Politecnico di Torino
Dipartimento di Scienze Matematiche "G. L. Lagrange"
DISMA ECCELLENZA 2018·2022

Comparison of the effects of the numerical scheme on the simulation of a flow around a square cylinder

Candidate:
Lorenzo Bellantuono
Michele Lupini
Andrea Tataranni

Supervisors:
Prof. L. Bruno

June 2023

Introduction

In computational wind engineering the investigation of the dynamic structural behavior in response to unsteady wind loadings is crucial to be investigated. In order to accomplish this task a typical civil structure can be imagined as a blunt body.

In this report we will consider some results from the scientific literature concerning the flow around a square cylinder and we will investigate the effects of the variation of the numerical convection scheme on the aerodynamic coefficients and the main quantities of the flow.

Introduction

Problem formulation

Let us consider a square cylinder subjected to an air flow and let's relate it to a dimensionless problem by utilizing density ($\rho = 1$), cross-sectional size ($B = 1$) of the cylinder's section and velocity ($U_\infty = 1$).
Then kinematic viscosity is $\nu = Re^{-1} = \frac{1}{2.2e+4} = 4.54e - 5$.

A RANS approach was followed to simulate the air flow around the cylinder by using a RNG k-ϵ model

- Time advancement: second-order implicit Euler scheme
- Pressure-velocity coupling: solved by a PISO algorithm
- Two cases of study were defined by using QUICK and UDS schemes for the convective term.

Introduction

Preparation to the simulation of the periodic flow

An analysis of the flow was conducted until it is fully established. We defined the end of the transient T_0 by evaluating the difference in the values of two consecutive maxima of the lift coefficient with a transient overshoot threshold $\alpha = 3e - 3$.

By assuming the perfect periodicity of flow, we derived the period of vortex detachment T, coincident with the period of lift oscillation, and we computed the associated Strouhal number $St = T^{-1}$

Case	T_0	T	St
QUICK	149.40	7.24	0.138
UDS	181.20	7.52	0.133

Truncation error

Let us take a generic mono-dimensional problem:

$$\frac{\partial u}{\partial t} + a\frac{\partial u}{\partial x} - \nu\frac{\partial^2 u}{\partial x^2} = g, \quad x \in \mathbb{R}\,, t \geq 0 \tag{1}$$

The truncation errors can be written as

$$\begin{aligned} \tau_j^c &= -\frac{a}{24}\frac{\partial^3 u}{\partial x^3}(x_j)\Delta x^2 + o(\Delta x^2) \qquad \text{QUICK} \\ \tau_j^c &= \frac{a}{2}\frac{\partial^2 u}{\partial x^2}(x_j)\Delta x + o(\Delta x) \qquad \text{UDS} \end{aligned} \tag{2}$$

Truncation error

QUICK It gives a second order approximation of the convective flux, with a third order numerical dispersive term.

UDS It gives a first order approximation of the convective flux, with a second order numerical diffusion term.

The consequence is an over-prediction of viscosity, hence of dissipation when using UDS scheme

$$\nu_{tot} = \nu_{num} + \nu_{air} = \nu_{num} + \mathrm{Re}^{-1} \tag{3}$$

In addition, because of the increased diffusivity, the gradients of the velocity field are flattened.

Aerodynamics coefficients

Case	St	$\overline{C}_D$	$\widetilde{C}_D$	$\widetilde{C}_L$
Lyn	0.135	2.05 $\div$ 2.23	n.a.	n.a.
Sakamoto	0.134	2.22	0.132	1.45
Durao	0.139	n.a.	n.a.	n.a.
Murakami	0.132	2.09	0.13	1.60
QUICK	0.138	1.90	0.056	1.39
UDS	0.133	1.57	0.0082	0.364

Table: Aerodynamic coefficients obtained by experiments and simulations for a flow around a square cylinder.

By observing Table 1 and Figure 1, we can make the following observations

- QUICK exhibit strong correlation with available data
- With UDS, the aerodynamic coefficients are consistently underestimated, particularly the fluctuating ones.
- Strouhal number is slightly underestimated with UDS, but it remains comparable to the results of other experiments [DL94, DD88, SM95, SS89].

