVM usually too diffusive

- Oscillation differential equation (1 dof)

$$m\ddot{y} + d\dot{y} + cy = F$$

- Testcase data

  - $D = \dfrac{d}{4\pi m f_0} = 0.0032$
  - $f_0 = \frac{1}{2\pi}\sqrt{\frac{c}{m}} = 3.27\mathrm{Hz}$
  - $L/H = 2$
  - $Sc = 4Dm/(\rho_F HL) = 2.88$



- Discretization

$$y_{t+\Delta t} = f(y_{\Delta t}, y_{t-\Delta t}, y_{t-2\Delta t}, y_{t-3\Delta t}, F_t) + O(\Delta t^3)$$

- Analytical solution available for validation

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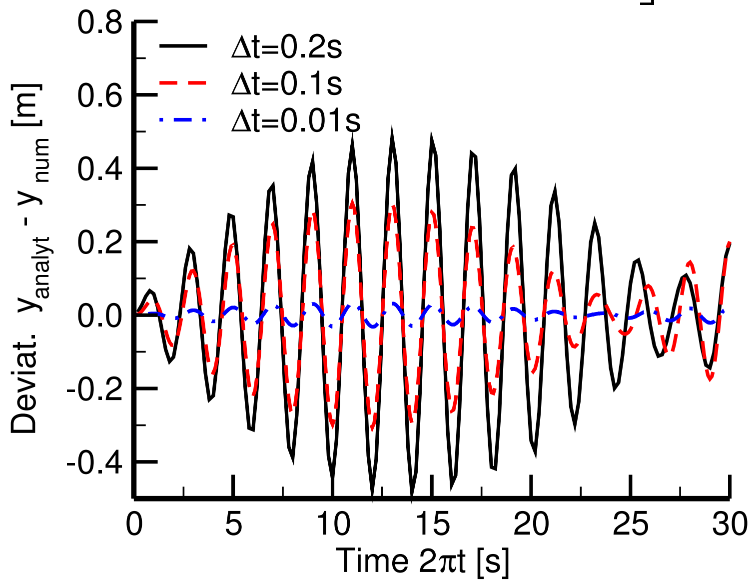
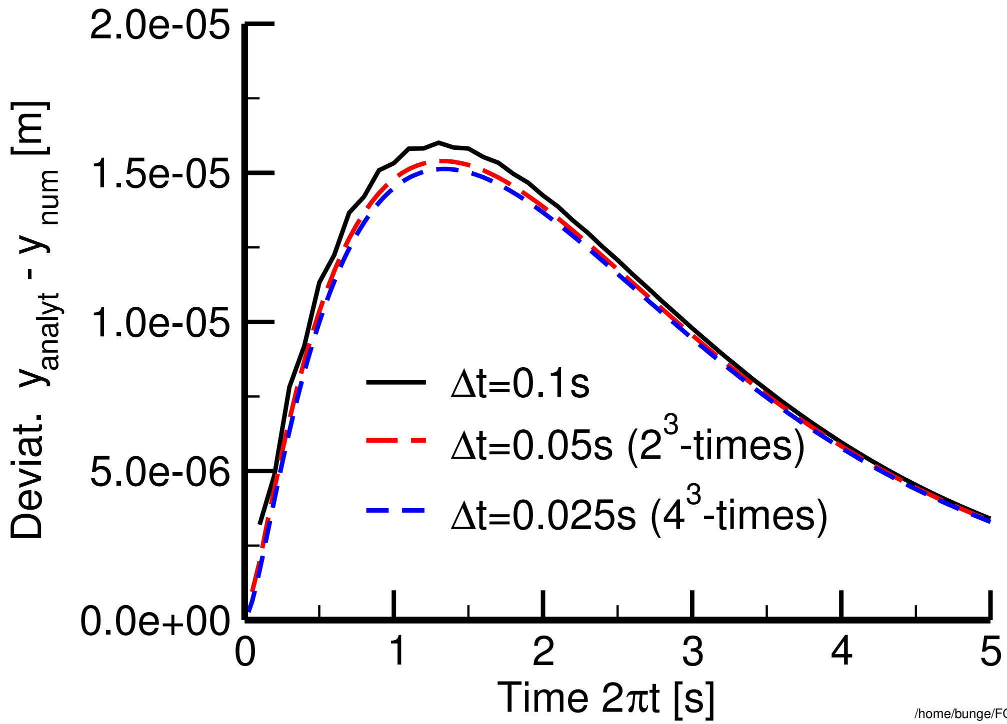
$$y(t) = Y[e^{-f_0 D t}\cos(f_D t + \varphi)] + A[\frac{1}{c}\alpha(\Omega)\cos(\Omega t - \delta(\Omega))]$$

- Discretized equation succesfully validated and tested

$$y_{m+1} = \frac{-1}{\left(\frac{11m}{12(\Delta t)^2} + \frac{d}{3\Delta t}\right)}\left[y_m\left(\frac{-5m}{3(\Delta t)^2} + \frac{d}{2\Delta t} + c\right) + y_{m-1}\left(\frac{m}{2(\Delta t)^2} - \frac{d}{\Delta t}\right) + y_{m-2}\left(\frac{m}{3(\Delta t)^2} + \frac{d}{6\Delta t}\right) - y_{m-3}\left(\frac{m}{12(\Delta t)^2}\right) - F_m\right]$$

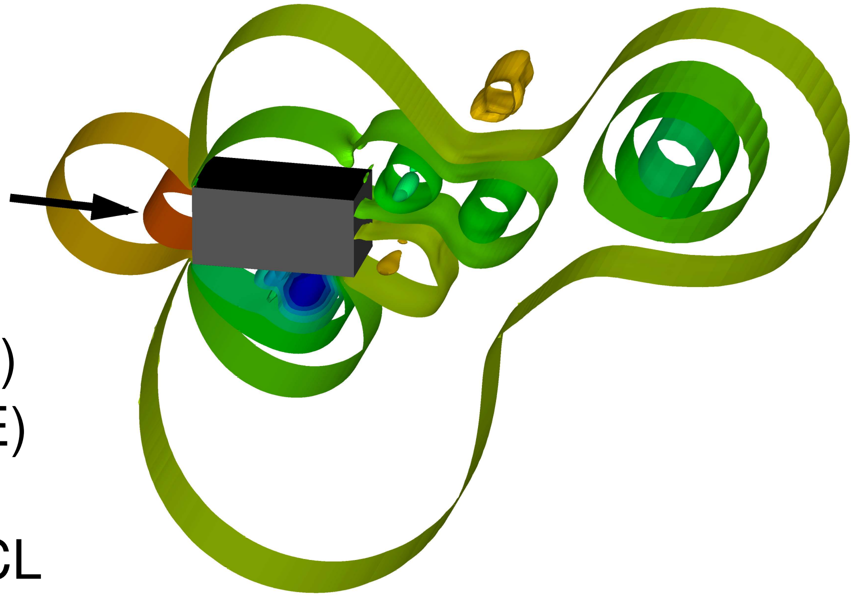




- Reynolds averaged Navier Stokes equations (ALE)

$$\int_V \frac{\partial U_i}{\partial t} dV + \oint_{\partial V} U_i (U_j - U_j^{\partial V}) \, dA_j = - \oint_{\partial V} \frac{P}{\rho} dA_i + \oint_{\partial V} \nu \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \overline{u_i' u_j'} \, dA_j$$

- Testcase data
  - $Re = UH/\nu = 1 \cdot 10^4 \ldots 6 \cdot 10^4$
  - incompressible, fully turbulent



- Numerics
  - Implicit FV method, cell-centered, semi block-structured (in-house code)
  - Pressure correction method (SIMPLE)
  - Conservative form in curvilinear, body-fitted coordinates employing SCL
  - Second order in space (TVD) and time
  - Variety of possibilities to treat turbulence

- Analytical solution not available

- Hybrider Ansatz aus RANS und LES
  - Detached–Eddy Simulation (DES)
  - Ersetzung des turbulenten Längenmaßes $l_{turb} = l_n$ oder $\frac{\sqrt{k}}{\omega}$ durch $MIN(l_{turb}\,; C_{DES}\Delta)$ im Dissipationsterm des Modells
  - Kalibrierung der Konstanten C_{DES} mittels DIT im LES Modus
  - Turbulenzmodell funktioniert wie SGS–Modell
  - Keine zusätzlichen Übergangsbedingungen ('gray area')
- Hybride Numerik
  - Hybrides Konvektionsschema (upwind basiert / zentral)
  - Kontinuerlicher Übergang durch Scherung und Rotation gesteuert
    CDS in Bereichen grosser Wirbelstärke
    UDS-basiert sonst (Wandnähe, Fernfeld)

→ Numerische Stabilität in Bereichen elementarer Strömung

→ Geringe numerische Diffusion in LES–Bereichen

Models rely on isotropic or linear eddy–viscosity principle

$$\overline{u_i'u_j'} = \frac{2}{3}k\,\delta_{ij} - \nu_t \underbrace{\left[\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \frac{2}{3}\frac{\partial U_k}{\partial x_k}\delta_{ij}\right]}_{=2S_{ij}}$$

