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# Tdyn-CFD+HT - Validation Case 2

## Flow behind a Circular Cylinder

Tdyn

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15.1.0

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# Table of Contents

# 1 Validation Case 2 - Flow Behind a Circular Cylinder

This case studies the wave development behind a circular cylinder, at Reynolds numbers from 20 to 1000, for which we expect a vortex street in the wake of the cylinder, the well known von Kármán vortex street.

The fluid domain Ω is a two-dimensional plane geometry with a cylinder of radius R=2 m. Numerical calculations of the 2-D flow past the cylinder are presented and results are compared against the experimental results found in reference [1]. Solutions are obtained for a wide range of Reynolds numbers from 20 to 1000.

The Reynolds number range of periodic vortex shedding is divided into two distinct subranges. At Re=60 to 150, called the stable range, regular vortex streets are formed and no turbulent motion is developed. The range Re=150 to 300 is a transition regime called irregular range, in which velocity fluctuations accompany the periodic formation of vortices.

The boundary conditions used in the problem are the following:

-Null normal velocity (free-slip condition) is applied at both upper and lower boundaries $\Gamma_{Velocity}$ of the domain. The vertical component of the velocity has been fixed to null value (Fix Y velocity is marked).

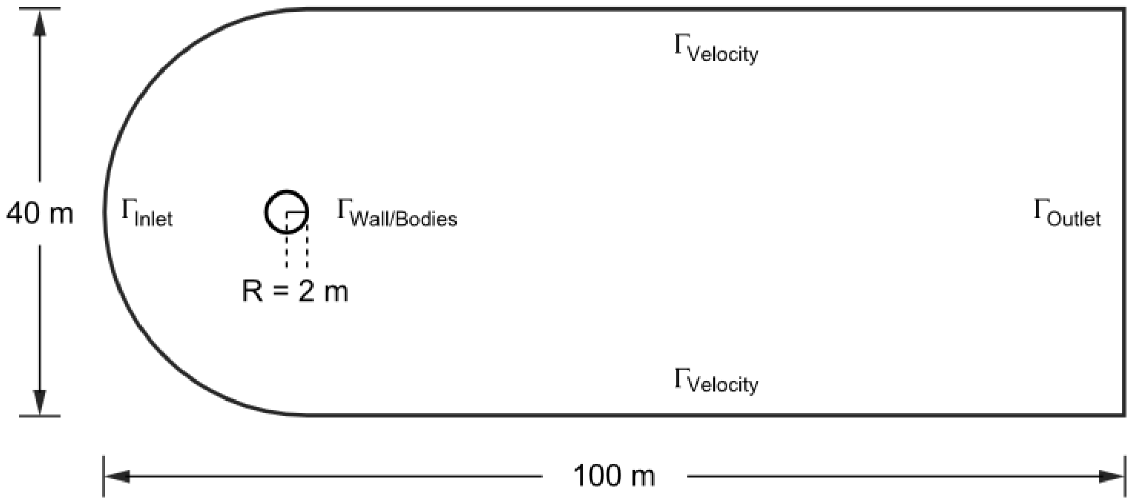
-Null velocity ('V FixWall' condition) is applied at the contour of the cylinder $\Gamma_{Wall/Bodies}$.

-The Inlet velocity is assigned at the left boundary $\Gamma_{Inlet.}$

-Fix pressure field is assigned at the right boundary $\Gamma_{Outlet.}$

A brief summary of the boundary conditions that have been applied on the space domain is given as follows:

| Condition | Boundary |
|---|---|
| V FixWall | $\Gamma_{Wall/Bodies}$ |
| Fix X velocity field | $\Gamma_{Inlet}$ |
| Fix pressure field | $\Gamma_{Outlet}$ |
| Fix velocity | $\Gamma_{Velocity}$ |




Schematic diagram of applied boundary conditions in the space domain

A complete description of this problem is presented in reference [1].

## Problem description

The problem consists of a two-dimensional flow over a circular cylinder, with the following characteristics:

- User defined problem
  Simulation dimension: 2D plane
  Multi-physics analysis: Fluid flow

- Geometry
  2D plane geometry of a cylinder with radius R=2 m.

- Domain
  Steady-state, stationary.

