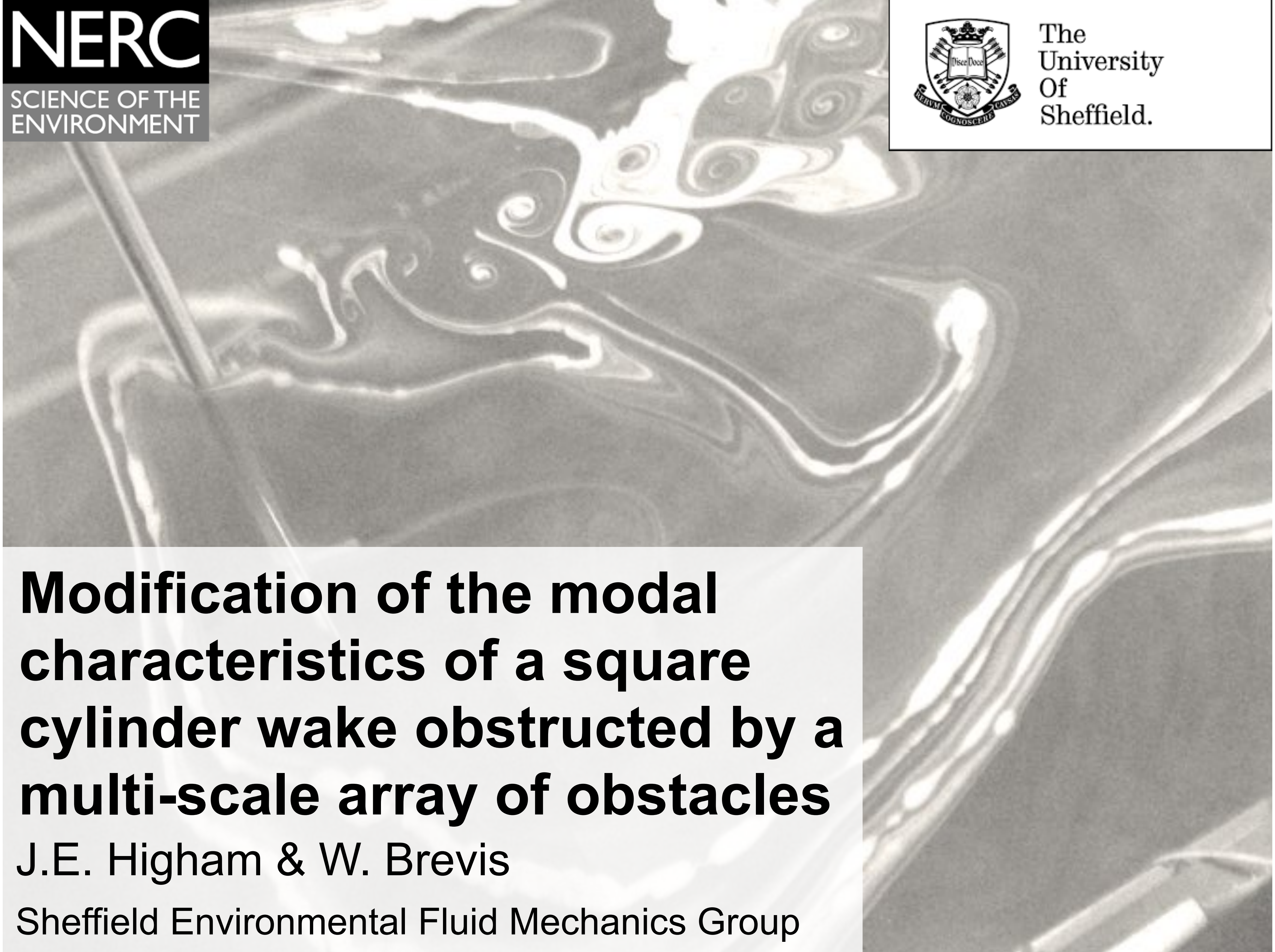

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The University Of Sheffield.

Modification of the modal characteristics of a square cylinder wake obstructed by a multi-scale array of obstacles

J.E. Higham & W. Brevis

Sheffield Environmental Fluid Mechanics Group

The governing equations of a fluid

Convection — Pressure Gradient — Viscous Forces

$$\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho}\nabla\mathbf{p} + \nu\nabla^2\mathbf{u}$$

