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Numerical Investigation of Unsteady Flows Using OpenFOAM

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Abstract: *In this paper OpenFOAM is used for the numerical investigation of the unsteady flow in a well known numerical benchmark. Von Karman vortex street is obtained in a flow of water past a square cylinder. The results are validated against experimental and numerical investigations from the literature using the drag coefficient. The bazaar-style development of the OpenFOAM toolkit and the principles of Free Software are confirmed to be valid even for the industrial requirements of the computational fluid dynamics (CFD) community. The bazaar-like costs of running OpenFOAM in an established high performance computer center are reduced to the cost of studying the software and understanding how it works.*

Keywords: *OpenFOAM, square cylinder, vortex shedding, Karman vortex street*

1. Introduction

Unsteady flows present one of the most complex natural phenomena and govern most engineering and technological processes involving fluids [23], [24]. Milk factories and plastic factories use vortex dynamics in order to prevent the fluid from clogging the pipes [18]. Lift-induced wingtip vortices and wake turbulence can have hazardous consequences to airliners [19] just as well as vehicle aerodynamics has a direct implication on passenger safety and gas consumption [20]. Turbulence causes bridge structural failures, insects flight and comet tails [17]. Unlike steady-state flows, unsteady flows are described by partial differential equations and quantities that depend on time. Von Karman vortex street is presented in Fig.1.
Numerical investigation of the unsteady flow with von Karman vortex street behind a bluff body is presented. A bazaar-like Free Software [9] system is used in order to model the phenomenon: an opensource computational fluid dynamics (CFD) toolkit called OpenFOAM [5]. The results are compared and validated with numerical and experimental data from literature.
The software system used belongs to a software paradigm contrasted to the classic hierarchical approach. OpenFOAM is free software as defined by [7] and has been created in the spirit of [8] with a bazaar-style development process [9] without any warranties for the validity of the numerical solutions. The software is used in the CFD industry as a substitute for highly expensive solutions which propose a cost model that depends on the number of computer processors in use.
A software solution is Free Software if it enables the following freedoms [7]:

- The freedom to run the program as anyone wishes, for any purpose (freedom 0).
- The freedom to study how the program works, and change it so it does the computing as anyone wishes (freedom 1). Access to the source code is a precondition for this.
- The freedom to redistribute copies so anyone can help their neighbor (freedom 2).
- The freedom to distribute copies of one's modified versions to others (freedom 3). By doing this one can give the whole community a chance to benefit from the changes. Access to the source code is a precondition for this.

The rest of the paper is organized as follows. Section 2 presents the test case used for comparison. Section 3 shows the results obtained and discusses them. In Section 4 conclusions are presented.