- Material properties
  Density $\rho$=1 kg/m$^3$
  Viscosity $\mu$=0.2 kg/(m·s)

- Fluid Models
  Laminar fluid model is assumed for all the simulations.

- Fluid properties
  Fluid parameters are adjusted in order to match the required Reynolds numbers. The fluid

is assumed to be incompressible in all the cases under analysis, and Re is the only dimensionless number governing the fluid flow behaviour. For the sake of simplicity, Re is modified for each case, by just changing the viscosity μ of the fluid, while keeping constant the density ρ, the inlet velocity V and the radius R of the cylinder.

| Re | ρ [ Kg/m3 ] | V [ m/s ] | R [ m ] | μ [ Kg/m·s ] |
|---|---|---|---|---|
| 20 | 1.0 | 1.0 | 2.0 | 0.2 |
| 40 | 1.0 | 1.0 | 2.0 | 0.1 |
| 100 | 1.0 | 1.0 | 2.0 | 0.04 |
| 200 | 1.0 | 1.0 | 2.0 | 0.02 |
| 300 | 1.0 | 1.0 | 2.0 | 0.01333 |
| 400 | 1.0 | 1.0 | 2.0 | 0.01 |
| 800 | 1.0 | 1.0 | 2.0 | 0.005 |
| 1000 | 1.0 | 1.0 | 2.0 | 0.004 |
| 2000 | 1.0 | 1.0 | 2.0 | 0.002 |

- Boundary Conditions

  Inlet: fix velocity condition is assumed at the left boundary of the space domain, which has been discretized by using a C-grid.

  Outlet: fix pressure is specified at the right boundary of the space domain.

  Wall/Body: V FixWall condition has been used to enforce the non-slip condition at the surface of the cylinder.

  Other: null normal velocity (free-slip condition) is assumed at both the upper and lower boundaries of the space domain.

- Initial conditions

  Velocity: initialized within the entire space domain to the value specified at the Inlet boundary.

  Pressure: automatically initialized to 0.0.

- Solver parameters

  All simulations were run using the implicit fractional step solver.

  Assembling type: mixed.

  Time step: 0.25 s.

  Non-symmetric solver: Bi-Conjugate Gradient (tolerance = 1.07E-07) with ILU preconditioner.

Symmetric solver: Conjugate Gradient (tolerance = 1.0E-07) with ILU preconditioner.

## Mesh

All the simulations has been performed with the same geometry, and mesh size parameters. In order to generate the mesh, some structured subdivisions of the space domain Ω were necessary.

The space domain is discretized by a structured grid of quadrilateral elements. The finite elements mesh has 7875 nodes, and 8605 quadrilateral elements.

## Results

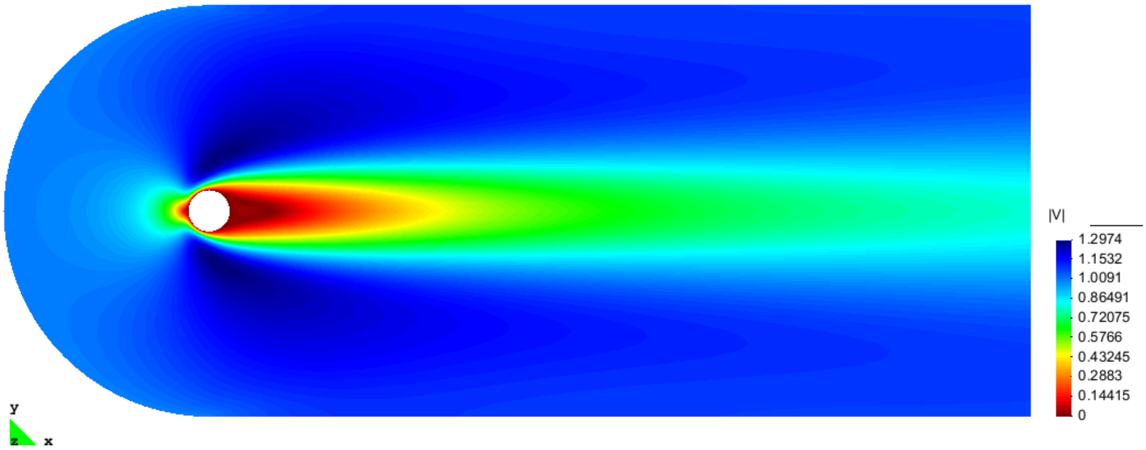
The frequency of the vortices shed in a Kármán vortex street is a characteristic of the flow behind a circular cylinder, and has been extensively measured and reported in references [1] and [2]. A regular Kármán street can be observed in the range 60 < Re < 5000. At lower Reynolds numbers the wake does not oscillate, while at higher Reynolds numbers there is a complete turbulent mixing.