∇ - gradient

$\mathbf{u}$ - velocity

$\mathbf{p}$ - pressure

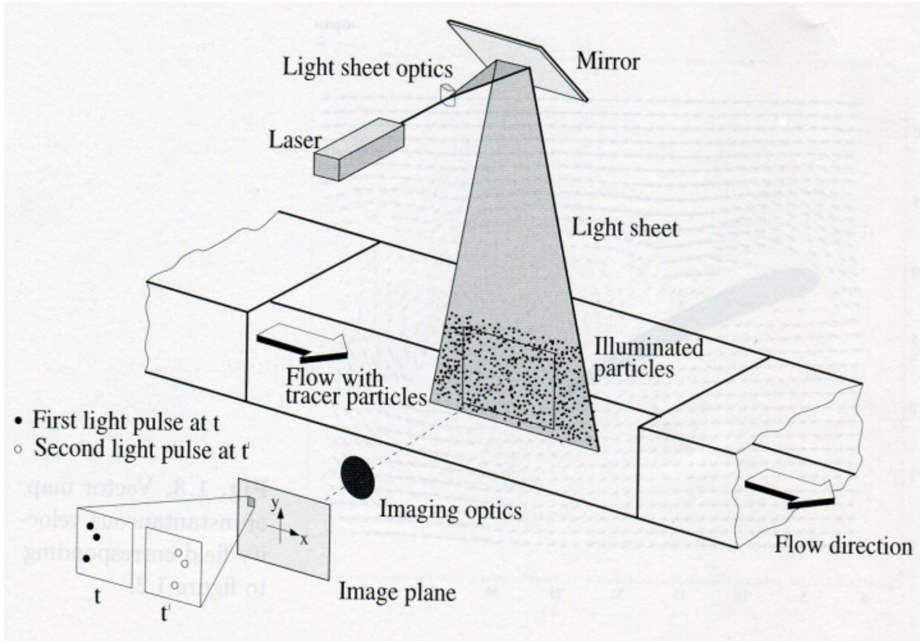
ρ - density

ν - kinematic viscosity

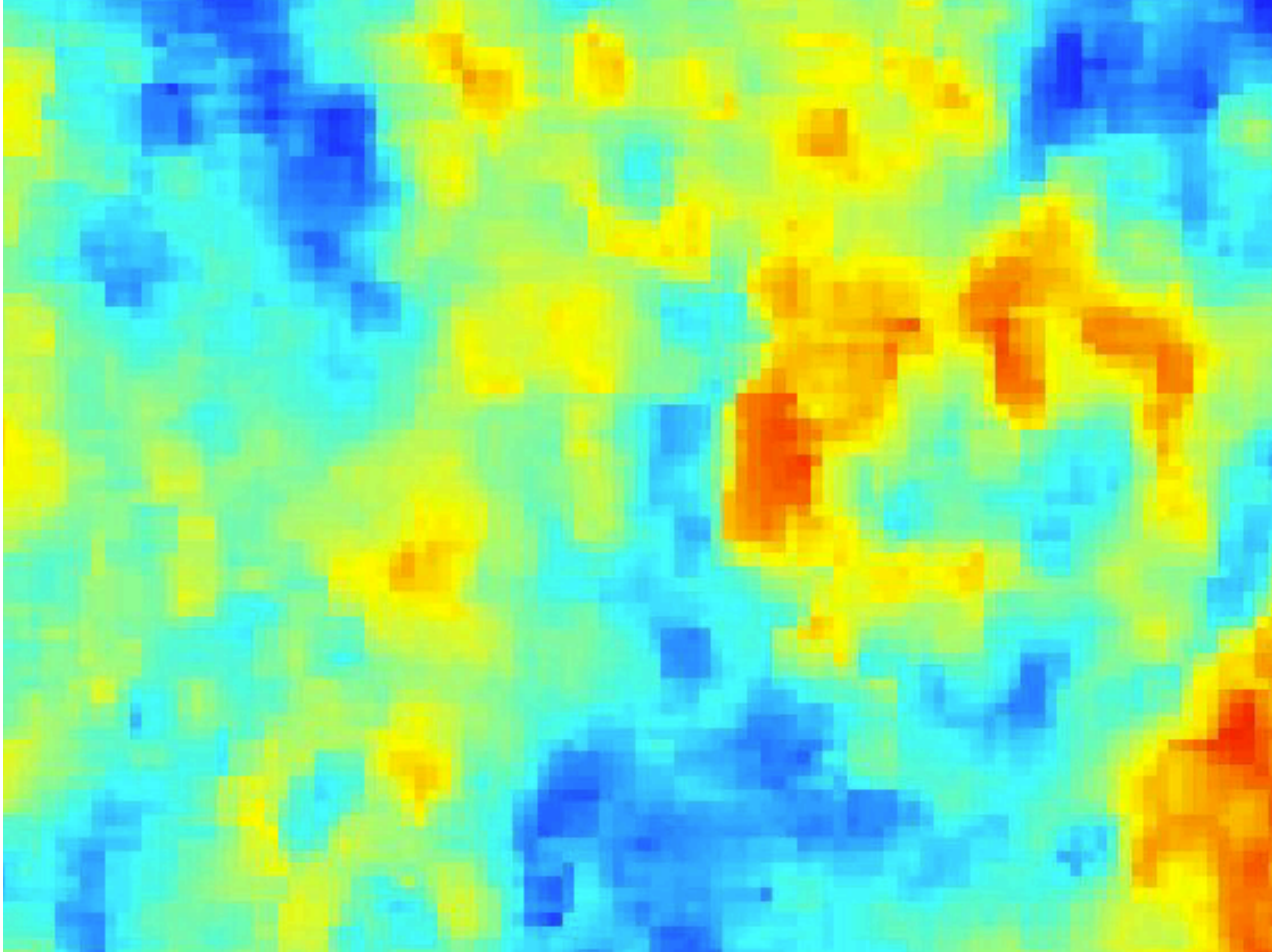
Particle Image Velocimetry

Is an image based method used to determine instantaneous velocity fields by measuring the displacement of a cluster of tracers in a fluid.

- Tracer particles are added to the flow.
- The particles are illuminated.
- Scattered light recorded.
- Displacements are determined from correlations in the Fourier domain.
- This is a fully non-intrusive method.
- PIV is NOT perfect.
- Tomographic PIV etc.



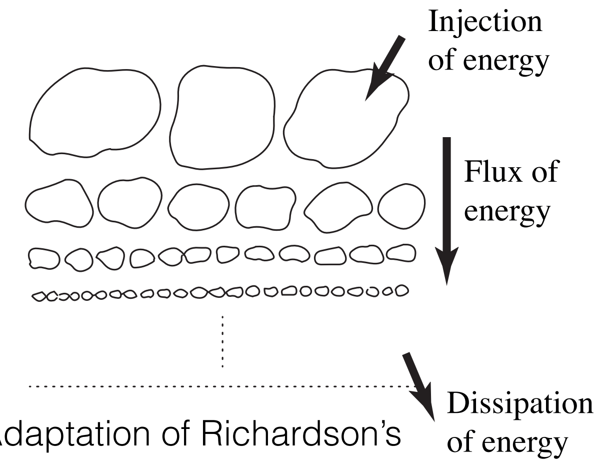
Raffel, Willert, Wereley, Kompenhans. Particle Image Velocimetry. 2nd Edition, Springer. 2007



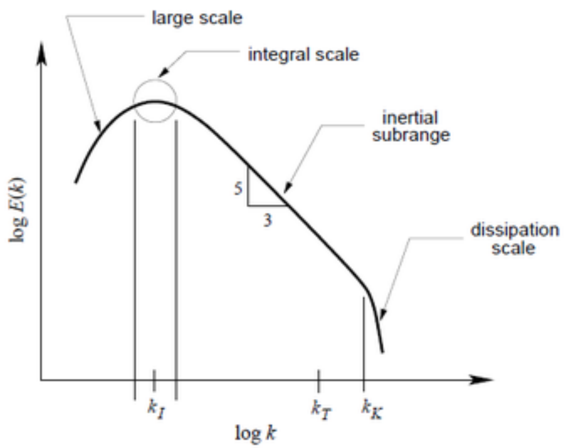
How do we interpret these data?

Osborne Reynolds' Decomposition

$$u_i = \overline{u}_i + u_i'$$



Adaptation of Richardson's picture (Frisch)



Adaptation of Taylor's spectrum (with Kolmogorov additions).

$$\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho}\nabla\mathbf{p} + \nu\nabla^2\mathbf{u}$$

$$\rho\bar{u}_j\frac{\partial\bar{u}_i}{\partial x_j} = \bar{f}_i + \frac{\partial}{\partial x_j}\left[-\bar{p}\delta_{ij} + \mu\left(\frac{\partial\bar{u}_i}{\partial x_j} + \frac{\partial\bar{u}_j}{\partial x_i}\right) - \rho\overline{u_i'u_j'}\right]$$

$$\tau_{ij} = -\rho\overline{u_i'u_j'}$$

This is the Reynolds stress i.e. momentum flux.

This show regions which can lead to erosion etc.