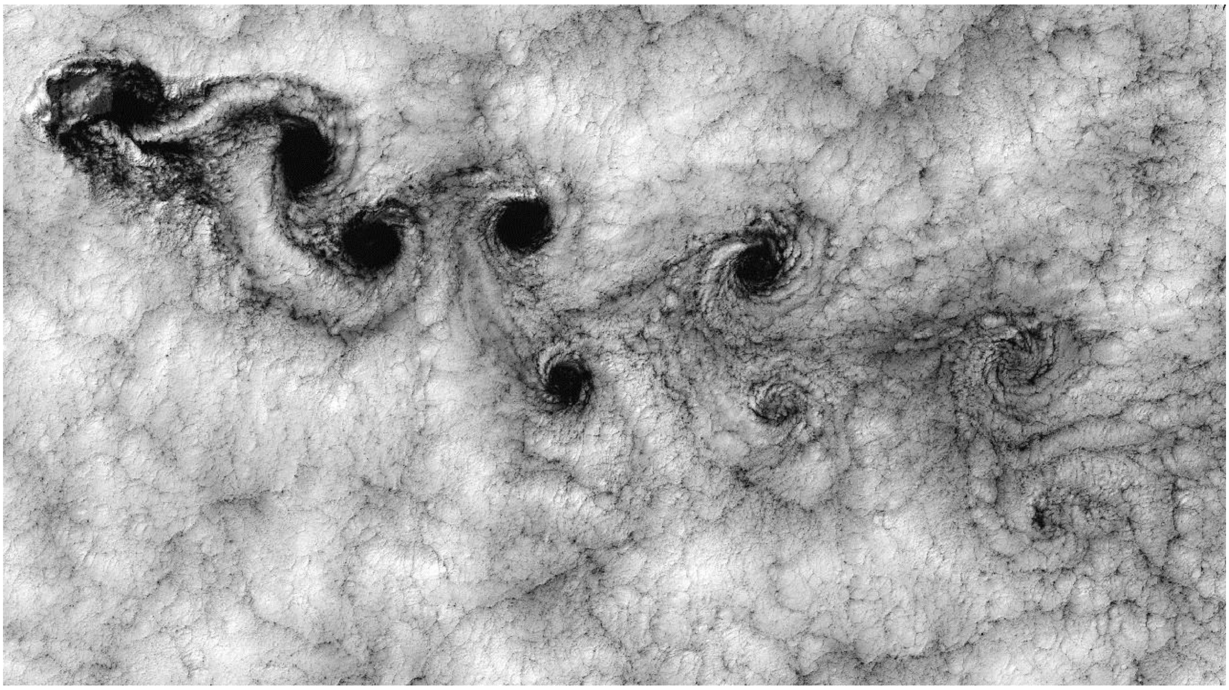

Fig. 1. Karman Vortex street formed by clouds near the Robinson Crusoe Island, courtesy of Landsat [21].

2. The OpenFOAM Test Case Setup

The European Research Community On Flow, Turbulence And Combustion (ERCOFTAC) created the square cylinder test case which is a well known CFD benchmark used for the validation of numerical solvers. The geometry is shown in Fig. 2.

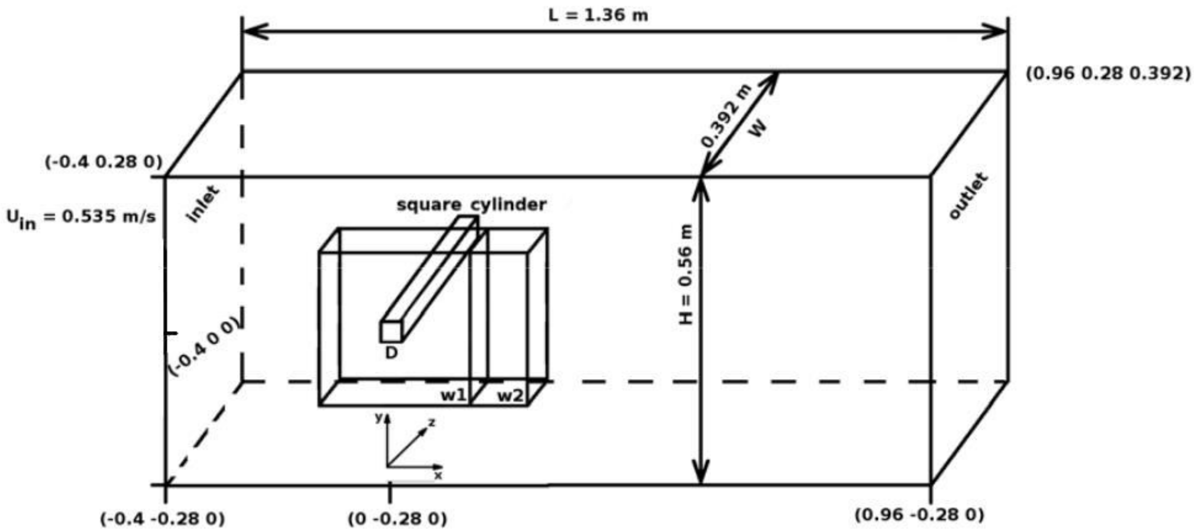

Fig. 2. The ERCOFTAC Square Cylinder Test Case

The governing equations are given in terms of continuity (1) and momentum (2) where v is flow velocity, ρ is fluid density, p is pressure,T is the stress tensor and f are body forces.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \tag{1}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v v) = \rho f + \nabla \cdot T \tag{2}$$

A square cylinder is positioned in a channel at 0.38 m from the inlet. The side of the cylinder is D = 0.04 m and the wideness is W = 0.392 m. The length of the enclosing channel is L = 1.36 m and the height is H = 0.56 m. The origins of the coordinate system are located in the center of the square cylinder on the surface of the viewpoint.

