Direct Numerical Simulation of an Oscillatory Boundary Layer close to a Rough Bed

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Introduction

- Outline
  - Sketch of the problem.
  - Numerical method.
  - Validation of the numerical results.
  - Flow field.
  - Coherent structures.
  - Time and spatial distribution of the different components of the forces on the bed.

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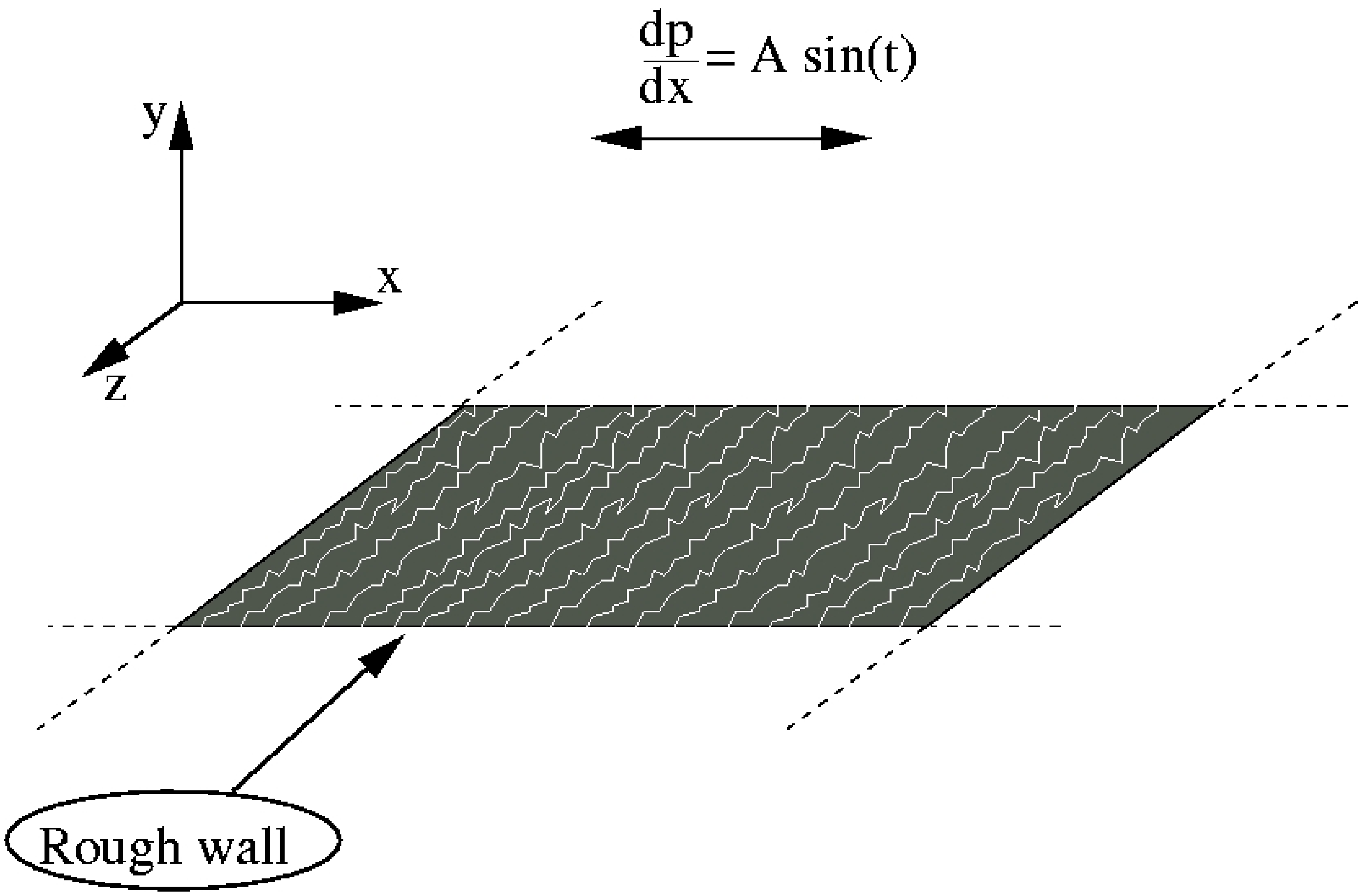
  - Flow field.
  - Coherent structures.
  - Time and spatial distribution of the different components of the forces on the bed.
- Applications
  - Industrial engineering
  - Chemical reactors
  - Marine and River engineering (pick-up of sediment)

Sketch of the Problem



Numerical Setup

- Direct numerical simulation of the incompressible Navier-Stokes equation.

- Finite difference approach.

- Use of the *immersed boundaries* technique (*Fadlun et al., 2000 J.Comp.Phys.*) to take into account the presence of solid surfaces.

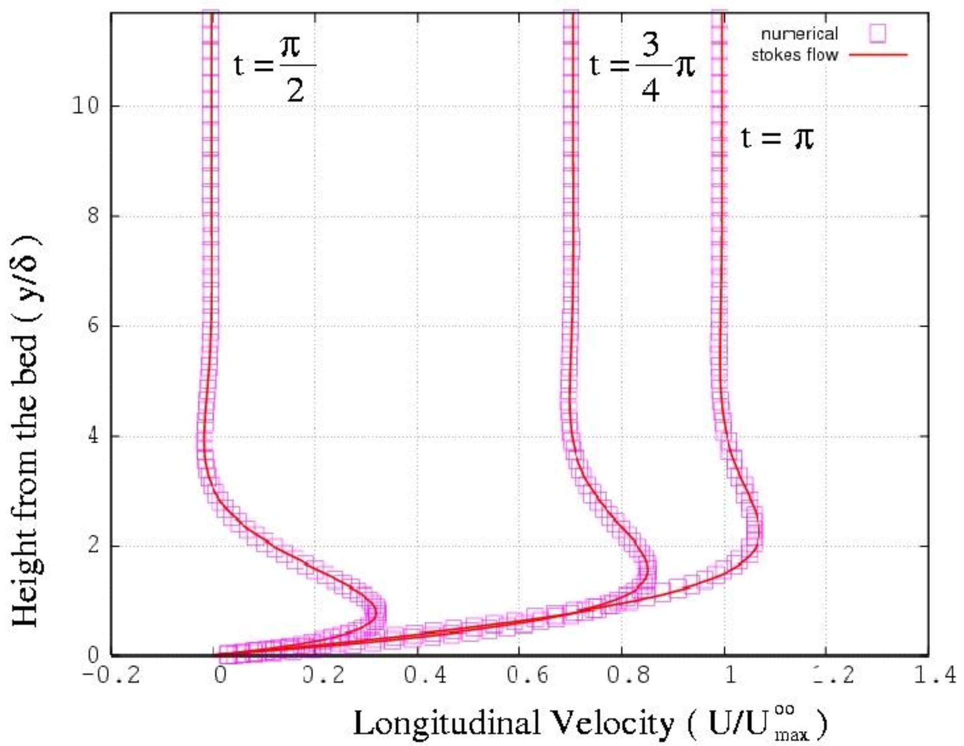
- Cartesian and orthogonal grid.