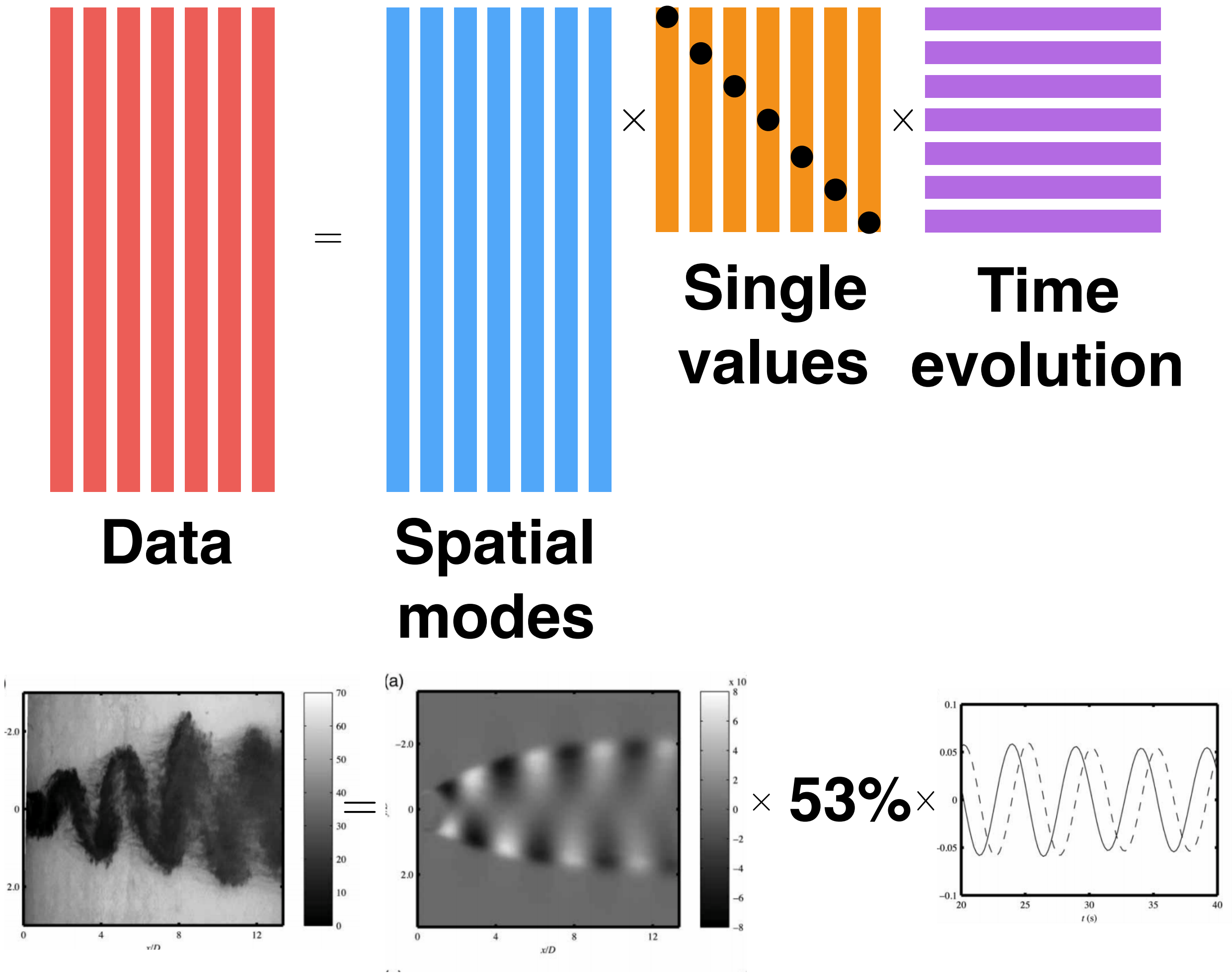
BUT

Does not represent any dynamics, is a very old hat approach.

Modal Decomposition Techniques

(Hussain, A. 1983) Coherent structures: reality of myth?

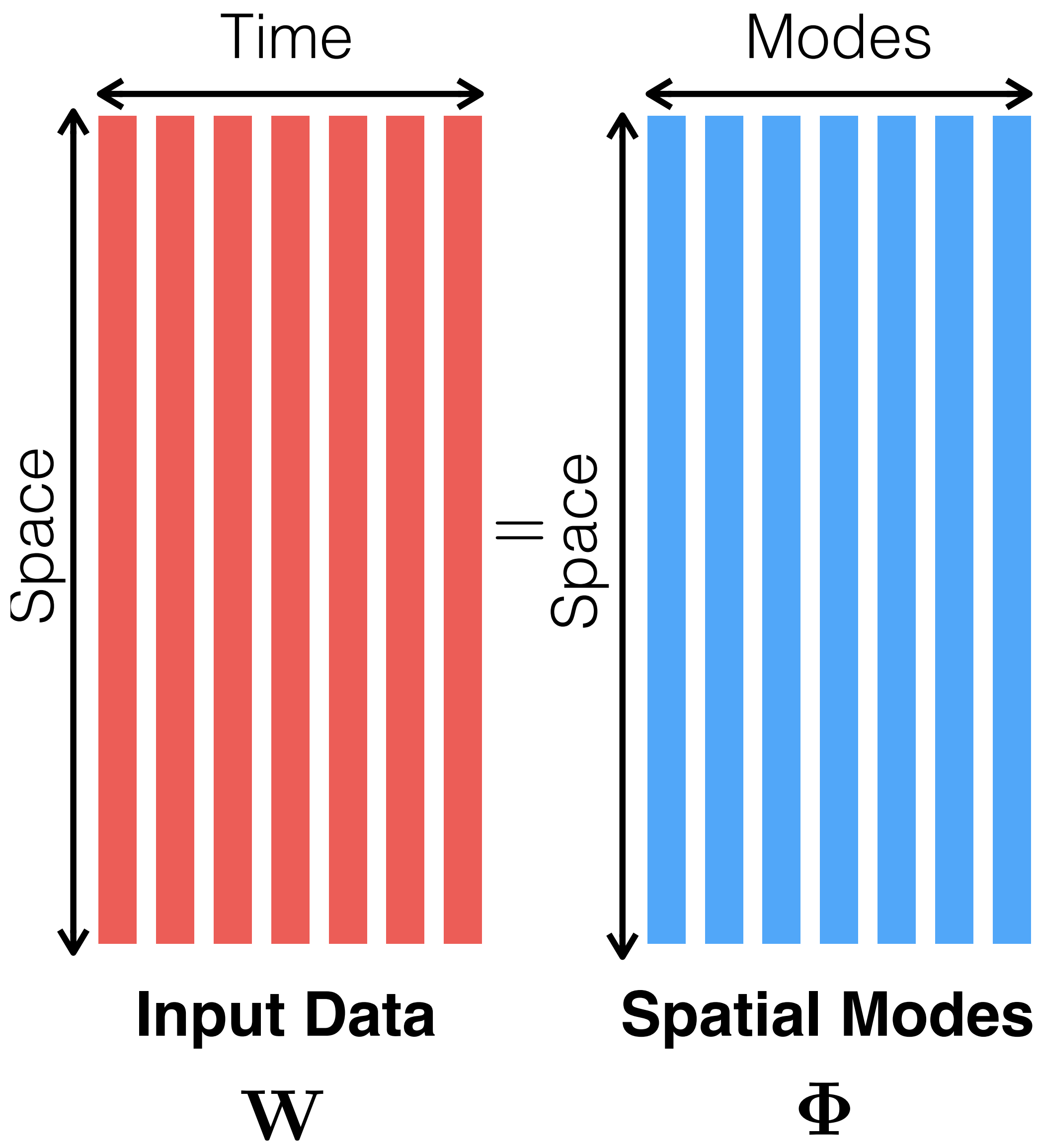
- In fluid mechanics there are two main techniques.
- POD (Proper Orthogonal Decomposition) - based on spatial correlations.
- DMD (Dynamic Mode Decomposition) - based on temporal correlations*.
- The main aim in a modal decomposition technique to to extract regions of coherence.
- But what is coherence **