Spalart & Allmaras Model transport equation

$$\frac{\partial \tilde{\nu}}{\partial t} + U_i \frac{\partial \tilde{\nu}}{\partial x_i} = c_{b1}\tilde{S}\tilde{\nu} + \frac{3}{2}\left[\frac{\partial}{\partial x_i}\left((\nu + \tilde{\nu})\frac{\partial \tilde{\nu}}{\partial x_i}\right) + c_{b2}\left(\frac{\partial \tilde{\nu}}{\partial x_i}\right)^2\right] - (c_{w1}f_w)\left(\frac{\tilde{\nu}}{l}\right)^2$$

with

$$\tilde{S} = S\left(\frac{1}{X} + f_{v1}\right), \quad S = \sqrt{2S_{ij}S_{ij}}, \quad f_w = g\left[\frac{1+c_{w3}^6}{g^6 + c_{w3}^6}\right]^{\frac{1}{6}}, \quad g = r + c_{w2}(r^6 - r),$$

$$c_{b1} = 0.1355, \quad c_{b2} = 0.622, \quad c_{w1} = \frac{c_{b1}}{\kappa^2} + \frac{(1+c_{b2})}{\sigma}, \quad \kappa = 0.41,$$

$$r = \tanh\left(\frac{\tilde{\nu}}{\kappa^2 l^2 \tilde{S}}\right)/\tanh(1), \quad c_{w2} = 0.3, \quad c_{w3} = 2, \quad \sigma = \frac{2}{3}.$$

SALSA Model: modified production term, c_{b1} enhanced/dependent on strain rate, sensitized to non–equilibrium effects, reduction of production for excessive strain rates

Based on transport equation for turbulent kinetic energy k

$$\frac{\partial k}{\partial t} + \frac{\partial U_i k}{\partial x_i} = P_k - \beta_k \omega k + \frac{\partial}{\partial x_i}\left(\left(\nu + \frac{\nu_t}{2}\right)\frac{\partial k}{\partial x_i}\right)$$

and for turbulent frequency ω

$$\frac{\partial \omega}{\partial t} + \frac{\partial U_i \omega}{\partial x_i} = P_\omega - \beta_\omega \omega^2 + \frac{\partial}{\partial x_i}\left(\left(\nu + \frac{\nu_t}{2}\right)\frac{\partial \omega}{\partial x_i}\right).$$

Both models:

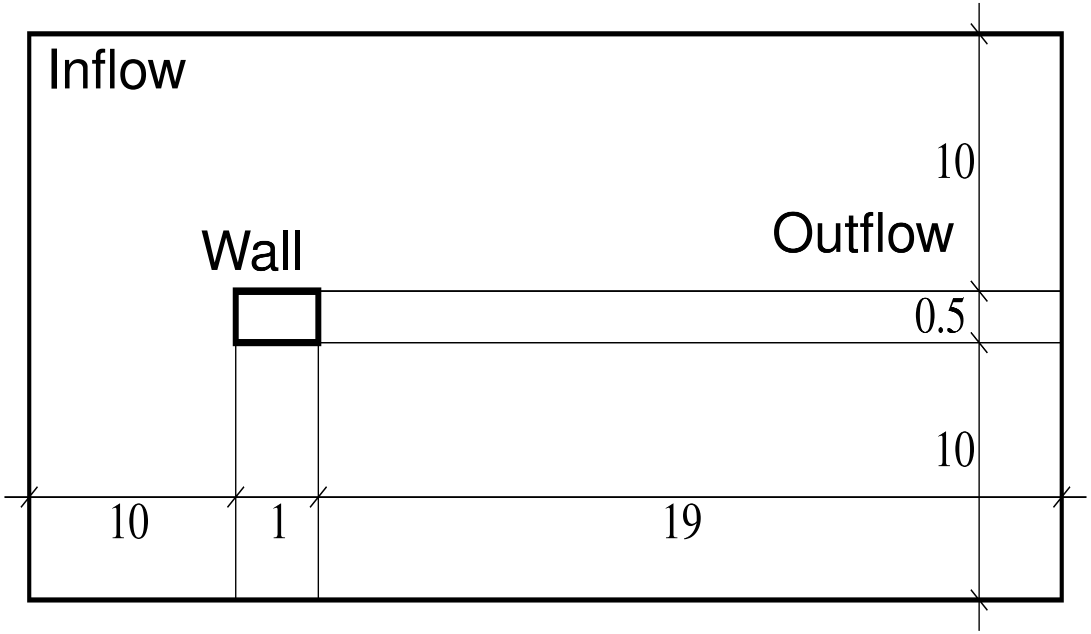
$$\nu_t = c_\mu \frac{k}{\omega}.$$

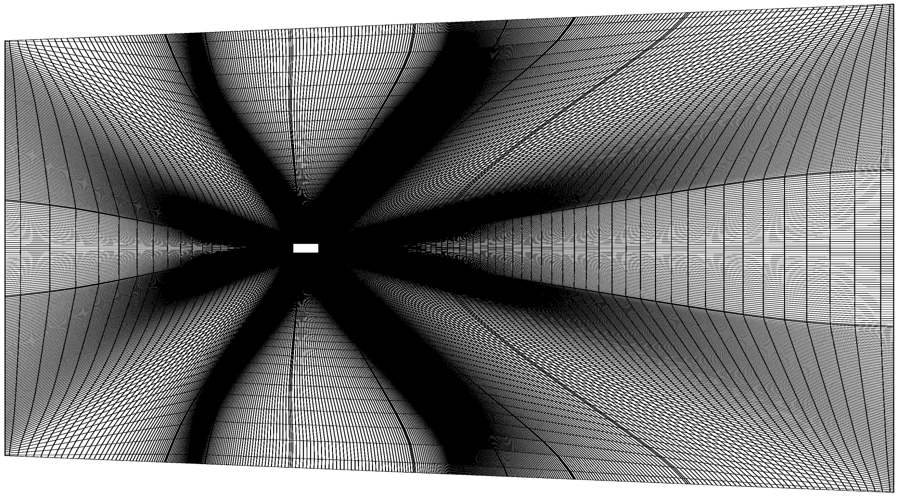
Models differ in constants β and representation of production terms

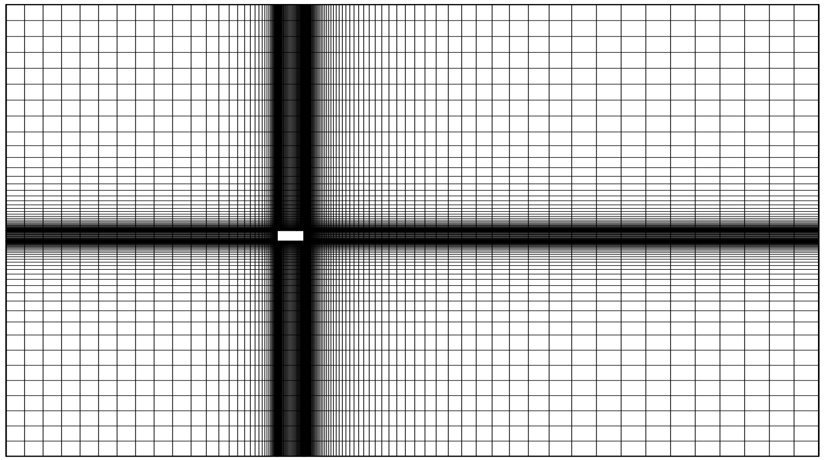
$$P_k = c_\mu \frac{k}{\omega} S^2 \quad \text{and} \quad P_\omega = \alpha S^2$$

<u>LLR $k - \omega$ Model</u>: c_μ, α determined in different ways, local linear, derived from realizability and non-equilibrium constraints, coefficients of stress–strain relation and transport equations are functions of non-dimensional invariants of mean strain and vorticity rates. (approach tries to accomplish consistent stress–strain distributions not only in plane shear flow, but also in more general flow situations)

- Different 2D grids
  $20,000$ to $80,000$ volumes
  rectangular, curved, ...
- Different 3D grids, $\Delta z = 1, 2$
  extended 2D grid, 10-40 levels
  up to $\sim 9,000,000$ volumes
- $Y^+(i_n = 1) = l_n \sqrt{\frac{1}{\nu} \frac{\partial U_t}{\partial Y_n}} \leq 1$