Validation of the Numerical Code

- Flow field generated by an oscillating pressure gradient. ($\frac{\partial p}{\partial x} = A \sin(\omega t)$).
- Flat wall.
- Small Reynolds number ($Re = 10$).

The analitical solution for the longitudinal velocity is:

$$u(h,t) = U^{\infty}_{max} e^{-\frac{y}{\delta}} \cos(\omega t - \frac{y}{\delta}) - U^{\infty}_{max} \cos(\omega t)$$



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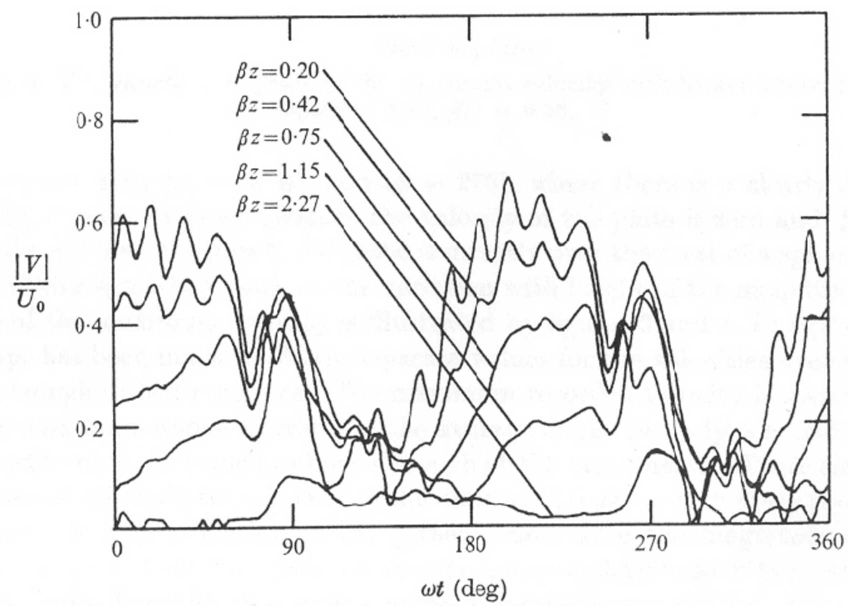
Keiller & Sleath, JFM 1976

- Regular roughness made with an hexaghonal array of spheres.
- Moving bed and still fluid.
- Secondary peak of the modulus of the velocity.

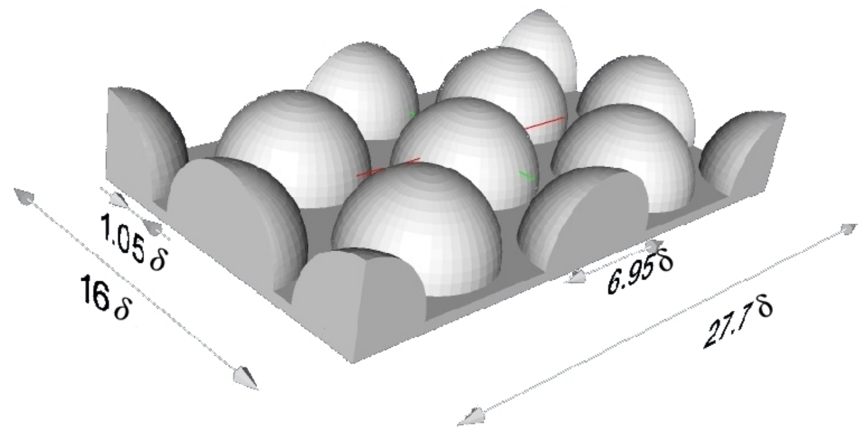


Variation in velocity module during the course of one cycle at various distances above the bed. ($\beta=1/\delta$)

- Reynolds number $Re_\delta = 95.5$.
- Spheres diameter $D = 6.95\delta$.

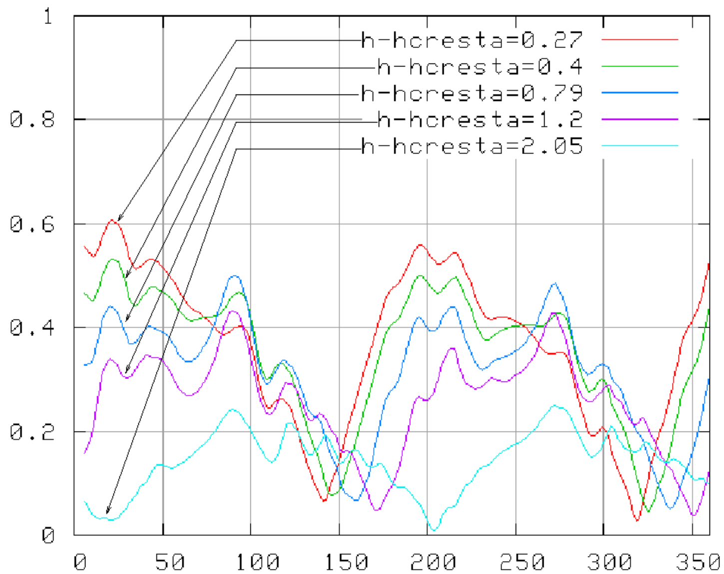
Numerical Parameters

- Hemispherical roughness elements.
- Hemispheres diameter $D = 6.95\delta$.
- Regular layout.
- Periodical boundary conditions in the horizontal directions.
- Reynolds number $Re_\delta = 95.5$.
- Grid points: $161 \times 161 \times 81$.