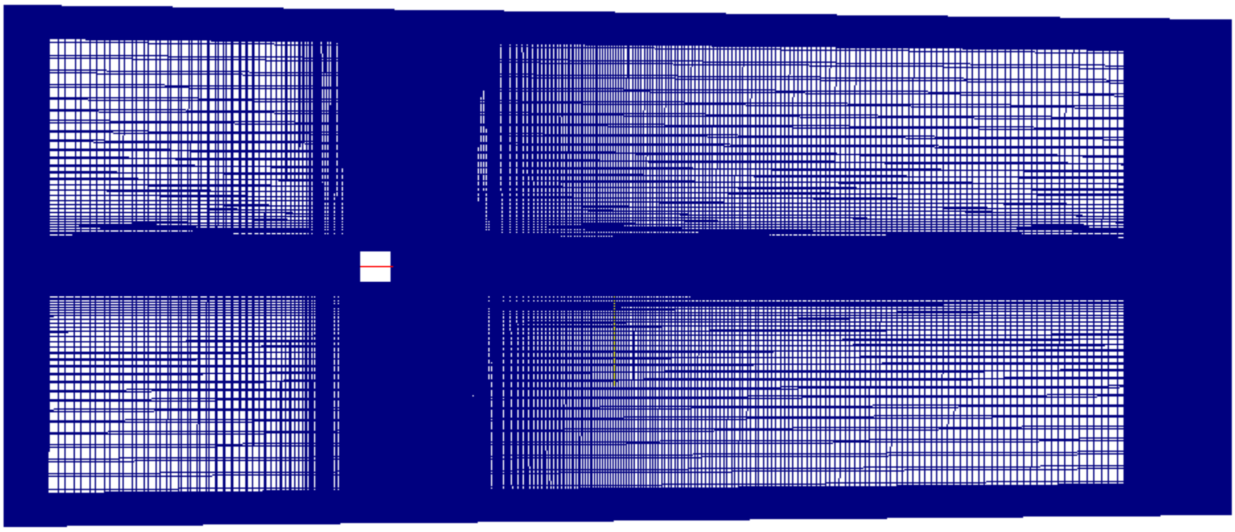

Fig. 3. The mesh generated with the blockMesh tool in OpenFOAM, rendered by ParaView [22]

Water enters the channel at inlet with U_{in} = 0.535 m/s and 2% turbulence forming a von Karman vortex street behind the cylinder. The Reynolds number is computed with the side of the square cross section of the cylinder as Re = 21400. The boundary conditions for the walls of the channel are modelled using slip conditions. Only the 4 surfaces of the square cylinder are considered to be walls. Constant pressure is imposed at zero value on the outlet.
The mesh generated with the blockMesh tool from the OpenFOAM toolkit is shown in Fig. 3. It contains 3 million hexahedral cells and is denser around the bluff body in order to capture the vortex street.
Large Eddy Simulation (LES) [11] is used with a sub grid scale (SGS) model [12]. The pressure-velocity coupling algorithm is a blend between Pressure Implicit with Splitting of Operators (PISO) and the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE). The test case is solved using the pimpleFoam application [13].