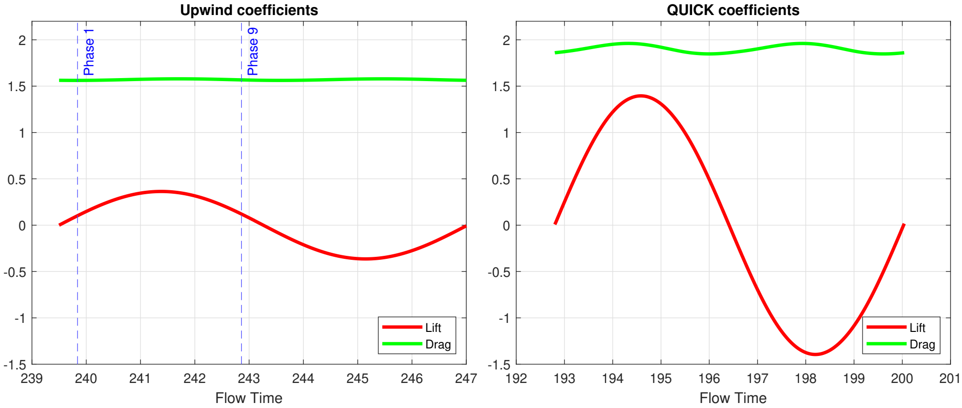


Figure: Graphs of the aerodynamic coefficients for both schemes.

Observing the figure it is evident how much the coefficients are underestimated: the drag coefficient for UDS is almost constant w.r.t. the QUICK's one, while the lift coefficient amplitude is 3 times smaller in UDS.

Politecnico di Torino

Pressure statistics

Pressure statistics around the cylinder are important in terms of structural safety and as a measure of radiated acoustic noise.
By representing mean and rms pressure coefficient distributions around the cylinder with respect to the curvilinear abscissa along the cylinder surface one can note that:

- Front pressure: simulations are in reasonable agreement with the available data
- QUICK: mean and rms pressure coefficients matches with the available data.
    - Side pressure: in agreement with experimental data (Ohtsuki, Lee) and high precision simulations (LES 3D, DNS 3D).
    - Back pressure: follow the trend given by LES 3D, but both are slightly overestimated compared with the experimental data.

Pressure statistics

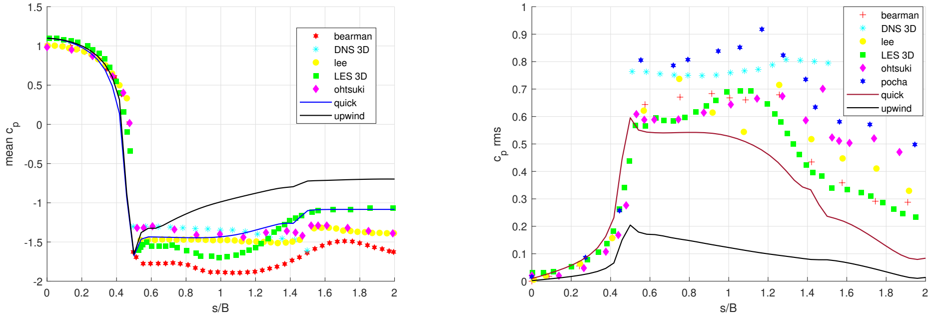


Figure: Mean and rms pressure coefficient distribution around the cylinder. The horizontal axis is the curvilinear abscissa along the cylinder surface, where s/B = 0 corresponds to the stagnation point, while s/B = 0.5 and 1.5 corresponds to the windward and leeward corner of the cylinder, respectively.

Pressure statistics

- UDS: predicts the highest side and back pressure with respect to experiments and simulations, while underestimating the fluctuating component.
  - The overestimation of the back pressure was observed in [Lee97] for all k-ϵ models, but the increase, obtained while maintaining the same turbulence model and varying numerical scheme, suggests another cause related to the overdiffusion of the scheme.
  - The results obtained are similar to the trend of the pressure coefficient of the standard k-ϵ model in [Lee97]. This can be related to the overestimation of the turbulent diffusion on the mean flow given by the standard k-ϵ model, which generates a similar effect to the one caused by the variation in the convection scheme.