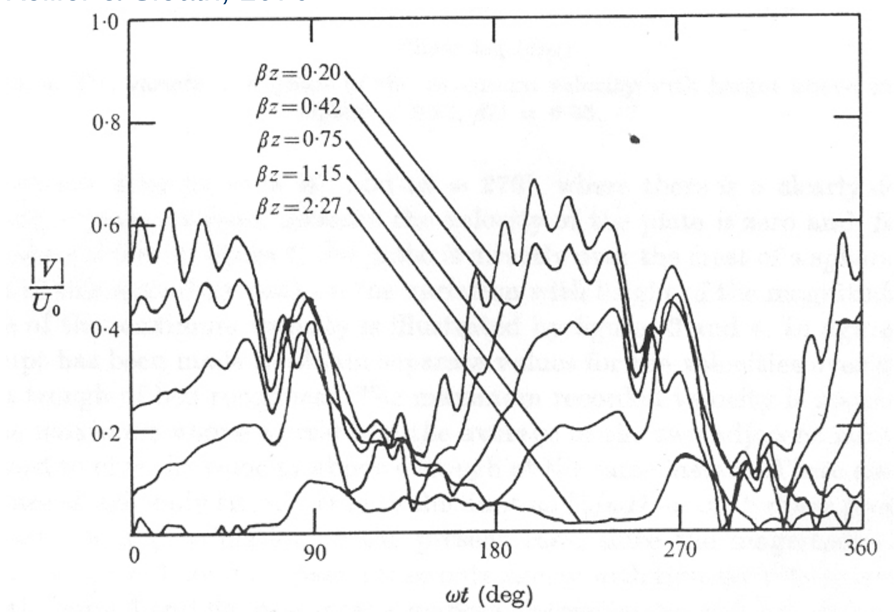


Comparison between Numerical and Experimental Results

Numerical results



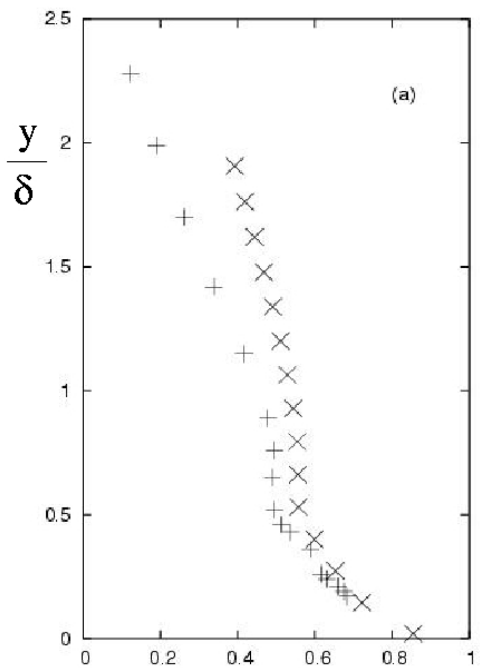
Keiller & Sleath, 1976



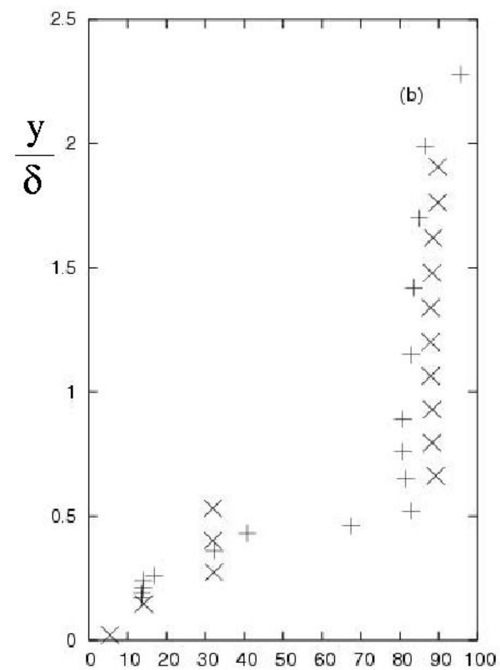
Phase average of the modulus of the velocity at various heights above the crest of the hemisphere.

Comparison between Numerical and Experimental Results

×: numerical results, +: experimental data by *Keiller & Sleath, 1976*



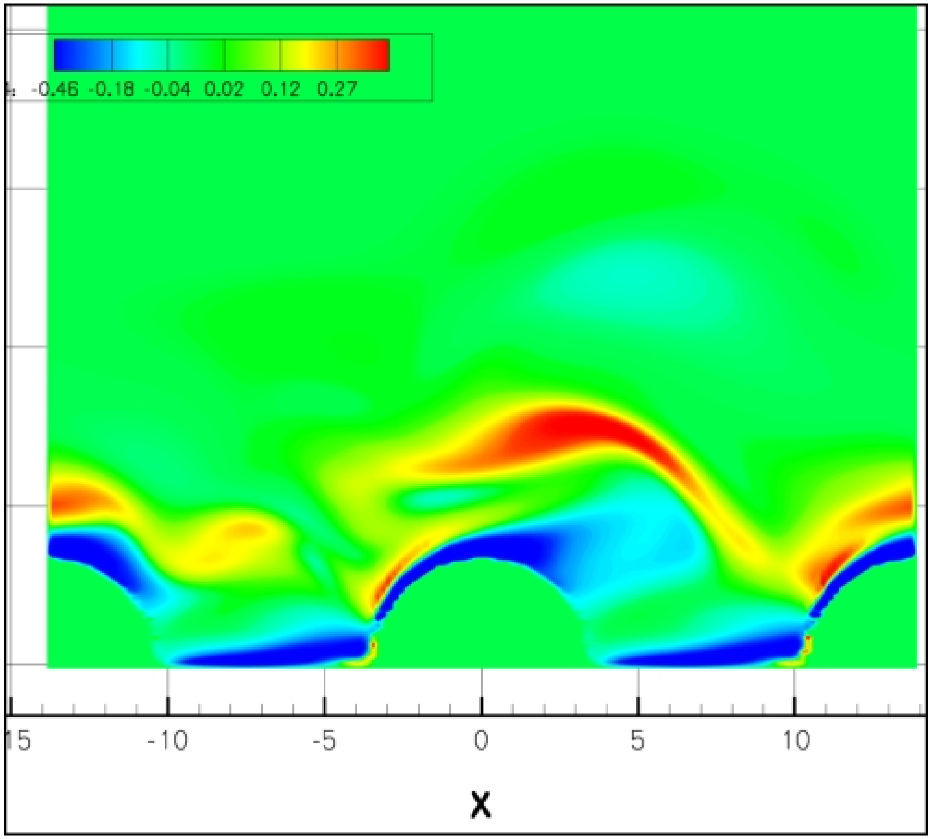
Maximum values of the modulus of the velocity at various heights above the crest