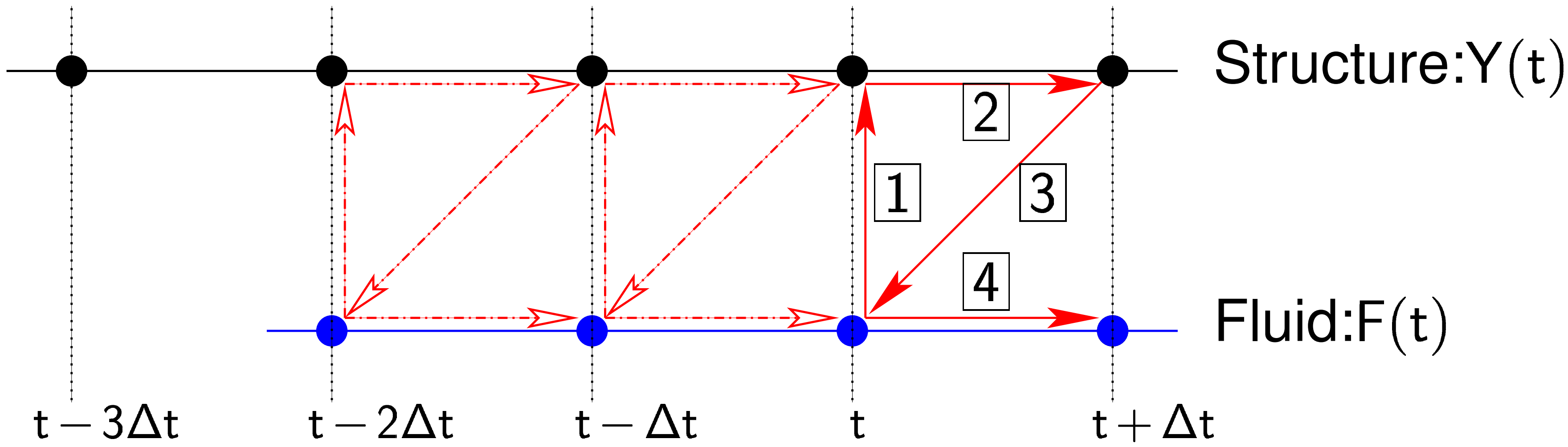


- Explicit, loose coupling
- First order in time

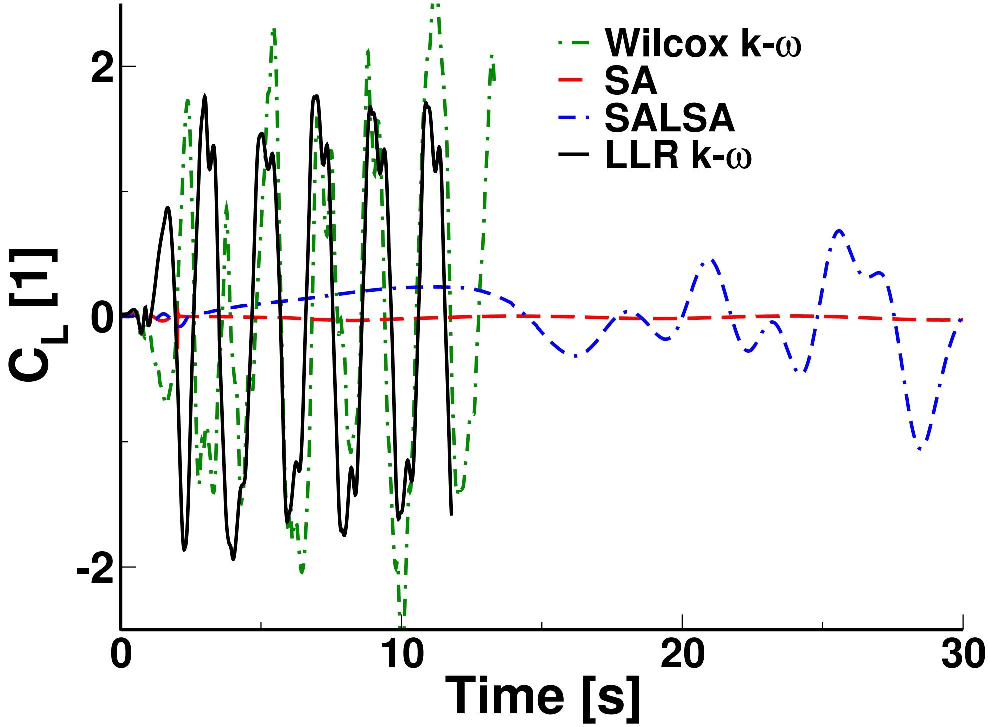
  although single procedures are of higher order
- Sufficient in this case

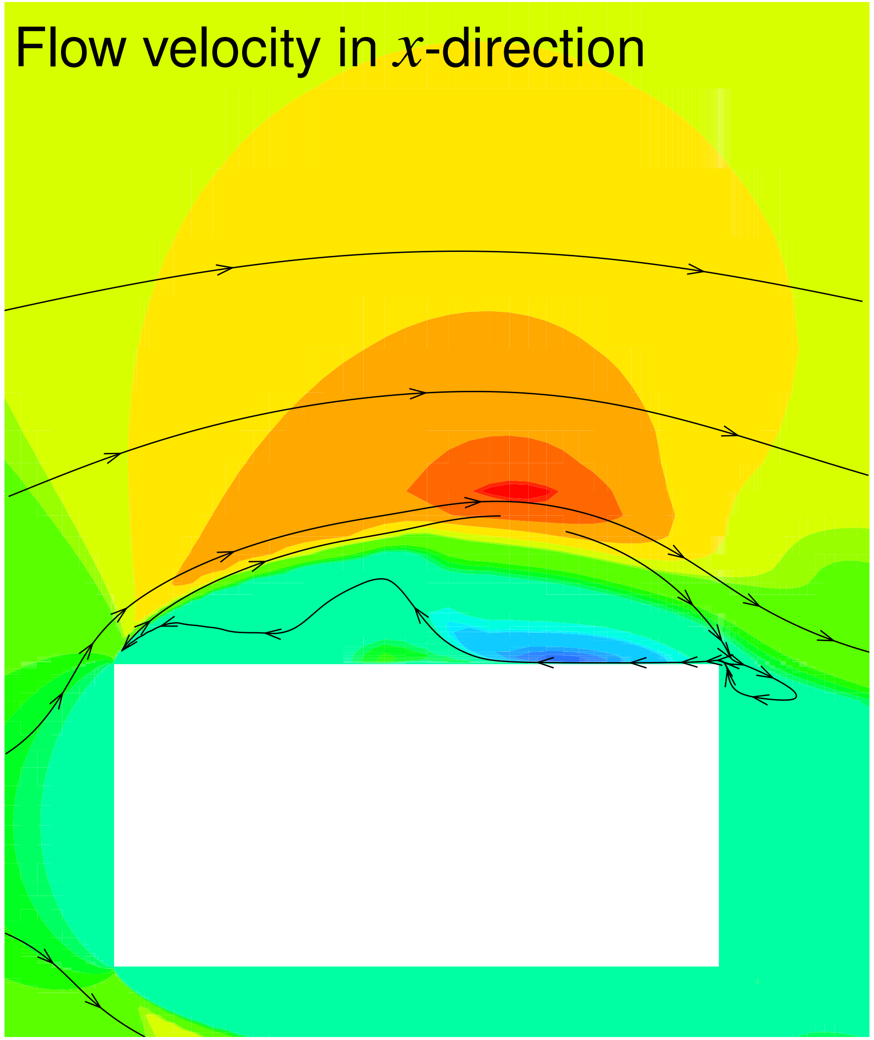
  small time step required for flow solution