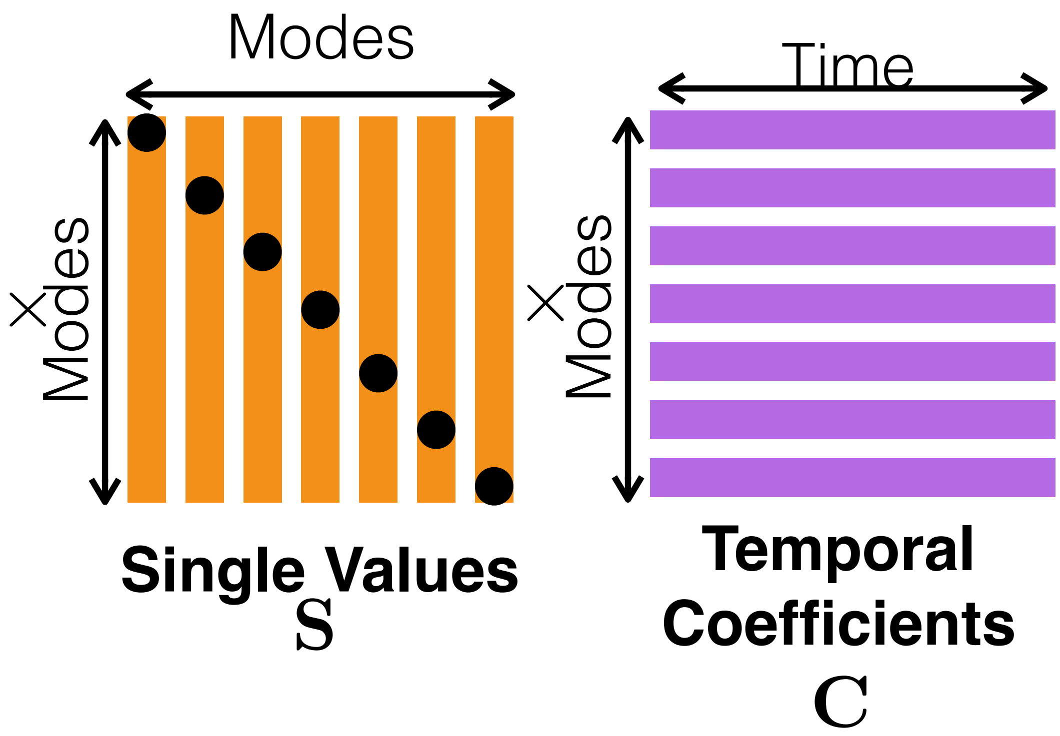


*not explained today, but see Higham et al. (2017) AWR

**not explained today, but see Higham et al. (In Press) JHR

Proper Orthogonal Decomposition





In a POD the spatial modes are ranked by their contribution to the **total variance.** In fluid mechanics this is could be turbulent kinetic energy / vorticity. We can solve this using a singular value decomposition.

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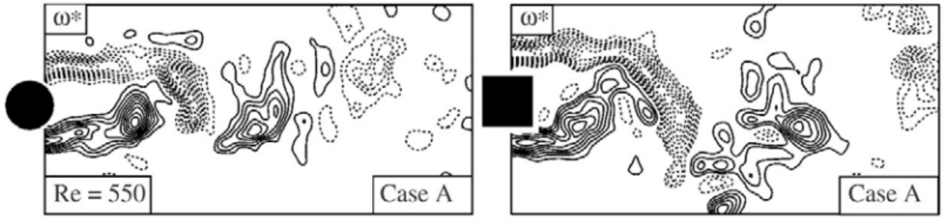
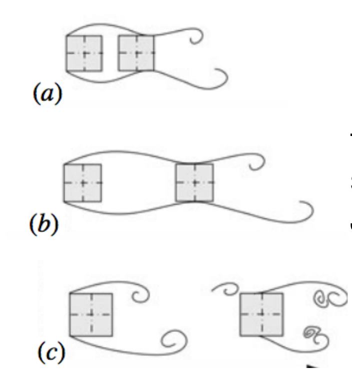
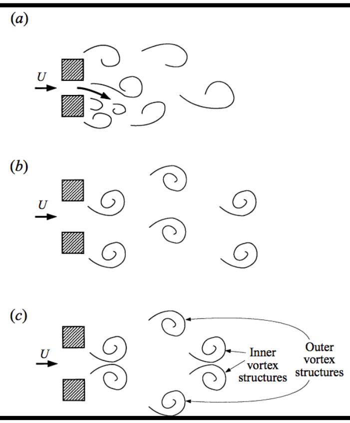
Cylinder wakes



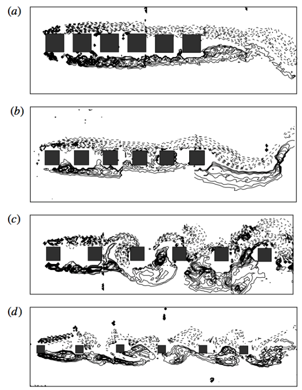
M. OZGOREN (2005)
Flow structure in the downstream of square and circular cylinders,
Flow Measurement & Instrumentation



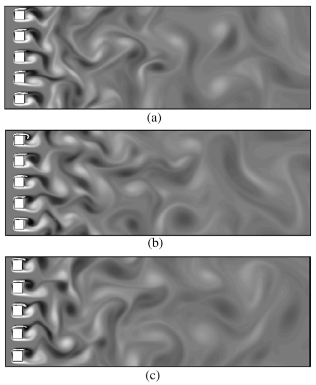
Md. MAHBUB ALAM,
HONGLEI BAI and YU ZHOU (2016)
Ensemble-averaged measurements in the turbulent near wake of two side-by-side square cylinders
Journal of Fluid Mechanics



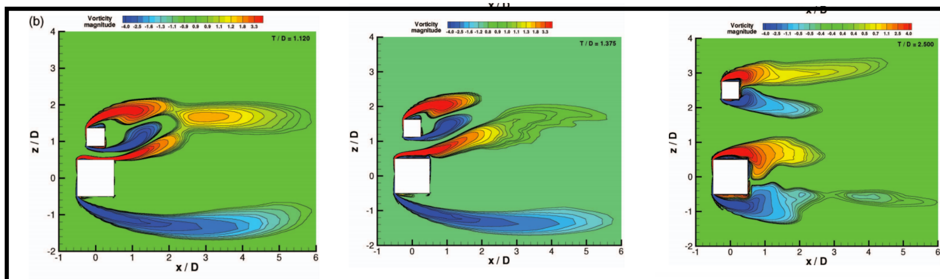
V. KOLÁŘ, D. A. LYN, and W. RODI (1997)
Ensemble-averaged measurements in the turbulent near wake of two side-by-side square cylinders
Journal of Fluid Mechanics



C. SEWATKAR, R. PATEL, A. SHARMA & A. AGRAWAL.
Flow around six in-line square cylinders.
Journal of Fluid Mechanics.



D. CHATTERJEE et al. (2009)
Numerical simulation of flow past row of square cylinders for various separation ratios.
Computers & Fluids



M.B. SHYAM KUMAR and S. VENGADESAN (2009)
Large eddy simulations of flow interference between two unequal sized square cylinders
International Journal of Computational Fluid Dynamics