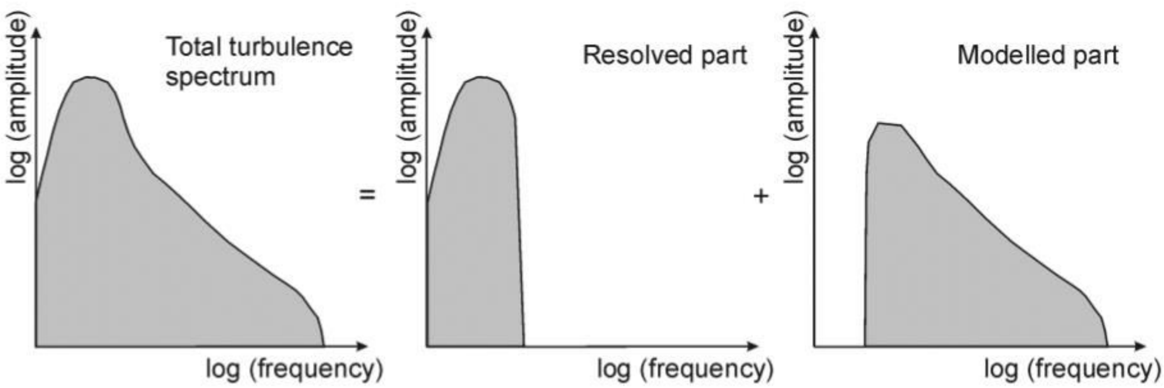

Fig. 4. Modelling approach in Very Large Eddy Simulation (VLES) [2]

Fig. 4 shows the modelling approach in VLES. The total turbulence spectrum is obtained by combining the resolved part with the unresolved or modelled part. The tendency to solve complex unsteady turbulent flows at high Reynolds number is to apply the principle "solve less – model more" [2].

TABLE 1: Computational requirements for turbulence modelling [14]

Approach	Reynolds dependency	Empirical	Required mesh size	Required time steps	Availability
RANS	Weak	High	10^7	$10^{3.5}$	1995
VLES	Weak	High	10^8	10^4	2000
LES	Weak	Small	$10^{11.5}$	$10^{6.7}$	2045
DNS	strong	Zero	10^{16}	$10^{7.7}$	2080

Table 1 presents the computational requirements for turbulence modelling. The Smagorinsky model is used [15].

3. Results and discussion

The simulation is performed on a cluster of 256 processors with a time step $\Delta t = 10^{-3}$ seconds and a fine mesh of 3 million hexahedral cells. The Courant number is monitored to vary between CFL = 0.8 and CFL = 1. Fig. 5 shows the von Karman vortex street forming behind the cylinder as captured by the simulation.

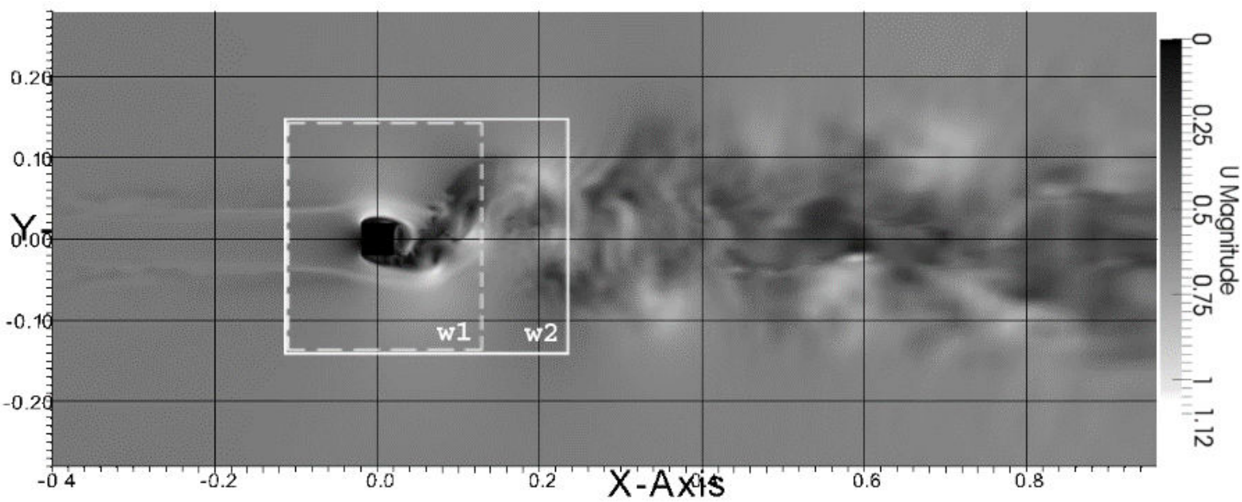

Fig. 5. Von Karman vortex street behind cylinder

Fig. 6 shows the drag coefficient for the square cylinder computed using a pressure probe installed downstream the cylinder, on its surface. The drag coefficient C_d varies around 2.2 in agreement with the numerical results of [1] and the experimental data of [3] and [4] where the same test case is analysed at Re = 21400.