  $T_S/\Delta t \geq 200$

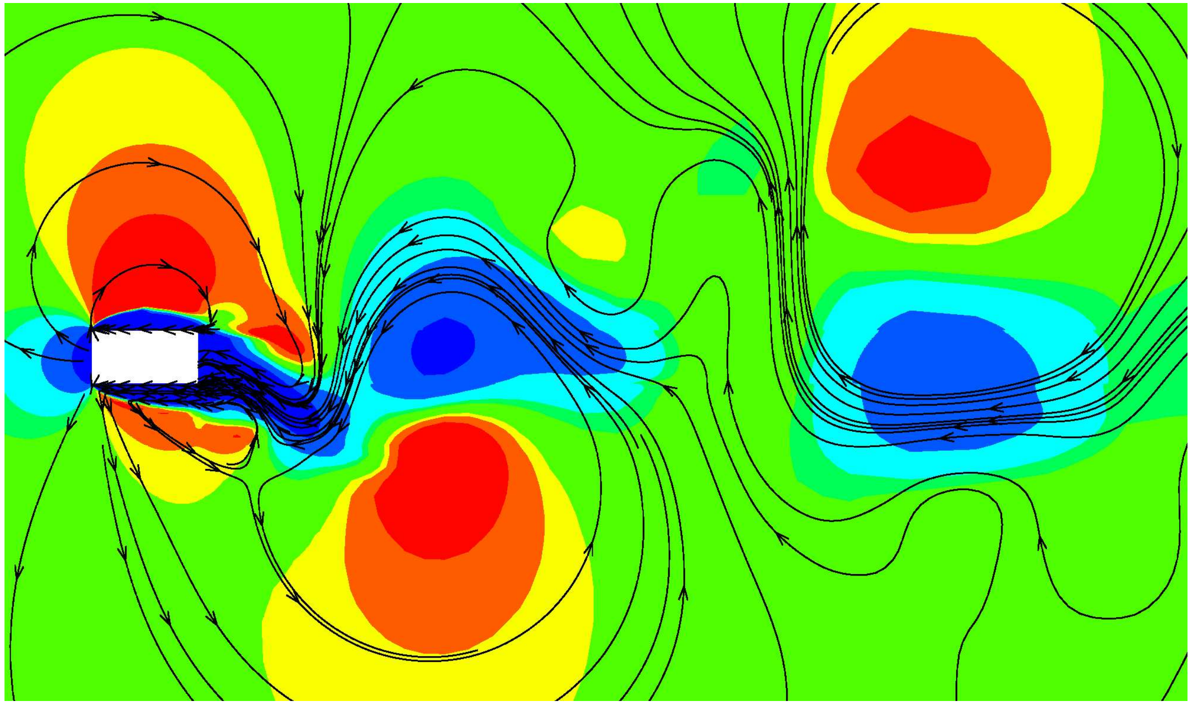


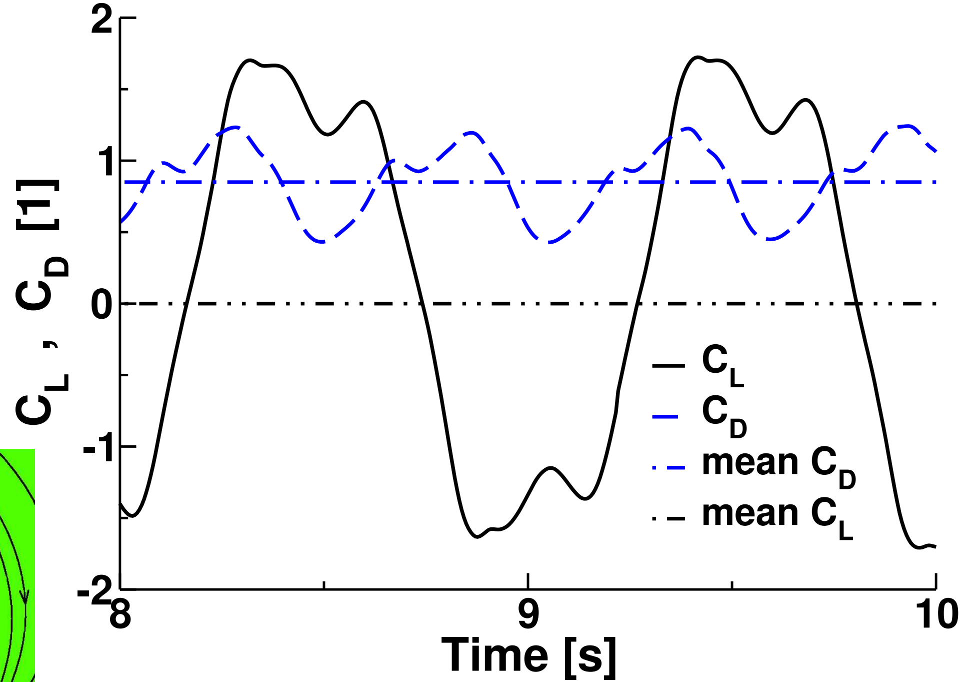
- Turbulence models
  - SA and SALSA
  - Wilcox k-ω and LLR k-ω





- Vortex shedding occurs
- Mean lift vanishes
- Agreement with experiments (excpet for frequencies)





- Mean $C_D \approx 0.85$
- Max drag = Max lift
- Min drag = dent in lift due to recirculation

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RESULTS – STATIONARY BODY 2D / 3D II

FLOW–INDUCED OSCILLATIONS OF A BLUFF BODY

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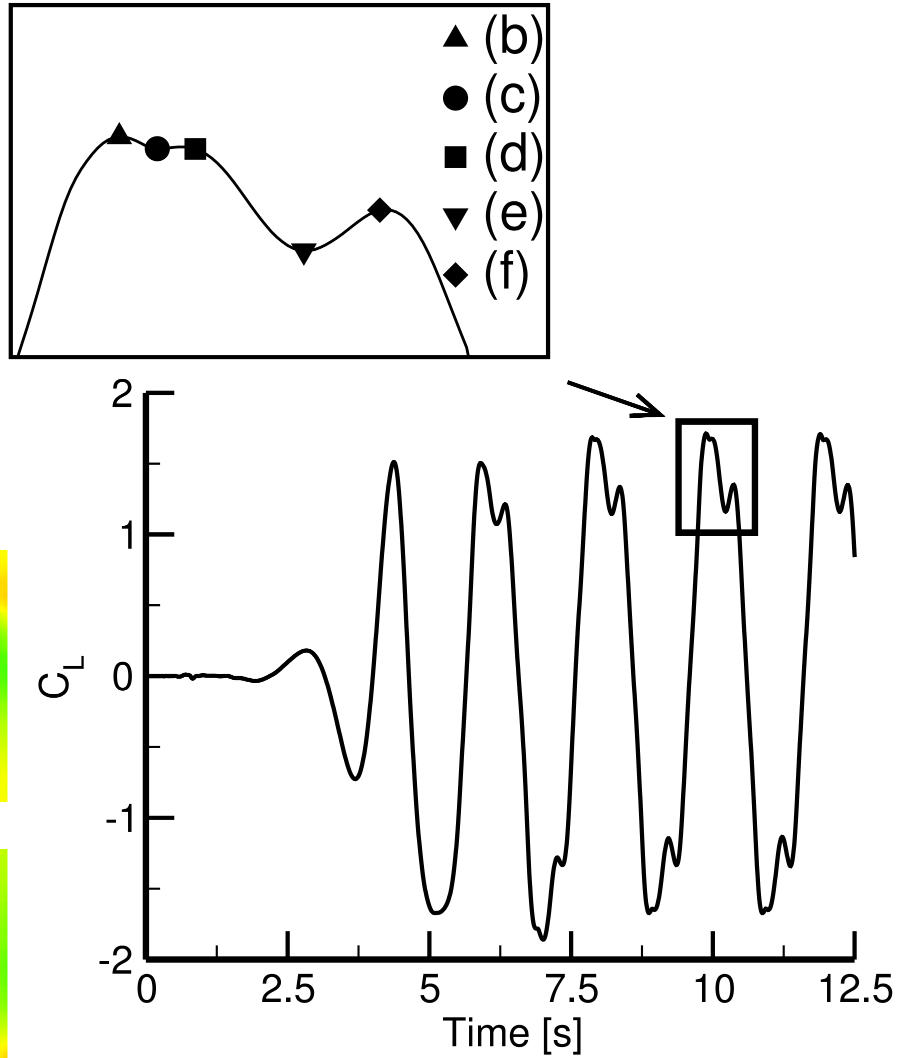
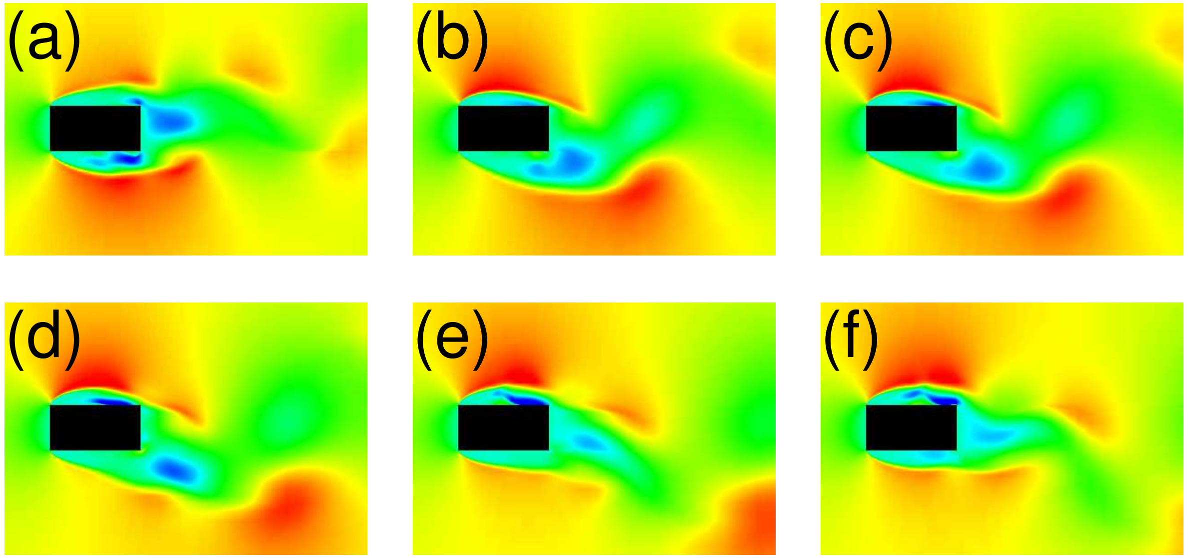
- (a) close to zero lift
- (b) maximum lift
- (c) - (e) trailing edge interference
- (f) disturbed vortices