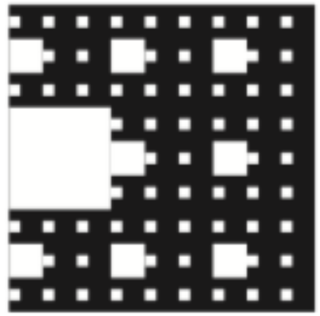
Test cases

Case I

Case II

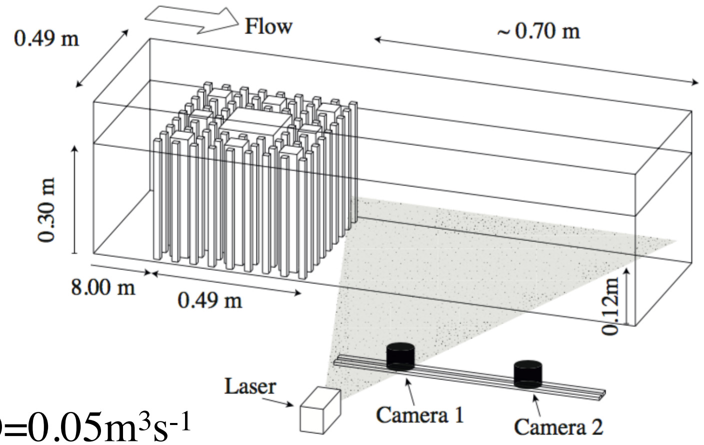
Case III

Case IV



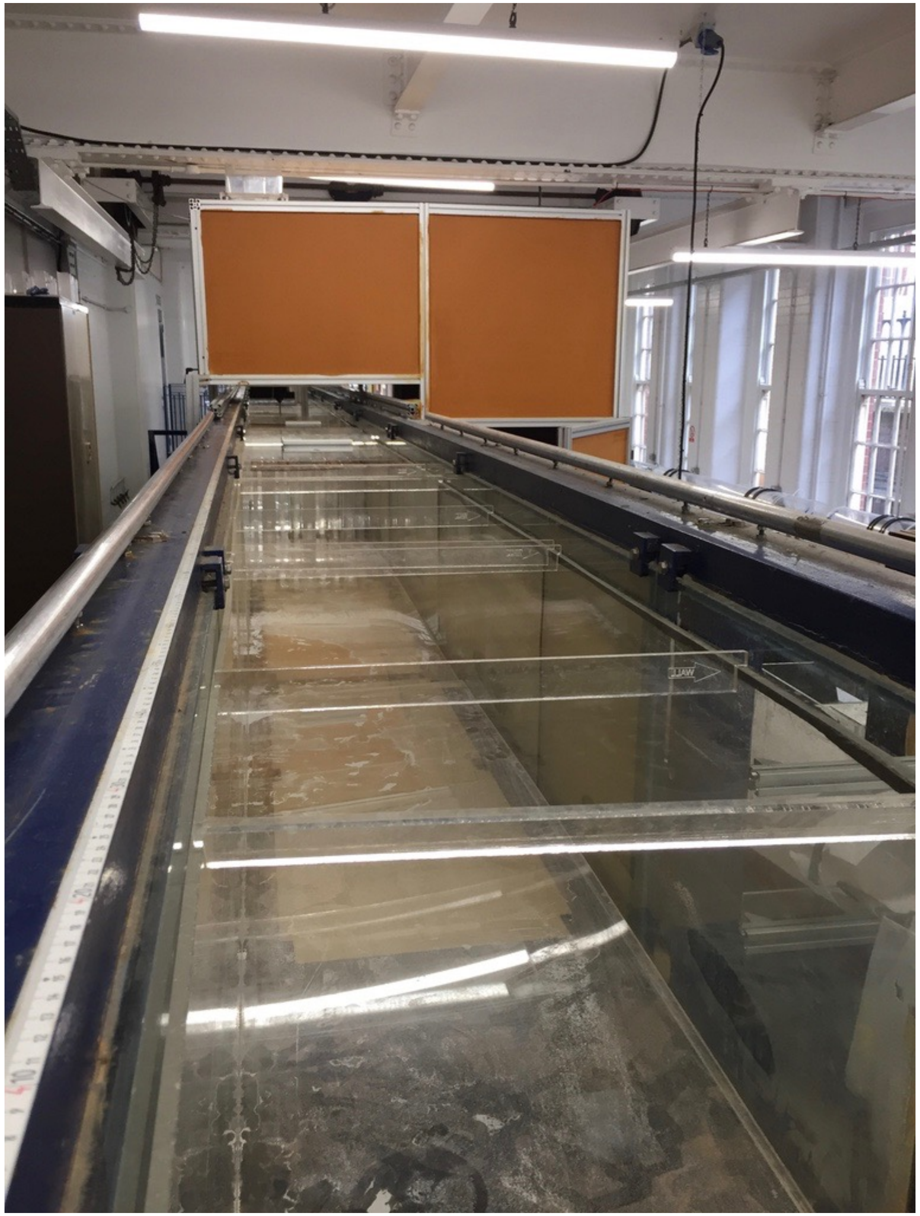
Experimental Setup

Seeding	Type	Polyamide powder
	Specific gravity	1.016 gcm^{-1}
	Diameter	100 μm
Light sheet	Laser type	Double pulsed Nd:YAG
	Maximum energy	200 mJ
	Wave length	532 nm
	Thickness	2mm
Camera	Type	Imager MX 4M
	Resolution	2048 × 2048 px
	Pixel size	0.21 mm
	Lens focal length	24 mm
Imaging	Viewing area	440 mm × 440 mm
PIV Analysis	Interrogation area	final integration window size 16 px × 16 px
	Overlap	75%
	Approximate resolution	3.5 mm × 3.5 mm × 3.5 mm



$Q=0.05 m^3 s^{-1}$

Figure 2: View of the measurement section and experimental setup (not to scale)