The shedding frequency is usually expressed in terms of the dimensionless frequency, known as Strouhal number $S$, as follows,

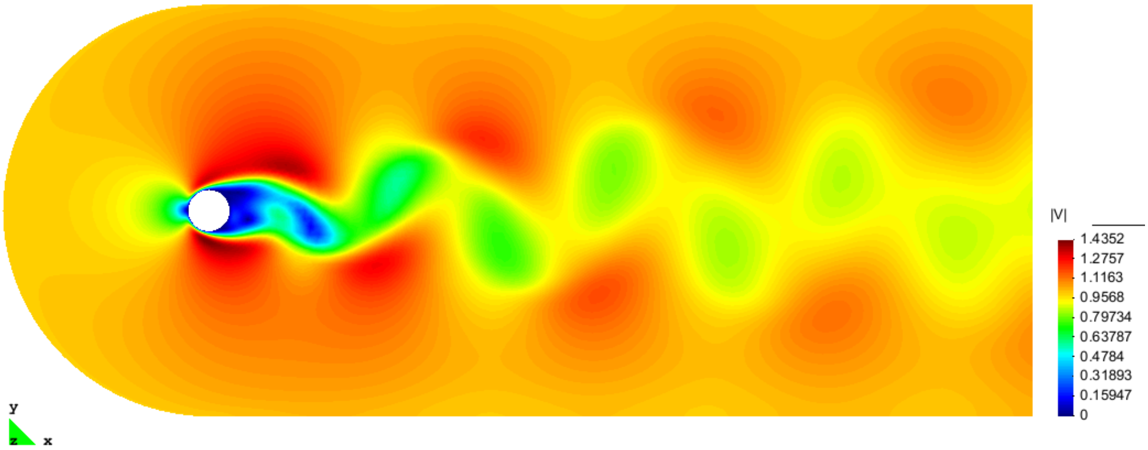
$$S = \frac{f \cdot D}{V}$$

where $f$ is the shedding frequency (from one side of the cylinder), $D$ is the cylinder diameter, and $V$ is the free-stream velocity. It should be noted that the Strouhal number depends only on the Reynolds number.

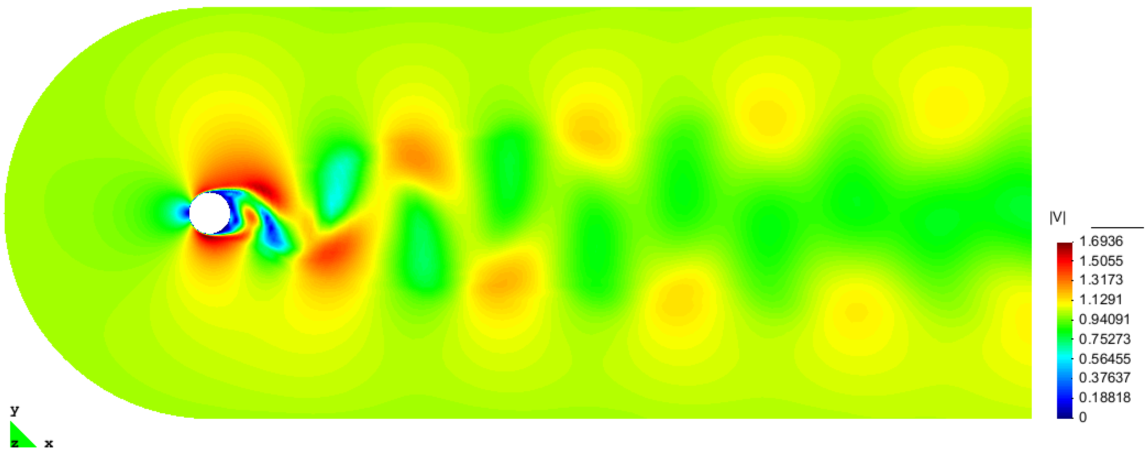
The figures below shows the velocity field around the cylinder at the last time step (t = 10.25 s) of the simulation, for the given mesh and for a range of Reynolds numbers. It can be appreciated the transition from a stationary symmetric wake for low values of Re, to the formation of the characteristic Kárman vortex street when Re is increased.