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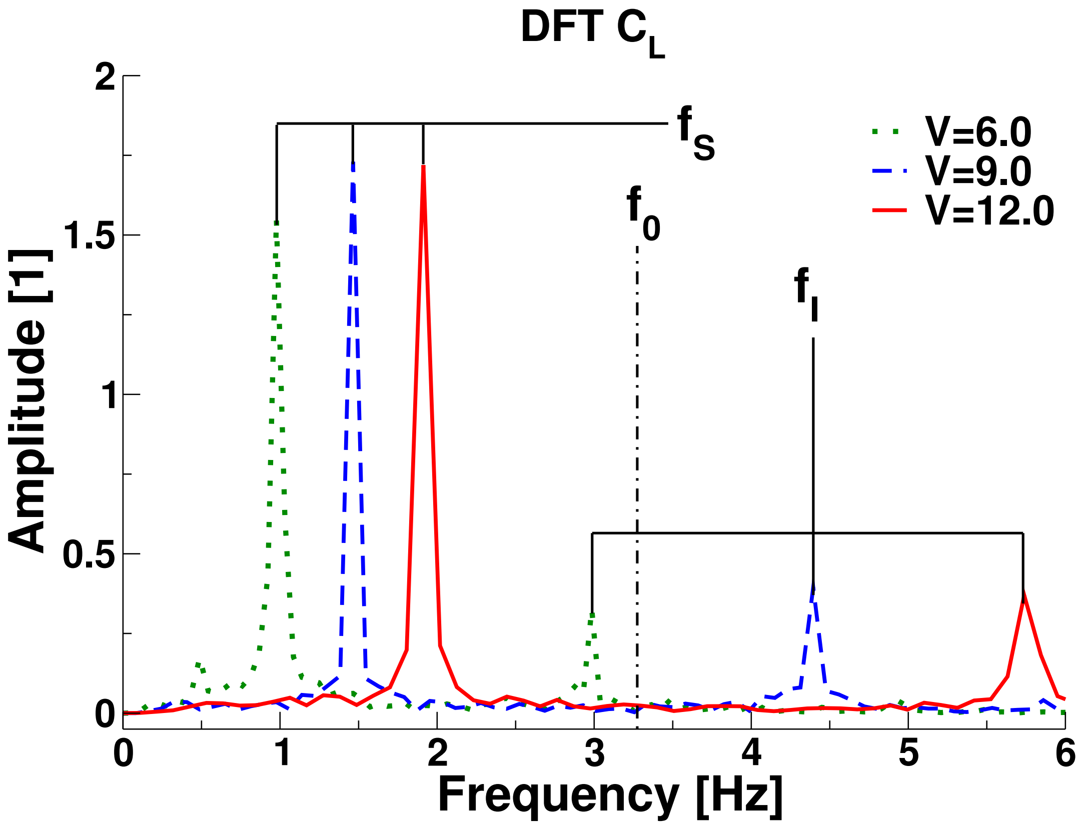
- Resonance possible
  - $f_0 = f_S \qquad V = \frac{Uf_0}{H} = \frac{1}{St_S}$
  - $f_0 = f_l \qquad V = \frac{1}{St_l} < \frac{1}{St_S}$
- Experimental results
  - $St_S \simeq 0.08$
  - $V = 5.5$ first resonance
- Numerical results
  - $St_S \simeq 0.06$
  - Variation of

    grid: 2D 80,000 CV

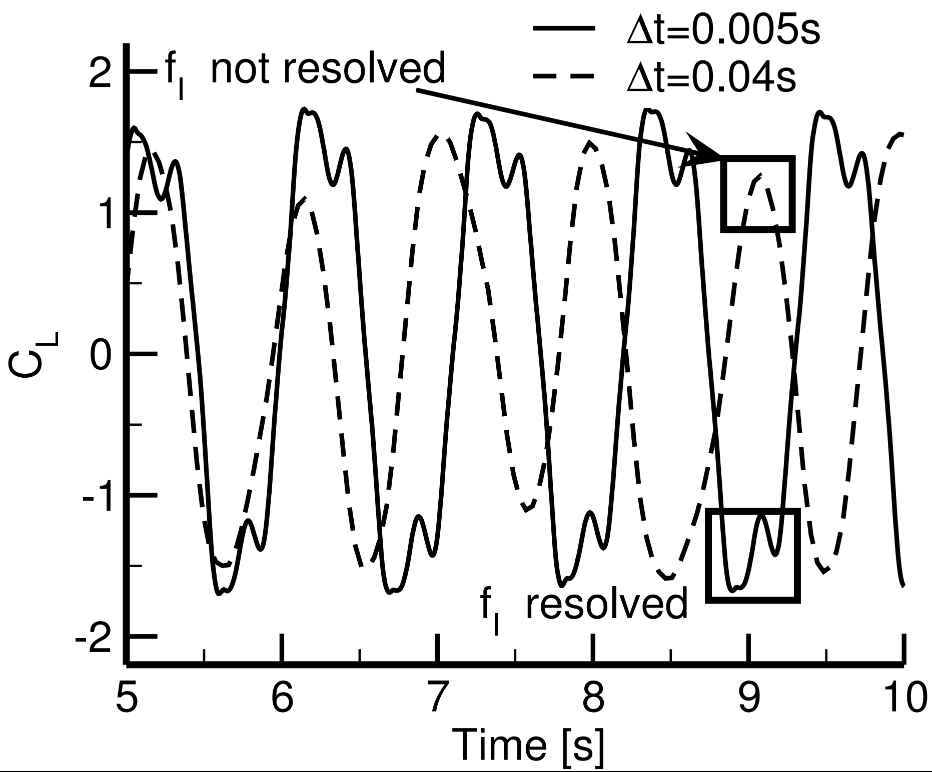
    time step: 0.015s (V=3.0) $> \Delta t_{dim} >$ 0.0015s (V=18.0)