Phase of the maxima of the modulus of the velocity

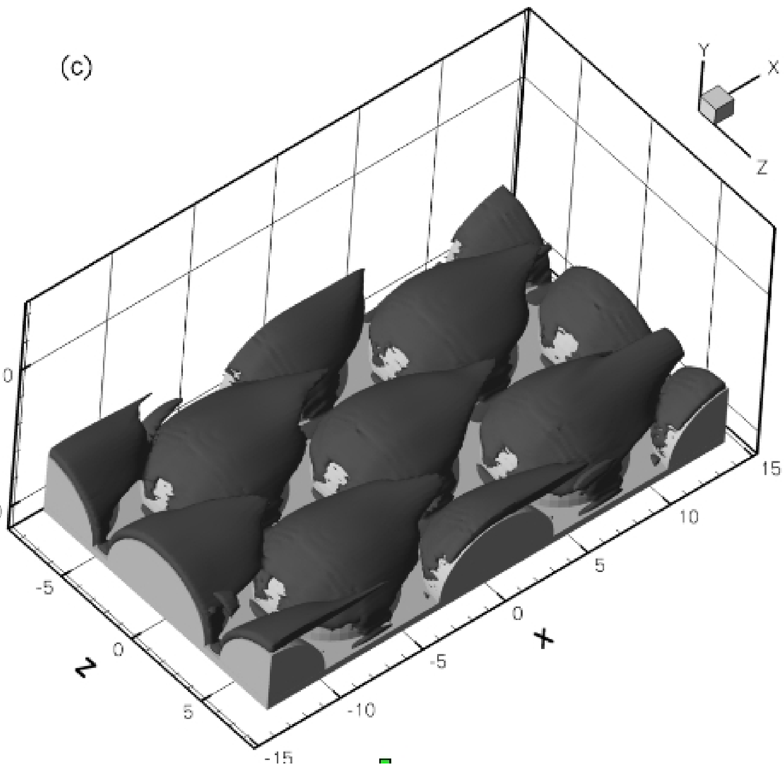
Spanwise Vorticity

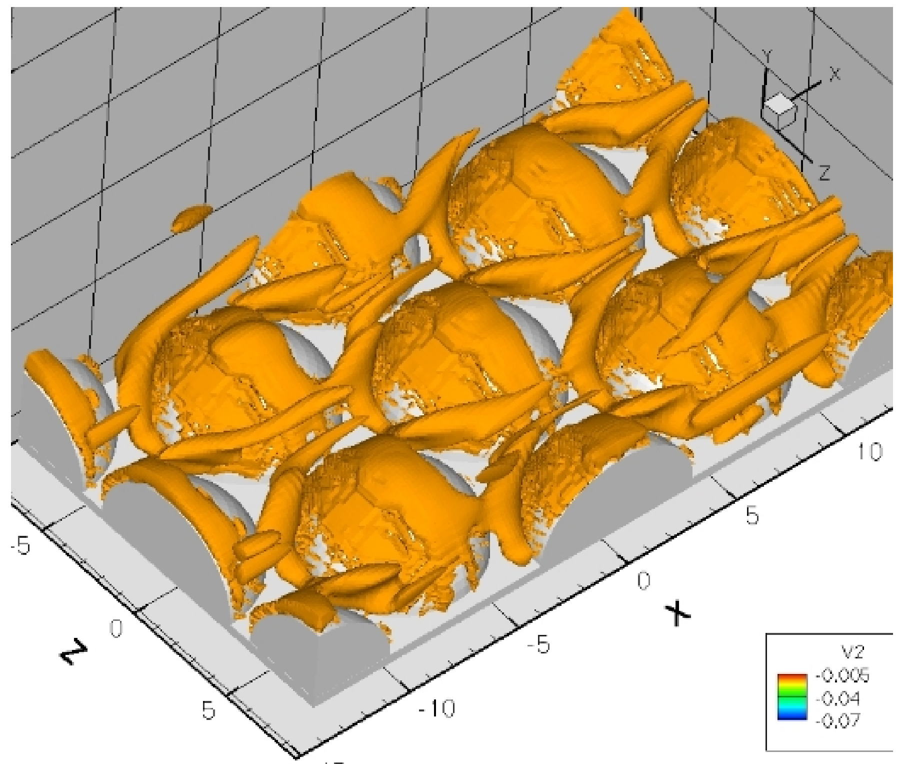
- Spanwise vorticity contour at flow reversal.
- Boundary layer separation at the crest of the hemispheres.
- Vorticity dipoles are located over the crests.



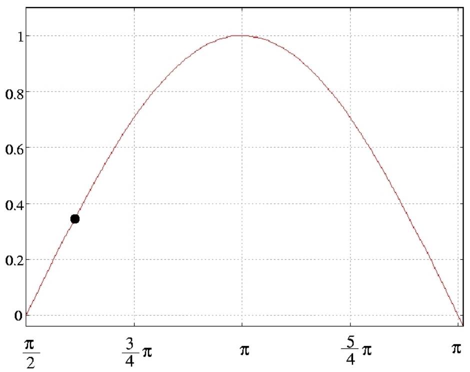
Coherent Structures

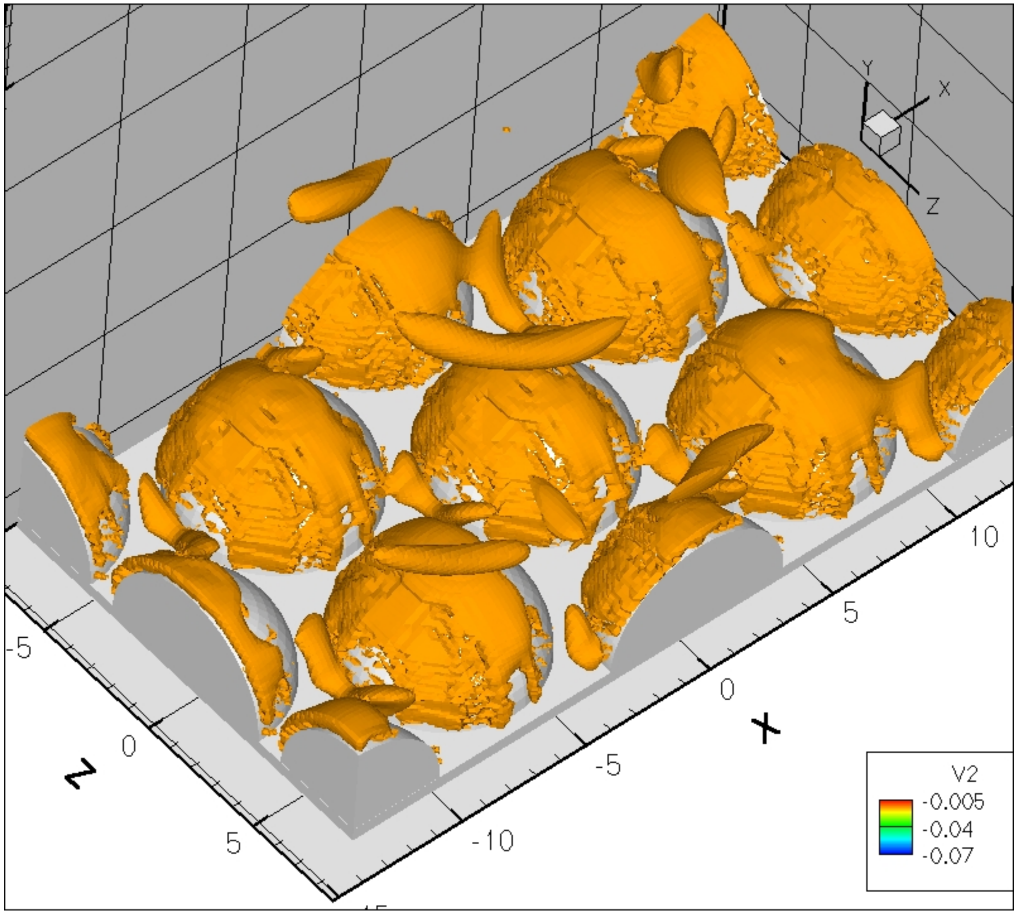
- On the left: Shear layer on the top of the hemispheres represented by the vorticity module.
- On the right: Coherent structures identified by λ_2 *criterion* (*Jeong & Hussain,JFM 1995*).