Flow velocity over the cylinder at the last time step (t = 10.25 s). Re = 20

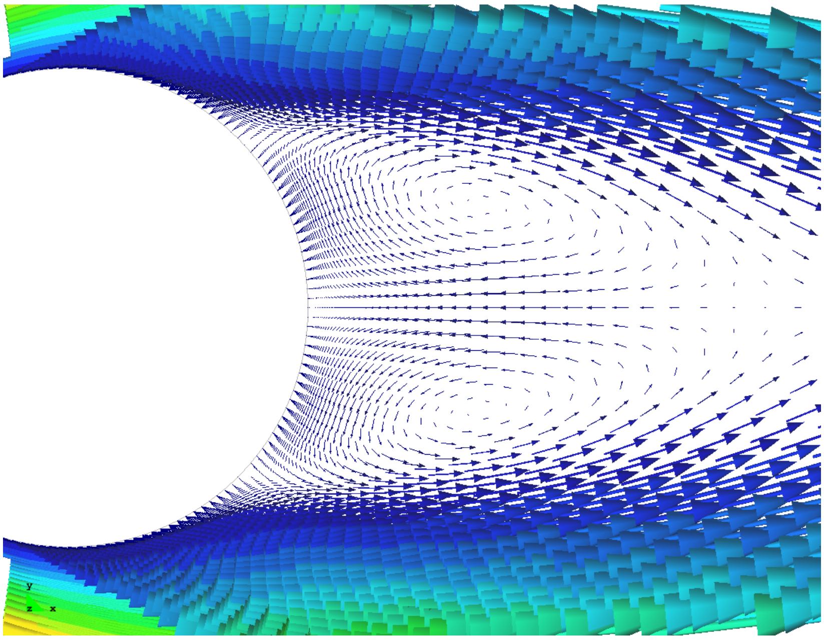



Flow velocity over the cylinder at the last time step (t = 10.25 s). Re = 100

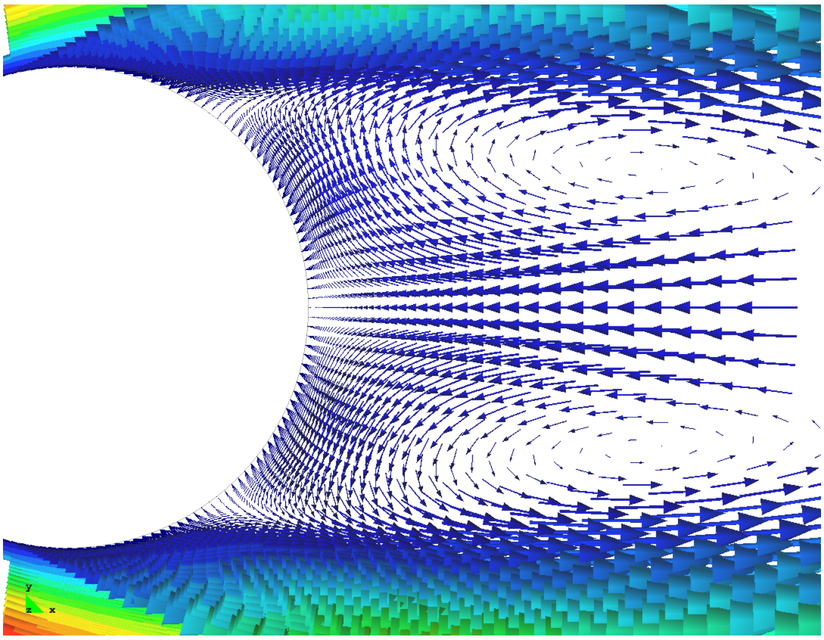



Flow velocity over the cylinder at the last time step (t = 10.25 s). Re = 1000

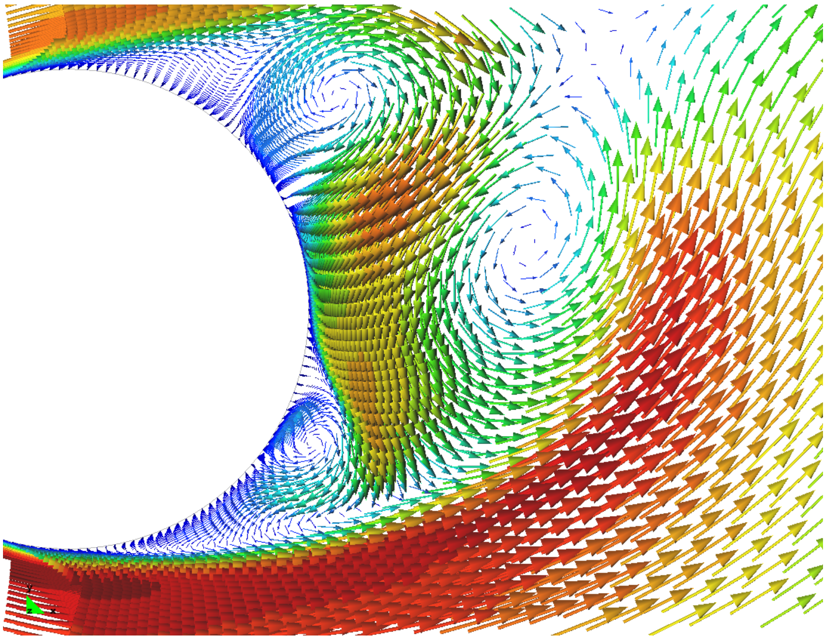