    turbulence model: EVM only, one– and two–equation models



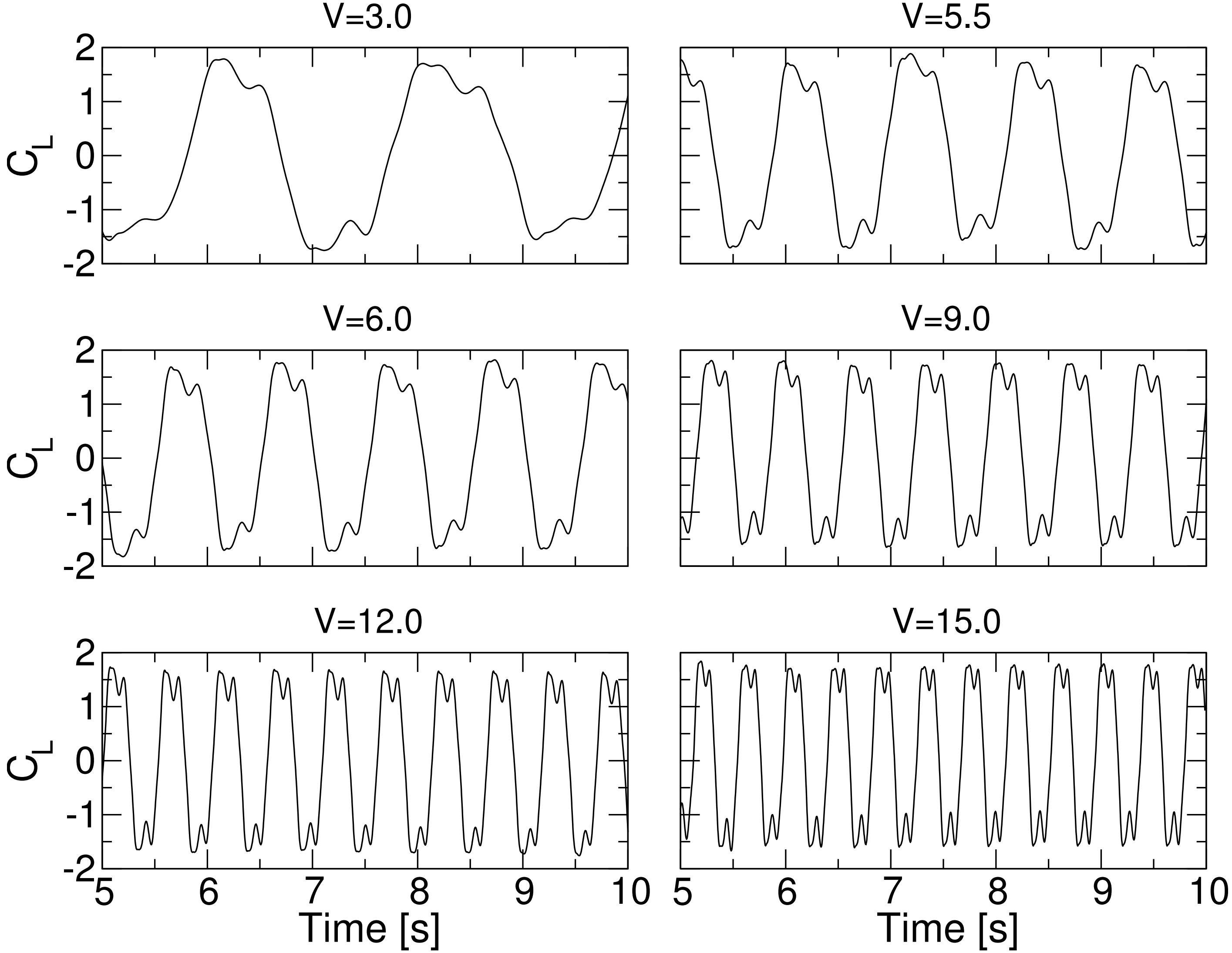
Parameters evaluated

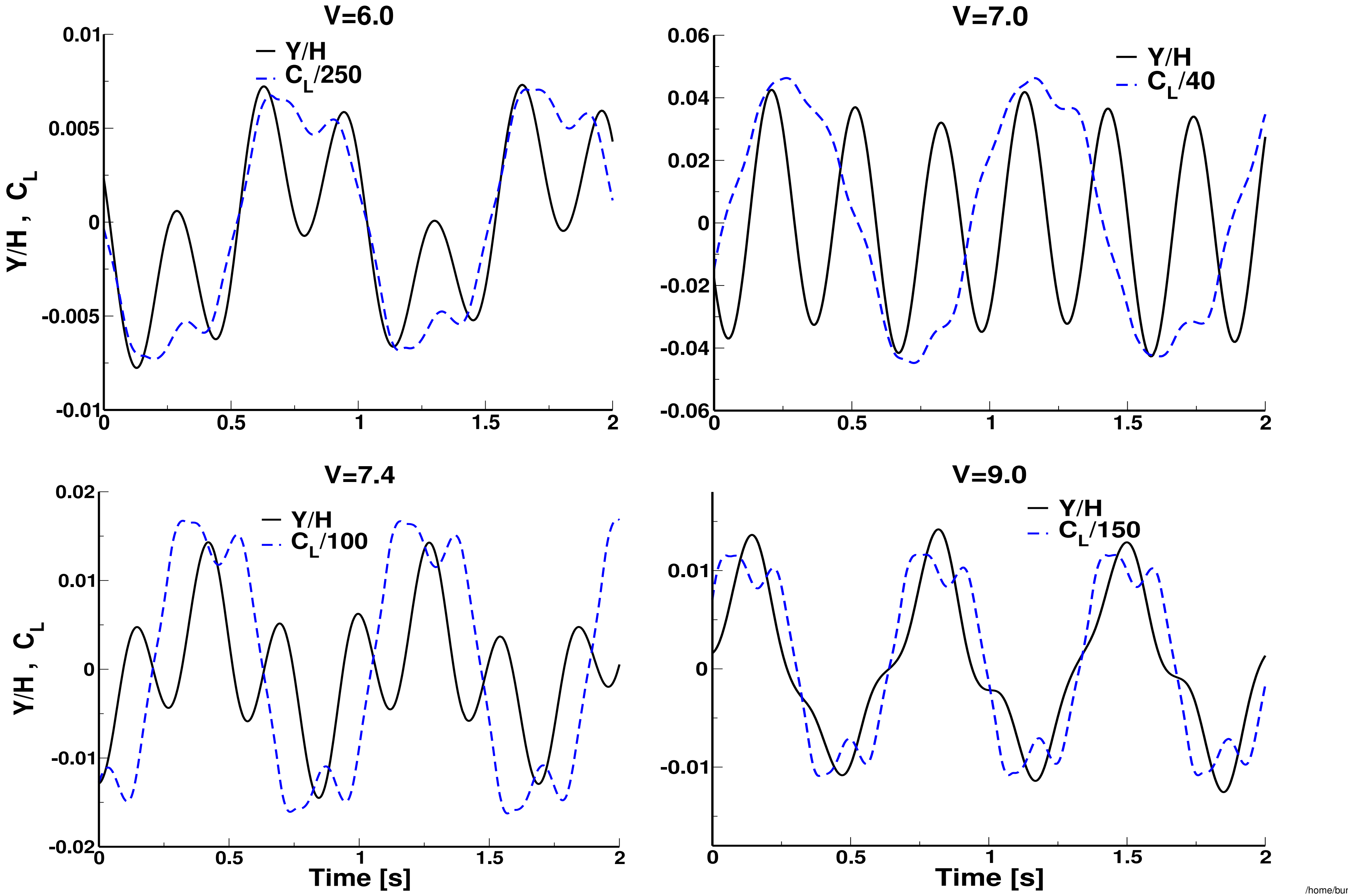
- Numerics
  - Temporal resolution →
    (Conclusion: $\Delta t \frac{U}{H} = \text{const}$)
  - Spatial resolution
  - Convection scheme
  - Convergence criteria
  - Relaxation
  - Coupling of equations
  - . . .
- Physics
  - Treatment of turbulence
  - Boundary conditions



$V = \frac{U}{Hf_0} =$	3.0		5.5		15.0	
$\Delta t_{dim}[s]$	$\Delta t \frac{U}{H}$	S	$\Delta t \frac{U}{H}$	S	$\Delta t \frac{U}{H}$	S
0.005	0.05	0.055	0.092	0.053	0.25	0.057
0.01	0.1	0.055	0.183	0.050	0.5	0.055
0.02	0.2	0.057	0.366	0.061	1.0	0.054
0.04	0.4	0.062	0.732	0.067	2.0	0.033

- Bewegung: Keine Änderung im Auftriebsverlauf (?)





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RESULTS – MOVING BODY 2D II

FLOW–INDUCED OSCILLATIONS OF A BLUFF BODY

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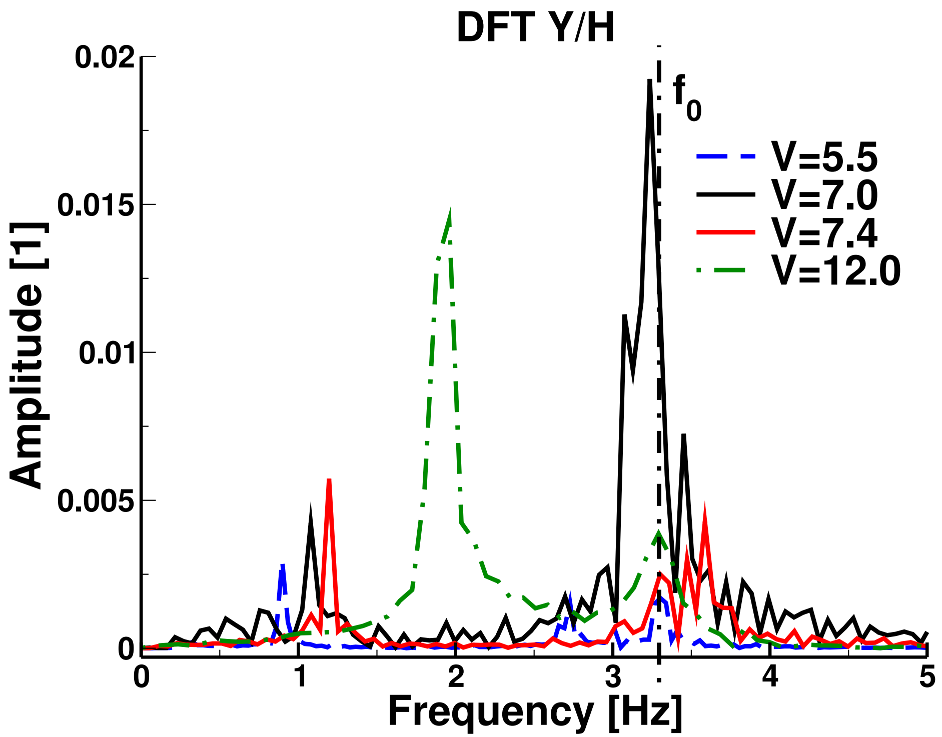
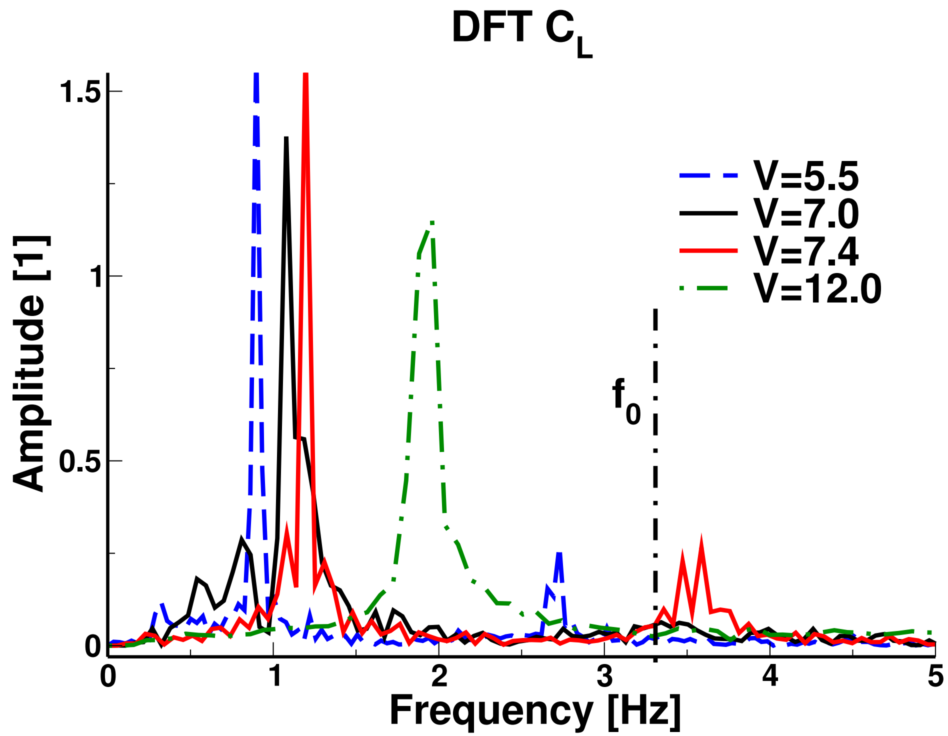