Coherent Structures





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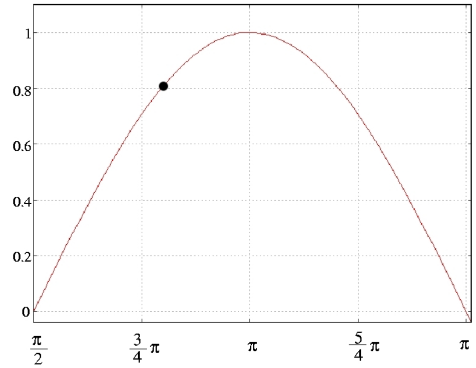

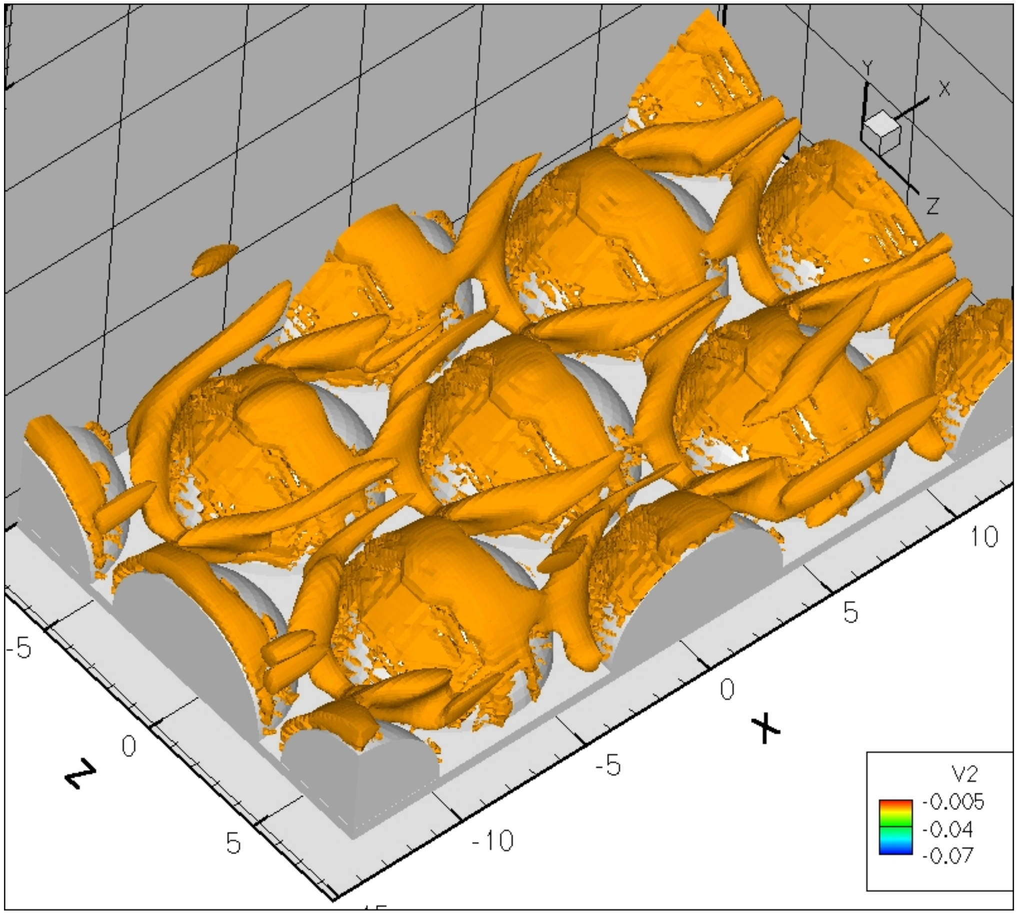

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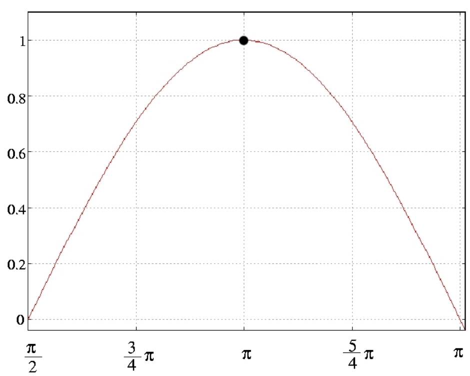