TABLE 2: Comparison with results from the literature

Results	Drag coefficient *Cd*	Reynolds *Re*	Investigation type
Reference [1]	2.03 – 2.78	21400	Numerical
Reference [3]	2.1	21400	Experimental
Reference [4]	2.1	21400	Experimental
OpenFOAM results	2.2	21400	Numerical

Table 2 compares the results obtained with OpenFOAM with well known literature investigations, both numerical and experimental. At Re = 21400 the obtained drag coefficient of C_d = 2.2 matches the values from the experimental results of [3], [4] and the numerical investigations of [1].Given that the Strouhal number in (3) is

$$St = \frac{fL}{U} \tag{3}$$

the frequency *f* obtained in Fig. 6 also confirms the results previously present in the literature.

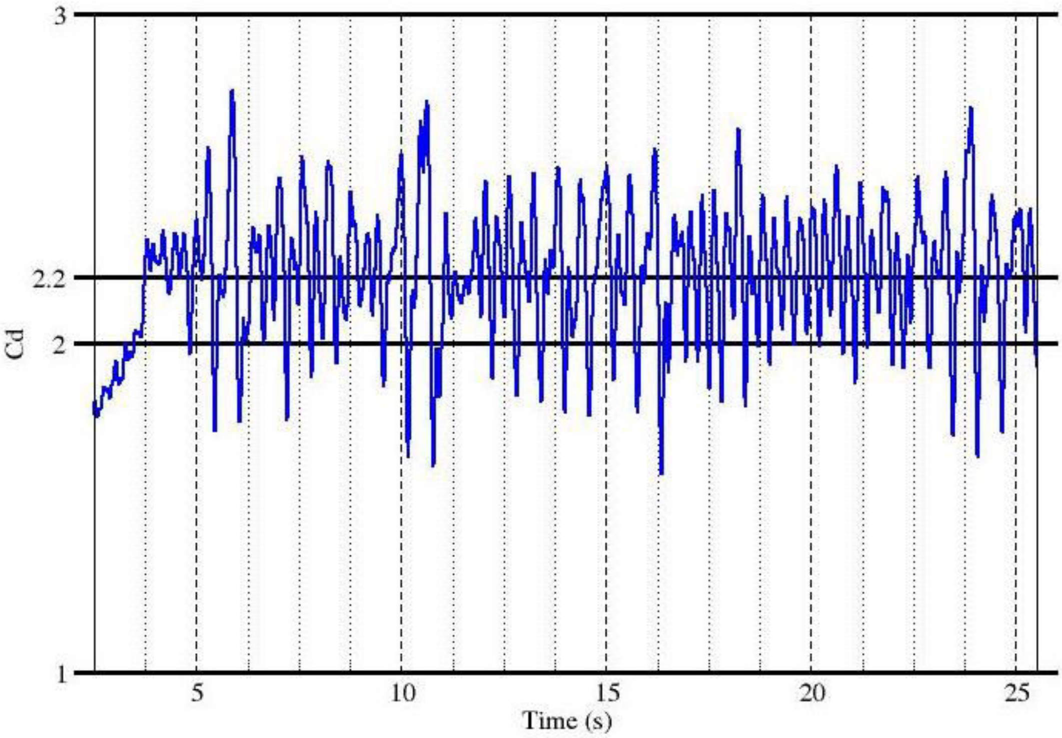

Fig. 6. The drag coefficient Cd for the square cylinder

Expensive and proprietary solutions can always be replaced by affordable Free Software with competitive results, which produce the same numerical data much faster and free of charge.

4. Conclusion

Numerical investigation of unsteady flow past a square cylinder has been performed. The numerical results obtained with OpenFOAM, a Free Software developed in bazaar-style process have been validated with data from the literature, both numerical and experimental. The drag coefficient has been obtained to be in agreement with the referenced results.

It can be concluded that even though OpenFOAM is a bazaar software with warrantless implementations of the numerical schemes, it provides valid results as compared to the benchmark test cases from the literature. The advantage of OpenFOAM is that of being Free Software and the fact that it also provides free solvers without embedding any additional costs for running it in parallel.

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