⇒ Excitation reveals peak value

Resonance flow velocity:

$V \approx 7.0$

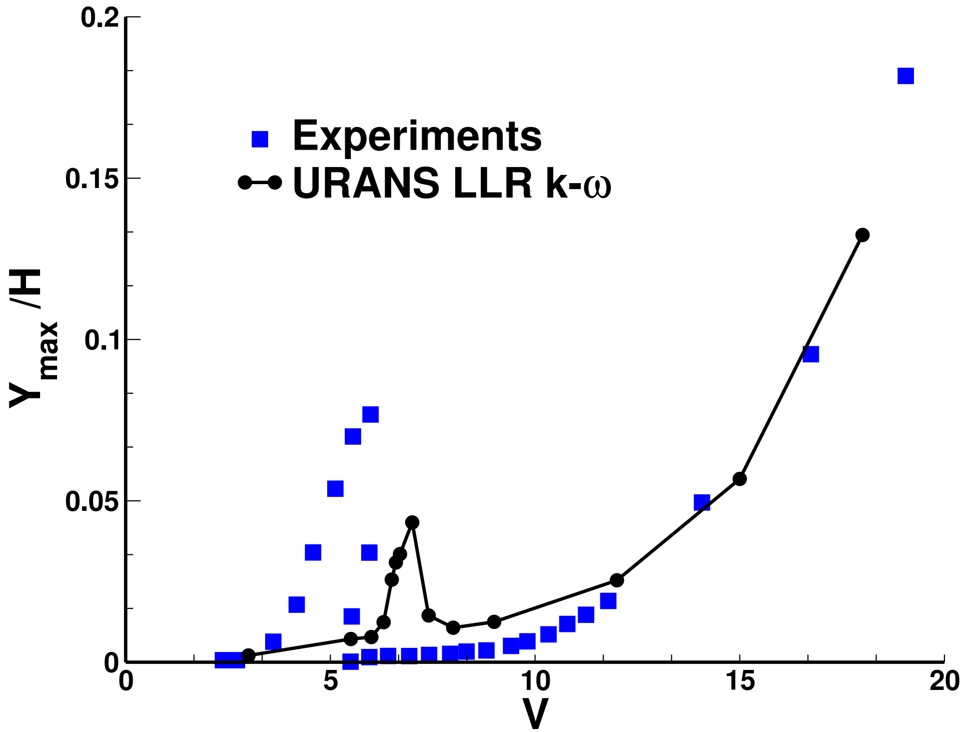


Lift peak value vanishes ⇐

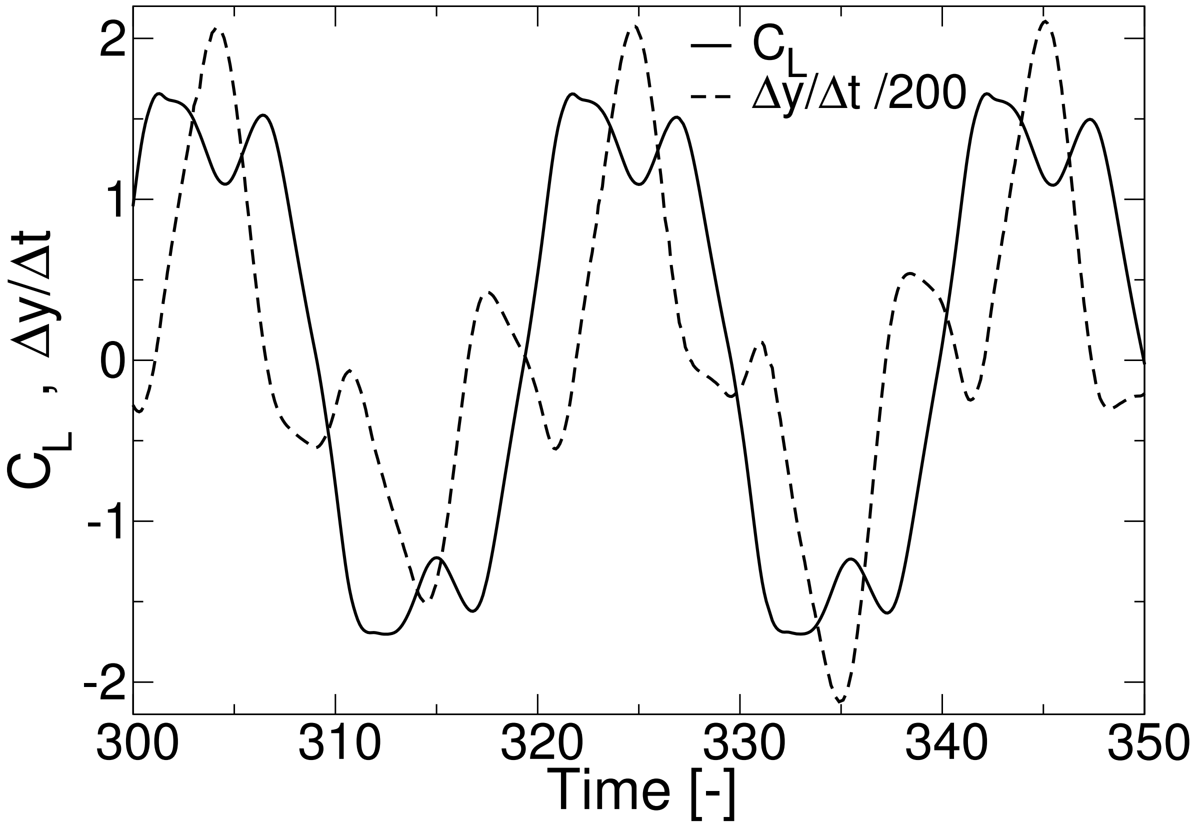
Interaction obvious

Frequency predictable
without movement

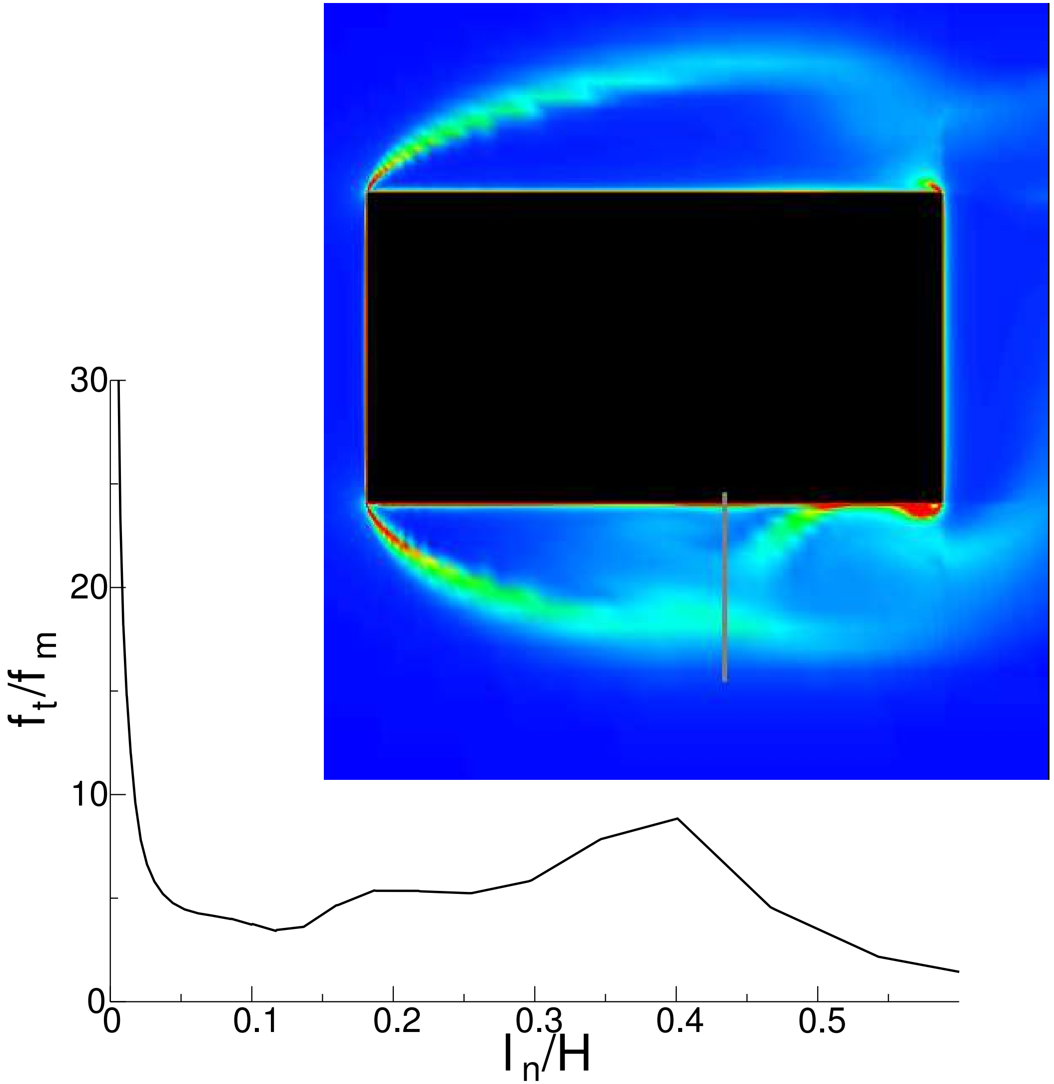
- Resonance velocity
  - $f_{l_{num}} < f_{l_{exp}}$
  - To much damping (viscosity)
  - Principal problem of URANS
- Maximum excitation
  - Also too much damping
  - Coupling procedure
- Experimental results
  - Confined to one case
  - Missing information on turbulence intensity and wind tunnel geometry