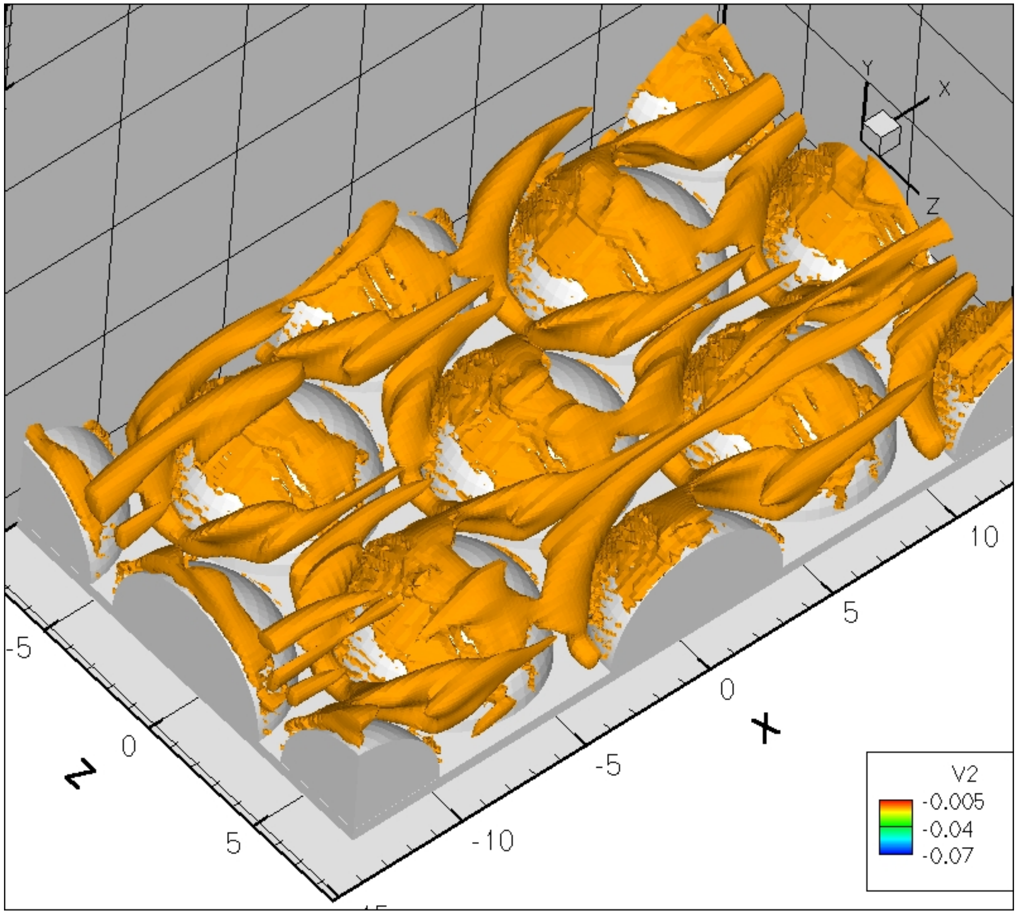

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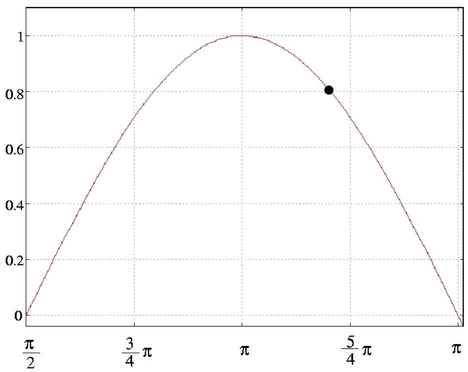