Streamwise mean flow

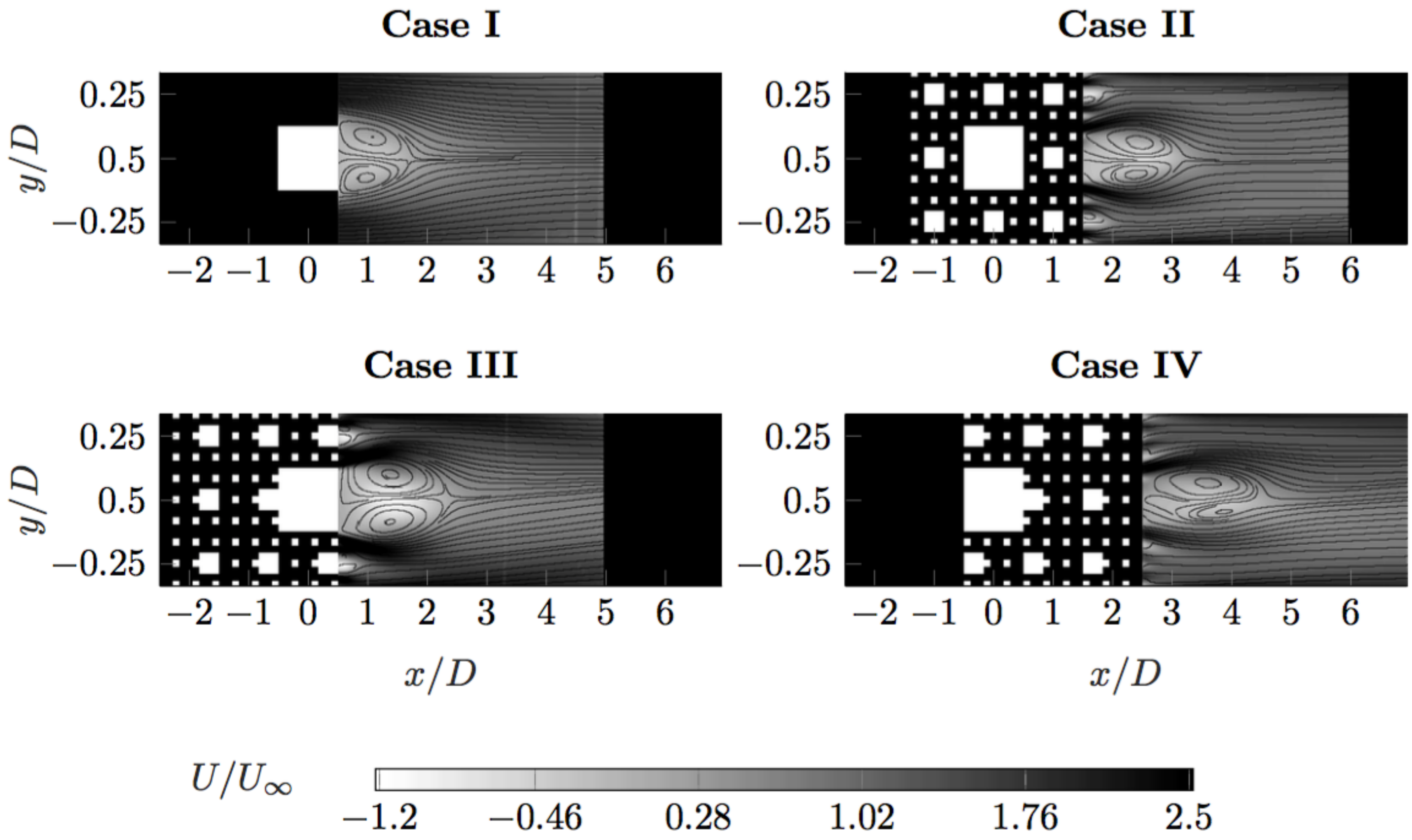


Figure 3: Contour plots of the streamwise mean velocity, U, normalised by the bulk velocity, U_{∞}, with streamlines overlaid

(Higham J.E. & Brevis W. (In Press) - Experimental Thermal and Fluid Science.)

Streamwise mean flow (centre line)

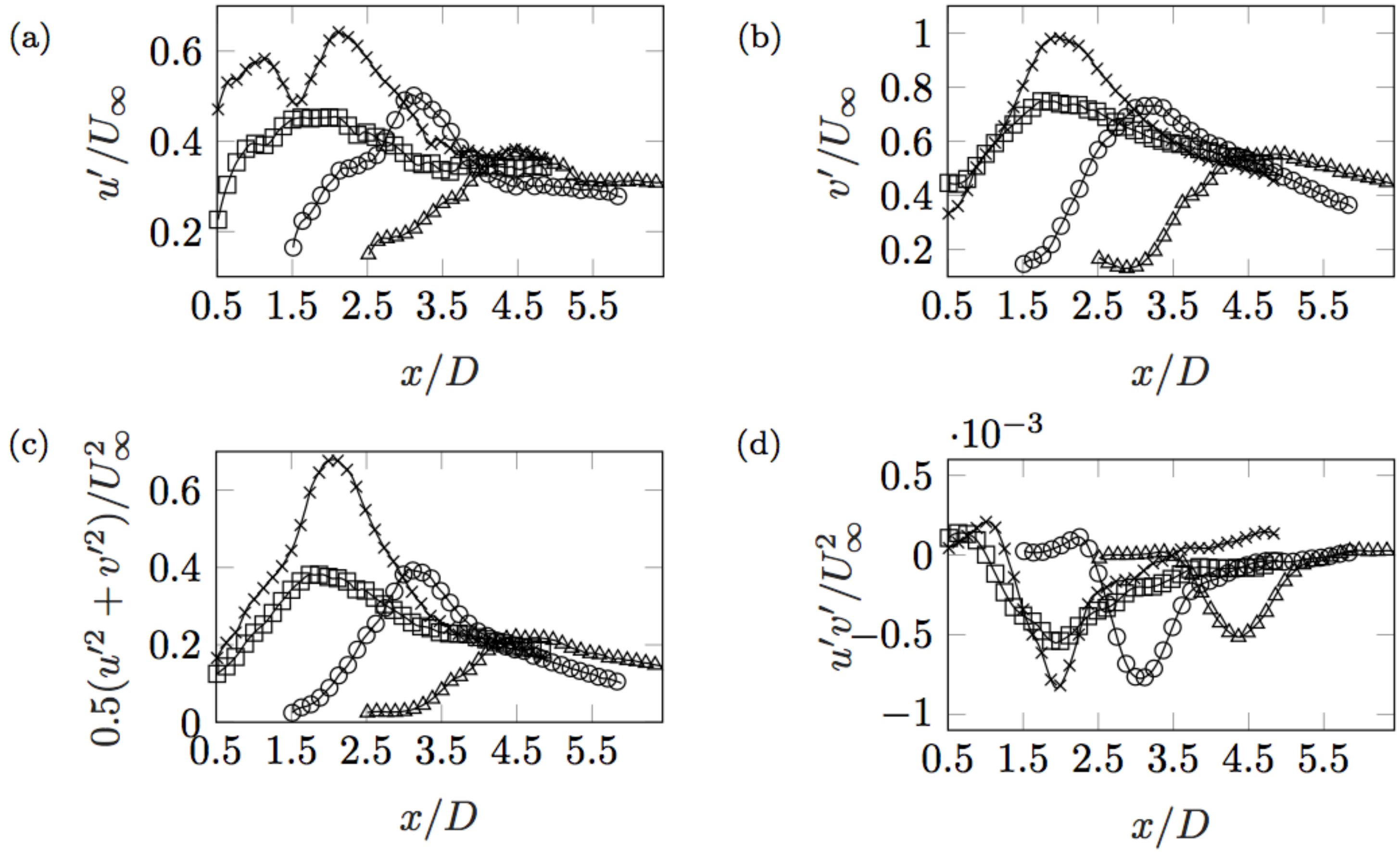


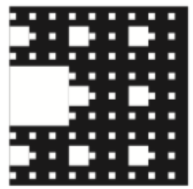
Figure 4: Centre line time averaged statistics. Case I – □, case II – ○, case III – × & case IV – △. (a) u'/U_∞, (b) v'/U_∞, (c) $0.5(u'^2 + v'^2)/U_\infty^2$ & (d) $u'v'/U_\infty^2$.

Case I

Case II

Case III

Case IV



(Higham J.E. & Brevis W. (In Press) - Experimental Thermal and Fluid Science.)