- Galloping velocity is captured
  - $V \approx 12.0$
  - Criterion:
    $$\frac{V}{4\pi Sc} + \frac{2}{\frac{\partial C_L}{\partial \alpha}\cos(2\pi\frac{\tau_r}{V})} = 0$$
  - Scruton number needed
  - $\frac{\partial C_L}{\partial \alpha}$ from experiments
  - τ_r = Time lag between lift and $\frac{\partial y}{\partial t}$ estimated $\rightarrow$
  - However, frequency to low



- Comparison of f_t and f_m
  - Turbulent frequency
    $f_t \sim \omega$, turbulent time scale
  - Maximum resolved frequency
    $f_m \sim 1/\Delta t$, time step
  - Gap exists up to
    10 CV from the wall
  - Minimum f_t in the wake
    7…15 H from the wall
  - Overlapping
    in the range of $\mathcal{O}(10^3)$
    even close to the wall
  - Hybrid methods should be chosen
    despite increased computational costs (DES)



- Physical phenomenon captured very well by 2D URANS
  - Validity of URANS doubtful when spectral gap not adhered to
- Frequencies are too low even for uncoupled (stationary body) computations
  - Coupling procedure sufficient
  - Drawback of methods (usually) add up (small Strouhal number)
  - Flow physics modeling has to be more sophisticated
  - Simple (one–equation) and unmodified standard two–equation turbulence models perform even worse
- Fine grids and schemes of higher order necessary
- 2D and 3D computations give equal results
  - So far only the same methods and models have been tested
- Not enough experimental data available for this case
- More effects have to be examined (to confirm results)

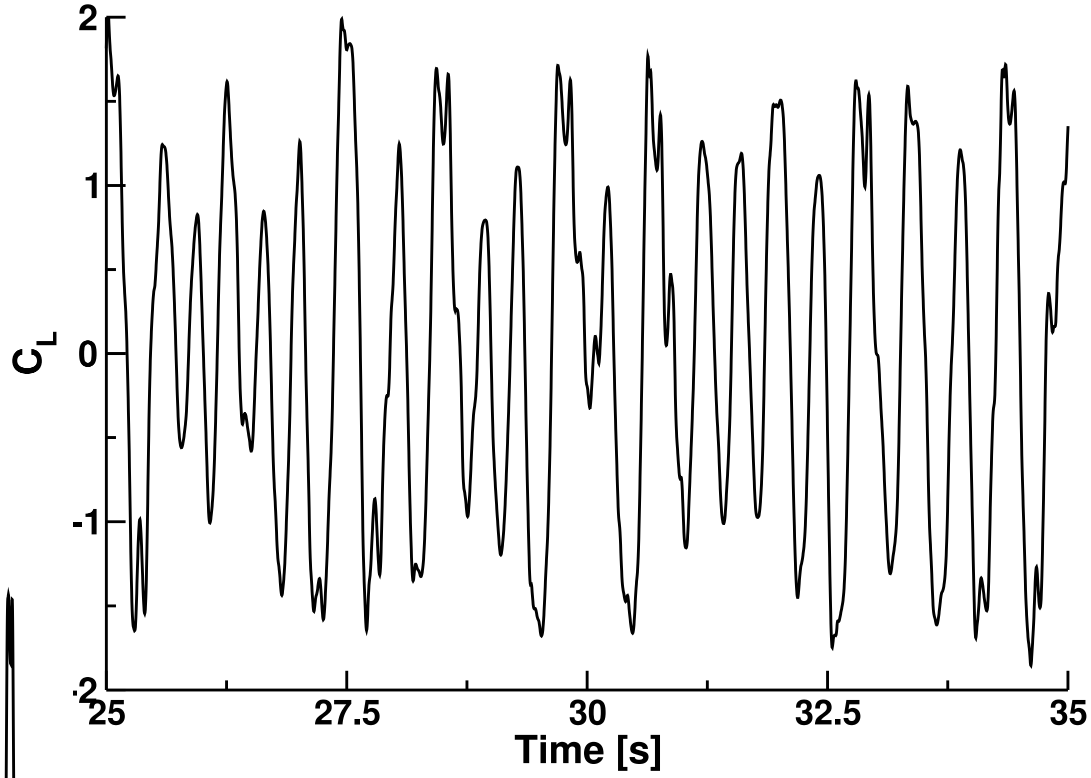
- More parameters will be examined:
  - ○ Geometric modeling, i.e. wind tunnel walls in different positions
    - ⇒ Movement of body will have more influence
    - ⇒ Deforming grids are necessary
  - ○ Flow physical modeling
    - ⇒ 2D URANS Limitation of ν_t
    - ⇒ Sophisticated models (EARSM), curvature correction
    - ⇒ 3D DES using EVM + EARSM
- Experimental data: any hint or collaboration is welcome
- Areas of application for URANS in FSI limited ! :
  - ○ Aerodynamic of buildings (bridges)
  - ○ Airfoil flutter (compressible)
  - ○ Unsteady flows in general

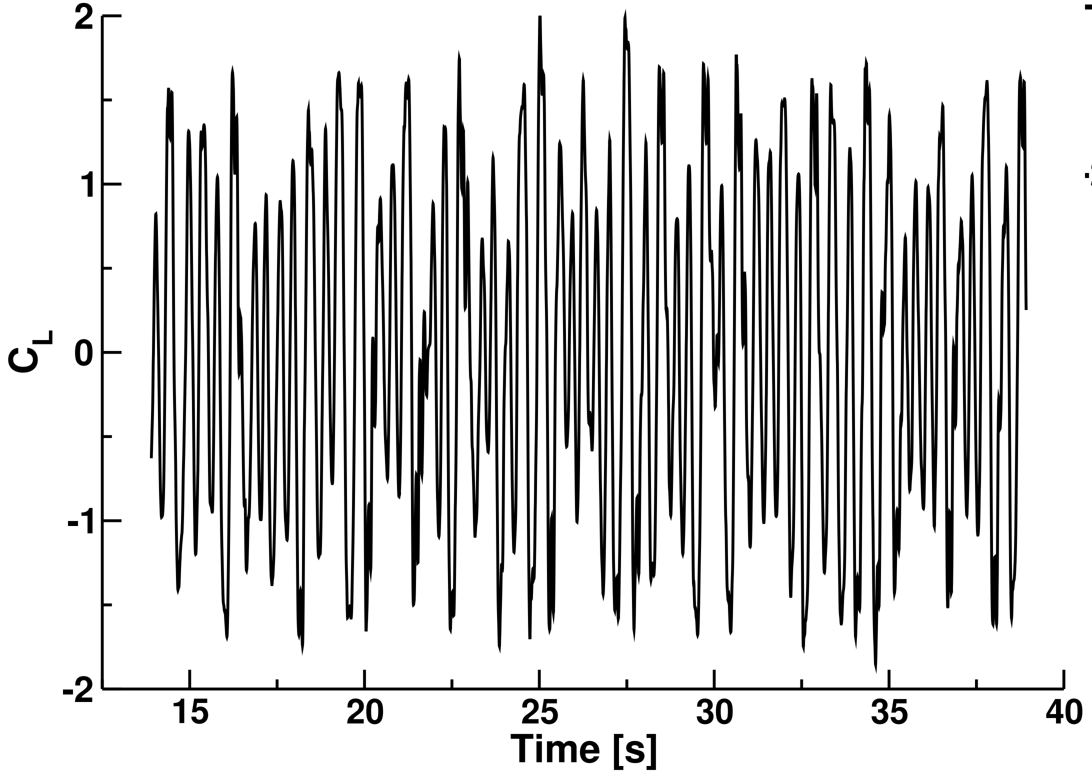
- Neue Ergebnisse für DES

  V=5.5, erste Auswertung

  2,000,000 nur ausgewertet

  $\Delta z = 1$ mit 15 Ebenen





- Verhalten unregelmäßiger
- Amplituden ähnlich
- 3D Effekte schon sichtbar
  trotz groben Gitters (ohne Bild)

- Frequenzanalyse
  - Frequenzen höher,
    nahe am Experiment
  - Breiteres Spektrum,
    keine ausgezeichneten peaks
  - Resonanzverhalten schwerer vorhersagbar
  - Kopplung mit schwingungsfähigem Körper als Filter (?)