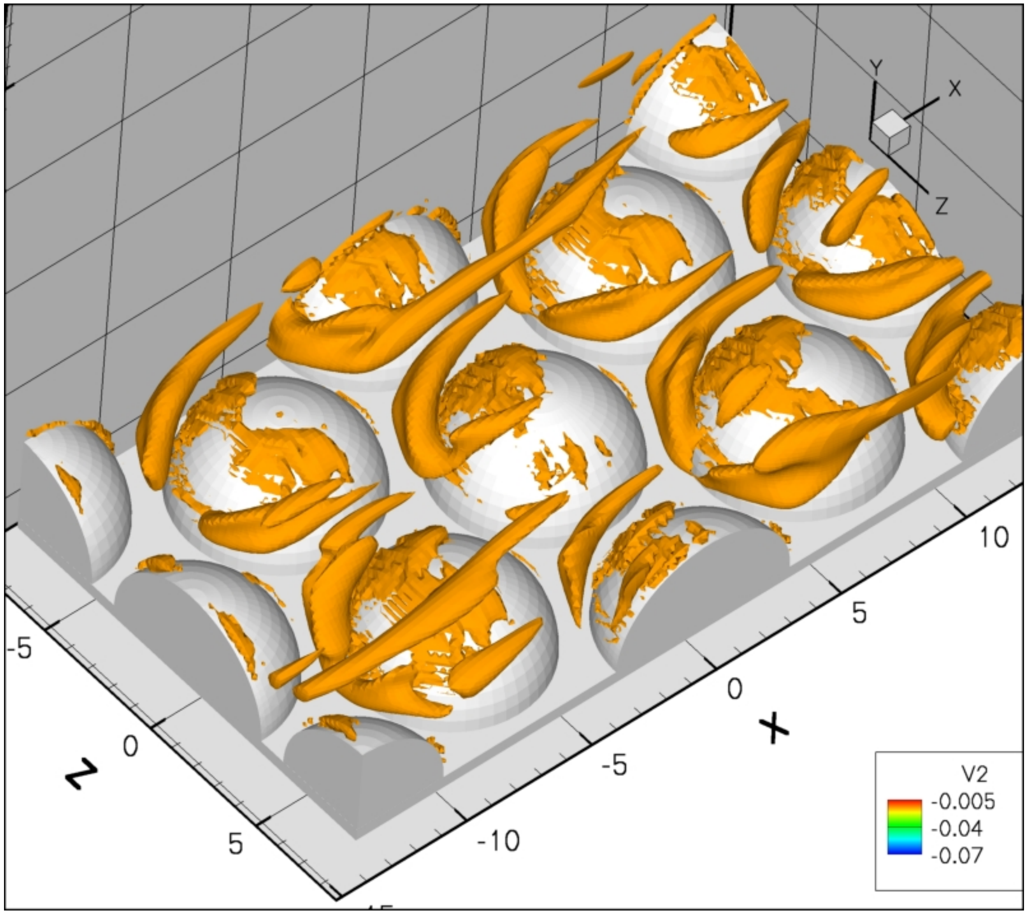

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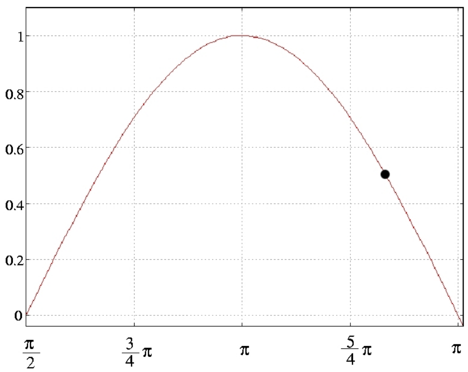
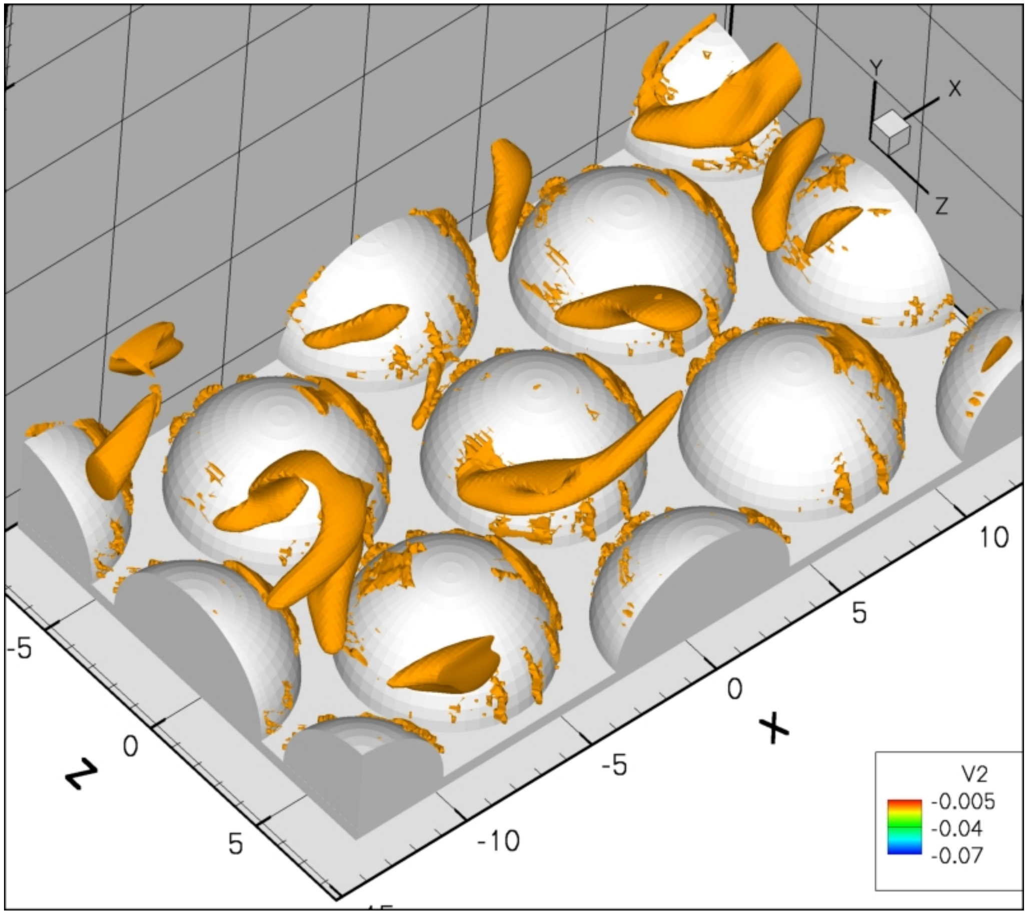
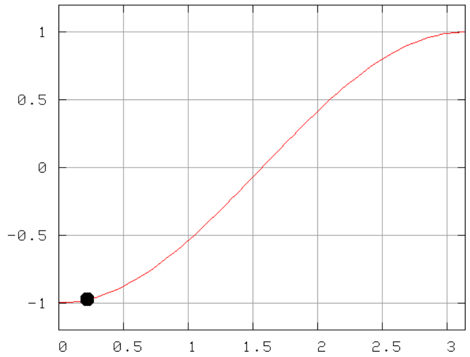
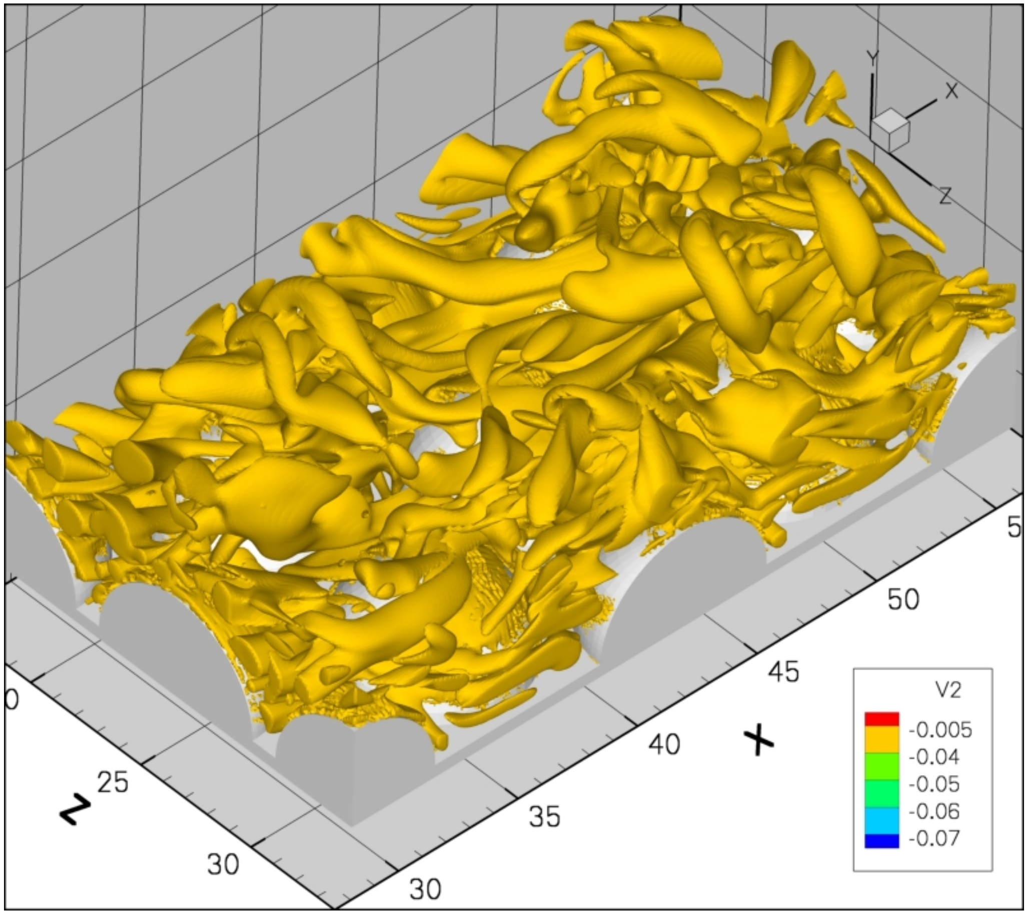




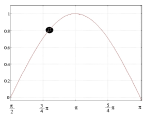
Coherent Structures ($Re_\delta = 200$)