Pressure statistics

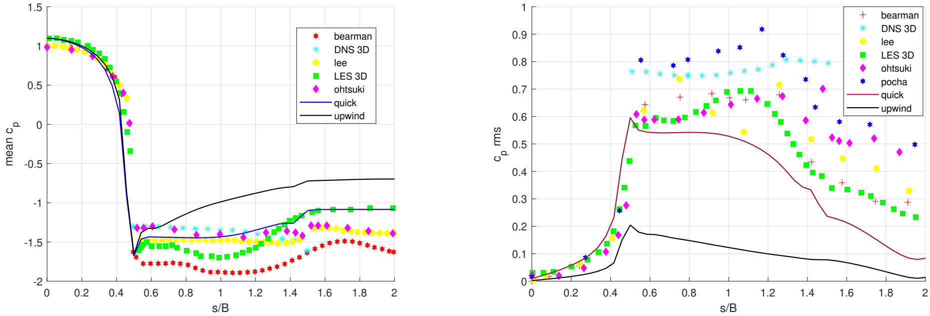


Figure: Mean and rms pressure coefficient distribution around the cylinder. The horizontal axis is the curvilinear abscissa along the cylinder surface, where s/B = 0 corresponds to the stagnation point, while s/B = 0.5 and 1.5 corresponds to the windward and leeward corner of the cylinder, respectively.

Velocity in the wake region along the centerline

QUICK: matches very well with the LES 3D results under all aspects, but also with the experimental data of Durao [DD88] and Lyn [DL94] for the length of the detaching vortex.

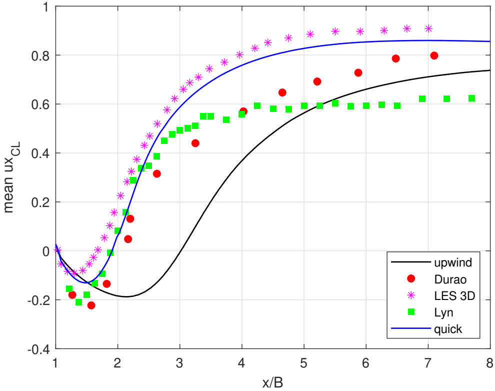


Figure: Mean horizontal velocity along the centerline ($y/B = 0$). $x/B = 1$ represents the downstream side face of the cylinder.

Velocity in the wake region along the centerline

UDS: 2 problems. Firstly, it predicts the detaching vortex too large by a factor of around 1.5 with respect to QUICK and Lyn [DL94]: this is motivated by the over-predicted viscosity, which is known to cause a diffusion of vortexes.

Then it shows a slower recovery of the free-stream velocity in the wake region that can be attributed to the excessive dissipation of kinetic energy in such region, related to the over-predicted length of the detaching vortex.

Velocity in the wake region along the centerline

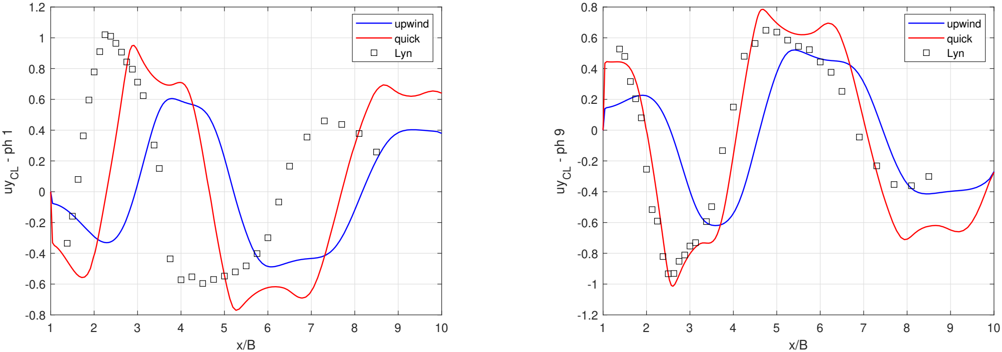
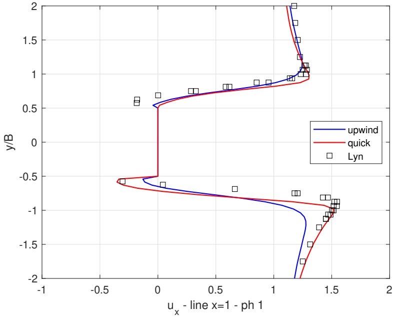


Figure: Instantaneous vertical velocity along the centerline, for phases 1 and 9.