POD ($\Phi_{1\ \&\ 3}$)

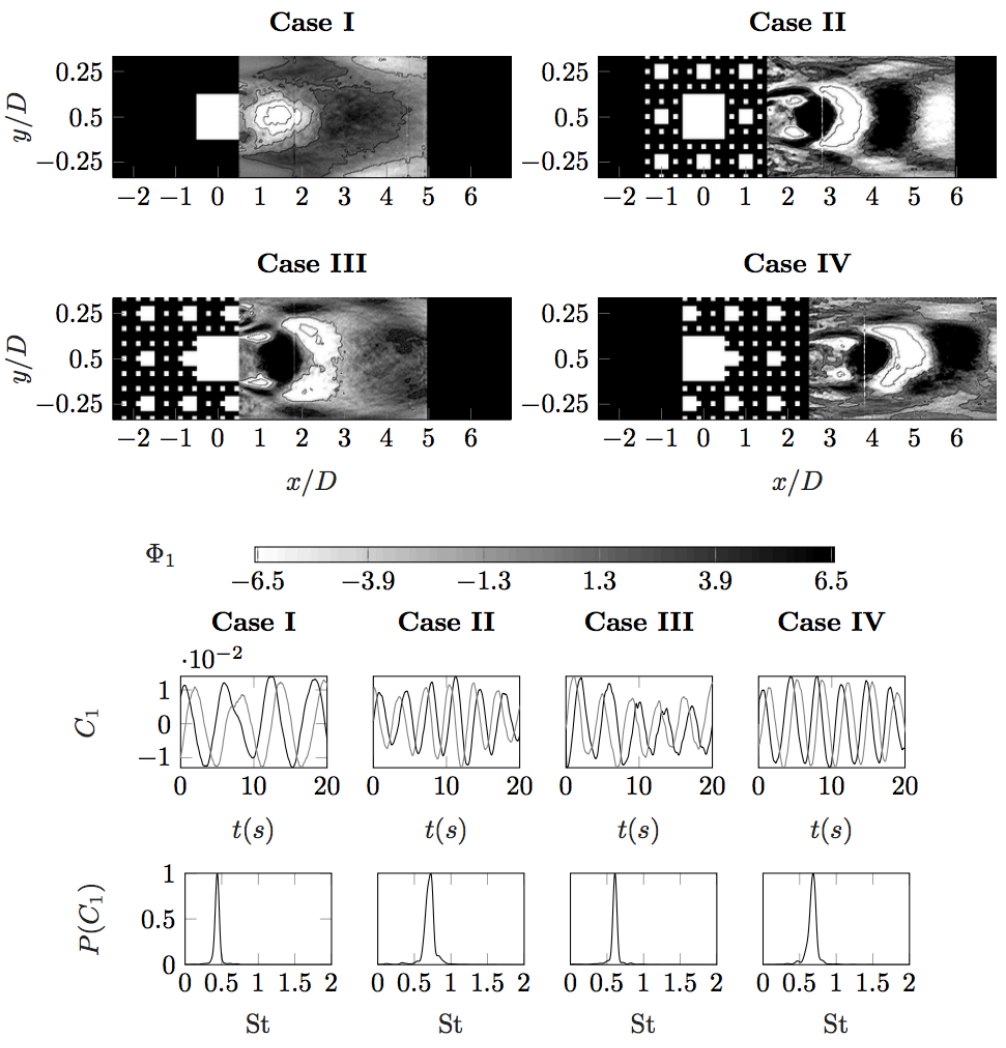


Figure 6: Top: POD modes $\mathbf{\Phi}_1$. Middle: POD temporal coefficients $\mathbf{C}_1$&$\mathbf{C}_2$ (grey). Bottom: Fourier power spectrum of $\mathbf{C}_1$. ($\mathbf{\Phi}_2$ is not plotted as it is a conjugate pair of $\mathbf{\Phi}_1$.)

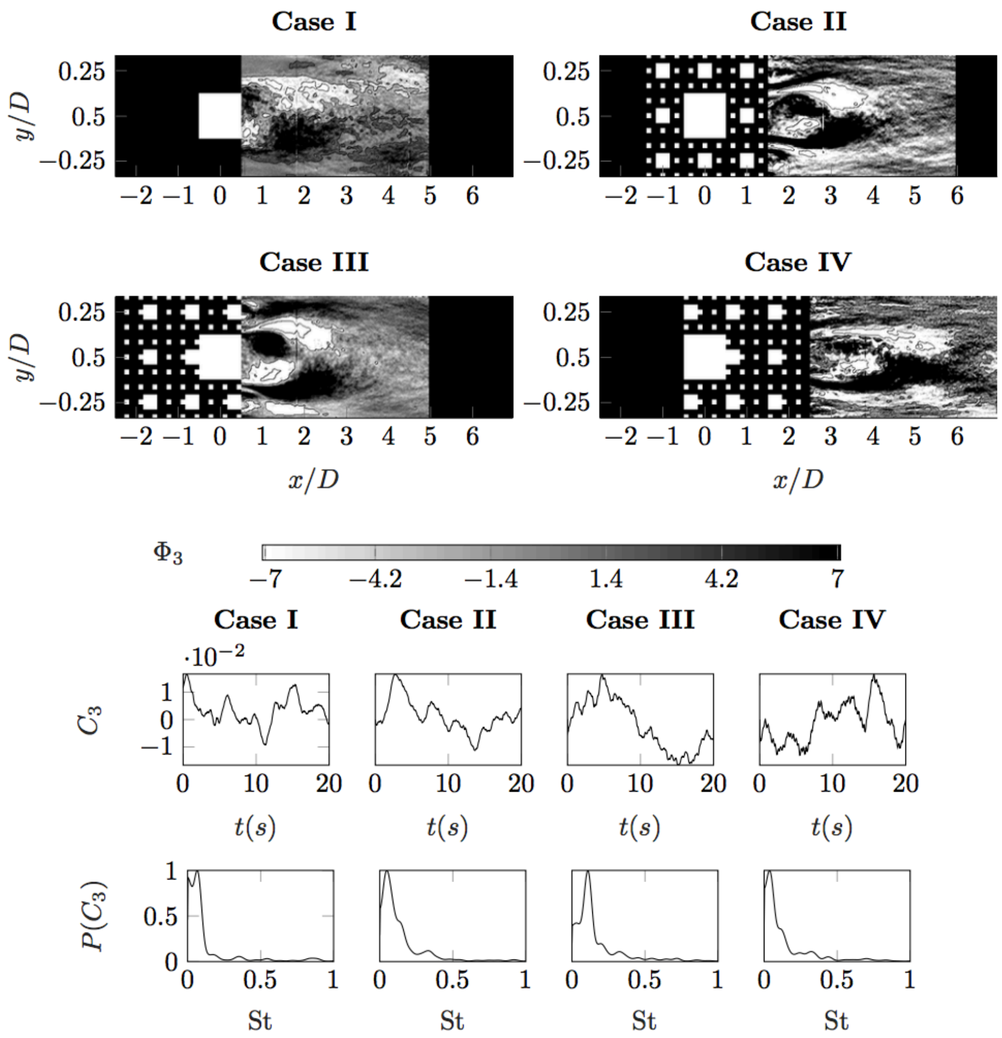


Figure 7: Top: POD modes $\mathbf{\Phi}_3$. Middle: POD temporal coefficients $\mathbf{C}_3$. Bottom: Fourier power spectrum of $\mathbf{C}_3$.