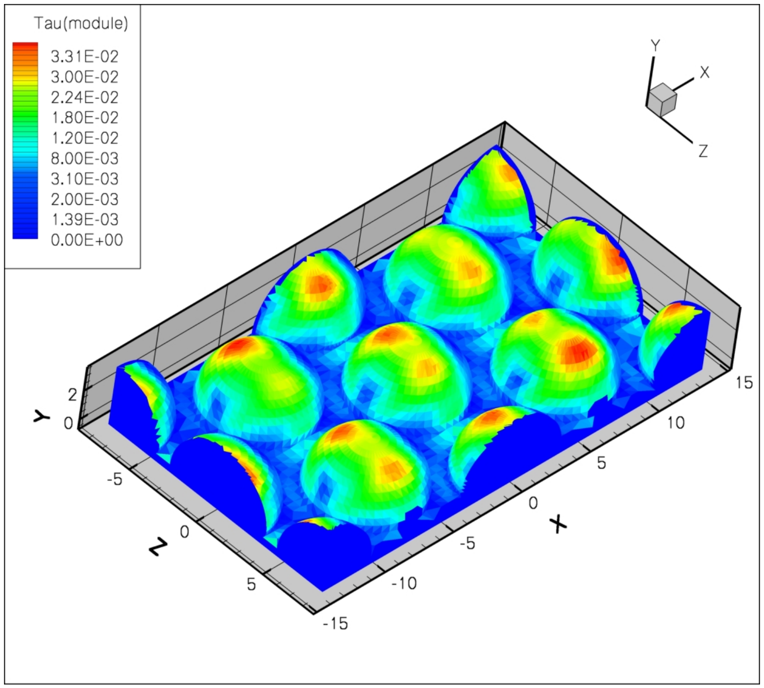




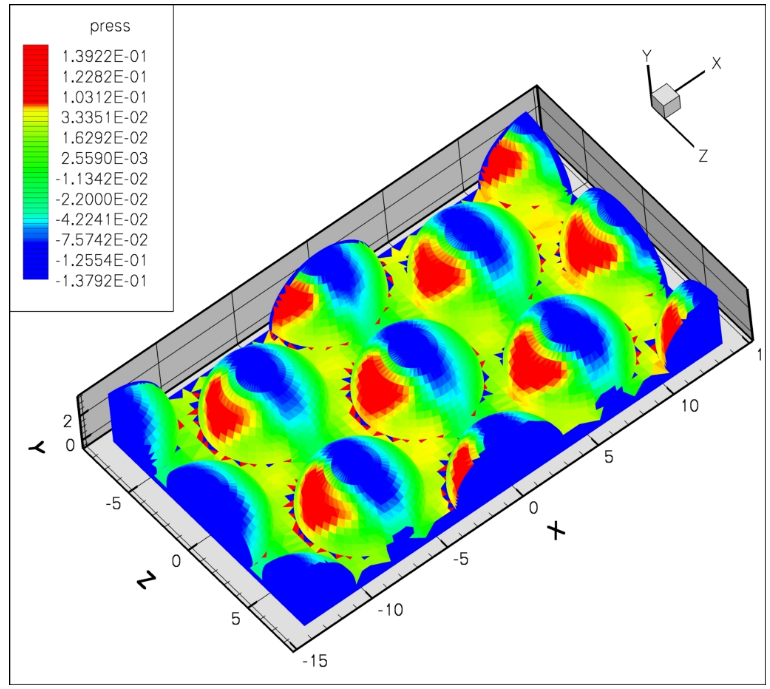
Spatial Distribution of the Force on the Bed

$t = 0.82\pi; U_\infty = -\cos(t)$





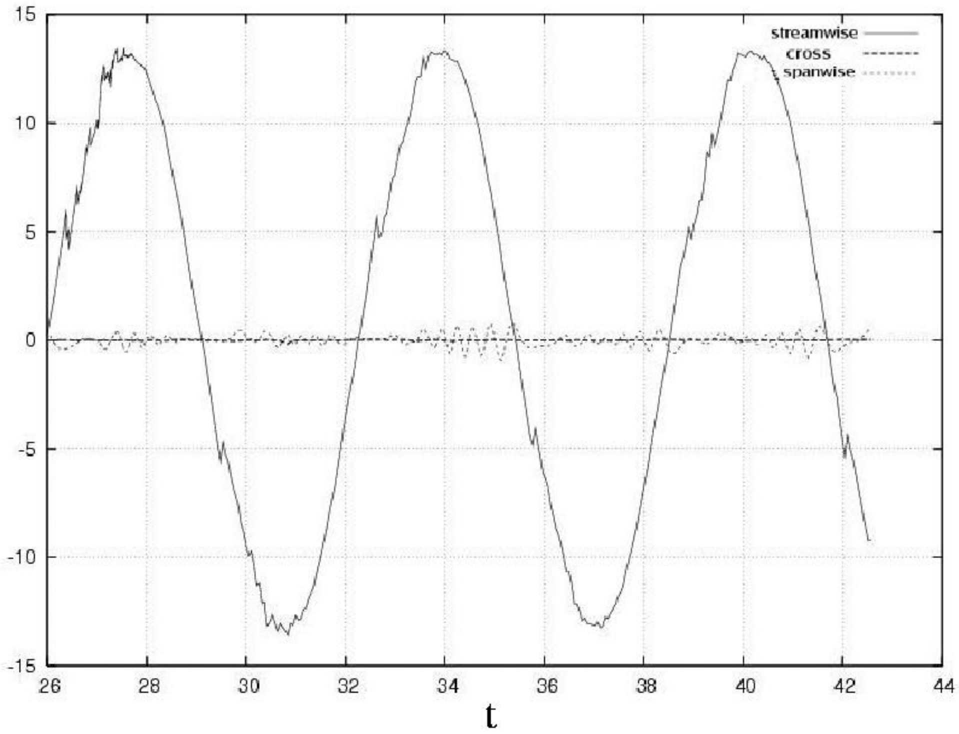
Spatial distribution of the modulus of viscous contribution of the force



Spatial distribution of the pressure component

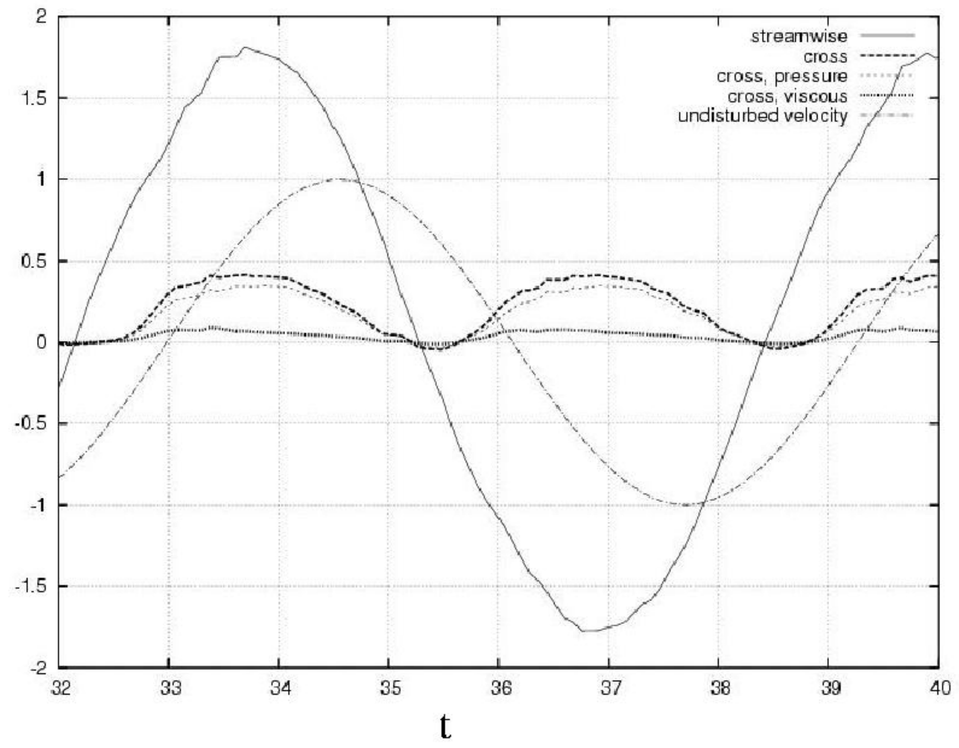
Forces on the Bed

- Time evolution of the components of the force over the bed.



Forces on a Single Roughness Element

- Net positive value of the time average of the vertical component of the force.



Conclusion

- Validation of the numerical method.
- Fair agreement with the experimental data by *Keiller & Sleath, JFM 1976*.
- Vorticity and coherent structures visualizations.
- Analisys of the forces over the bed.

Future Issues

- Further numerical simulations at higher Reynolds numbers.
- Analisys of the main turbulence quantities.
- Study of the influence of the profile of the wall on the flow field.

Thank you!