UDS: over-diffusive effect from the flattening of velocity gradients.
QUICK: dispersive effect showed by the oscillations around the regions with steep variations of the vertical velocity.

Velocity distribution on the line $x/B = 1$



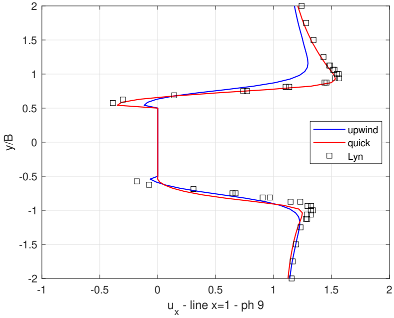


Figure: Longitudinal component of the instantaneous velocity, along the vertical axis passing through the back face of the cylinder ($x/B = 1$), for phases 1 and 9.

UDS: decreased slope of the velocity, but predicts a small reversed flow also on the side in which the vortex is not detaching, **as Lyn's experiments do**.
QUICK: fits well with Lyn's experiments, apart from fixes the velocity to zero in the same point. This holds for both phase 1 and phase 9.

Conclusions

The QUICK scheme is found to adequately reproduce the aerodynamic coefficients.

Instead, UDS tends to underestimate aerodynamic coefficients, while overestimating the side and back pressure and the size of the detaching vortex.

Despite this behaviour, UDS could be helpful when using an approach affected by numerical instability, but as a downside it gives lower accuracy.

In summary UDS could be fine in predicting stationary fluxes with low gradients, but for the examined case of study, which is turbulent and time-dependent, it is not efficient, since we would need a higher spacial resolution to make an accurate prediction, which could be computationally too expensive.

References I

- J.C.F. Pereira D.F.G. Durao, M.V. Heitor, *Measurements of turbulent and periodic flows around a square cross-section cylinder*, Experiments in Fluids **6** (1988), 298–304.
- W. Rodi D.A. Lyn, *The flapping shear layer formed by flow separation from the forward corner of a square cylinder*, Journal of Fluid Mechanics **276** (1994), 353–376.
- S. Lee, *Unsteady aerodynamic force prediction on a square cylinder using k–ϵ turbulence models*, Journal of Wind Engineering and Industrial Aerodynamics **67–68** (1997), 79–90.
- Y. Ohtsuki, *Wind tunnel experiment on aerodynamic forces and pressure distributions of rectangular cylinders in an uniform flow*.

References II

- E.D. Obasaju P.W. Bearman, *An experimental study of pressure fluctuations on fixed and oscillating square-section cylinders*, Journal of Fluid Mechanics **119** (1982), 297–321.
- J.J. Pocha, *On unsteady flow past cylinders of square cross-section*, Ph.D. thesis, Department of Aeronautics, Queen Mary College, London, 1971.
- A. Mochida S. Murakami, *On turbulent vortex shedding flow past 2D square cylinder predicted by cfd*, Journal of Wind Engineering and Industrial Aerodynamics **54** (1995), 191–211.
- S. Sakamoto S. Murakami, A. Mochida, *Cfd analysis of wind-structure interaction for oscillating square cylinders*, Journal of Wind Engineering and Industrial Aerodynamics **72** (1997), 33–46.

References III

Y. Kobayashi S. Sakamoto, H. Haniu, *Fluctuating forces acting on rectangular cylinders in uniform flow*, Transactions of the Japan Society of Mechanical Engineers Ser. B. **72** (1989), 2310–2317.

Grazie per l'attenzione

Politecnico
di Torino

1859