(Higham J.E. & Brevis W. (In Press) - Experimental Thermal and Fluid Science.)

POD (Φ_4)

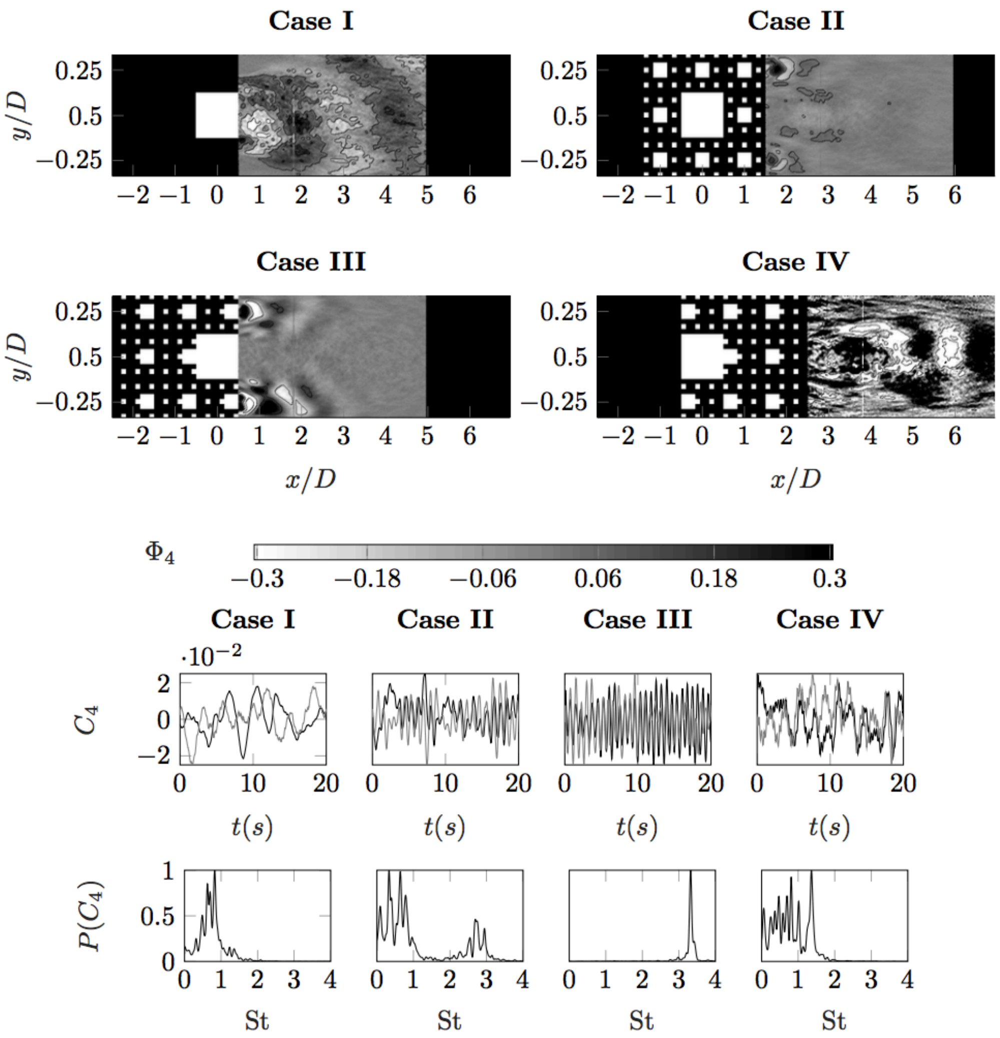


Figure 8: Top: POD modes $\mathbf{\Phi}_4$. Middle: POD temporal coefficients $\mathbf{C}_4$&$\mathbf{C}_5$ (grey). Bottom: Fourier power spectrum of $\mathbf{C}_4$. ($\mathbf{\Phi}_5$ is not plotted as it is a conjugate pair of $\mathbf{\Phi}_4$.)

(Higham J.E. & Brevis W. (In Press) - Experimental Thermal and Fluid Science.)

POD Spectra

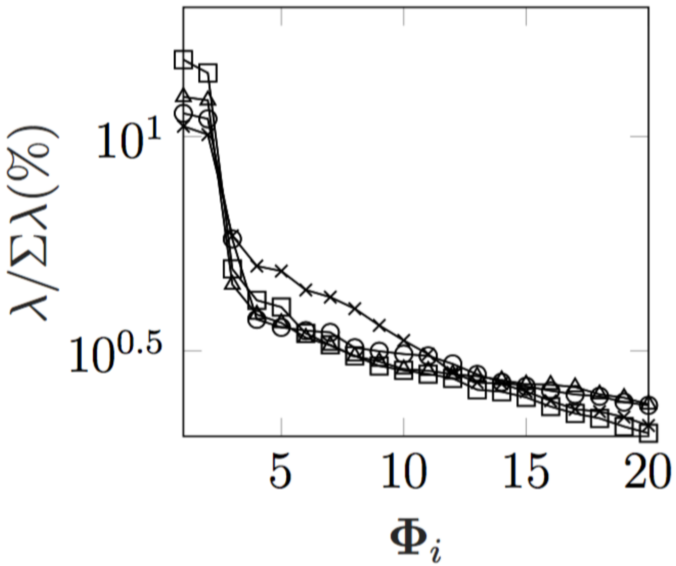
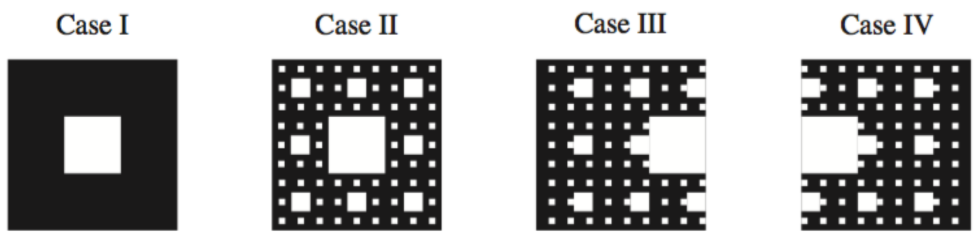


FIGURE 6.5: POD spectra where $\lambda = diag(\mathbf{S})$, these values represent the contribution of each the spatial modes $\mathbf{\Phi}_i$ to the total variance. Case I – $\square$, case II – $\bigcirc$, case III – $\times$ & case IV – $\triangle$.



(Higham J.E. & Brevis W. (In Press) - Experimental Thermal and Fluid Science.)

Conclusions

- The POD offers a wealth of information not typically attained from time-averaging.
- From these results we can see that the structures of the turbulence has changed.
- Therefore, we suggest that the arrangement of the multi-scales can be used to manipulate the turbulent flows.
- From further work we also show from time resolve data the ratio between the Taylor and Kolmogorov micro scales changes.

Future…

- So we know the Navier-Stokes doesn't apply - can we apply these modal decomposition techniques to the fluidised beds and the risers…

Questions?

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