Figures below show the velocity vector field over the cylinder.



Velocity vector field, Re = 20



Velocity vector field, Re = 40

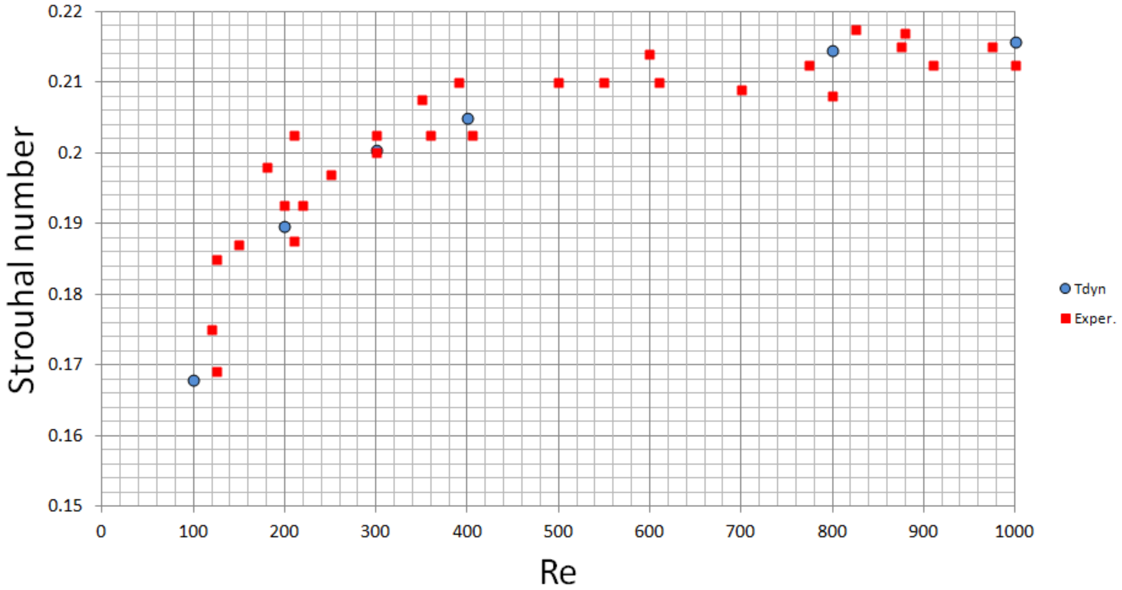


Velocity vector field, Re = 2000

It is important to note that a pair of symmetric vortices is formed at low Reynolds numbers. These vortices are stretched when Re is increased. Moreover, vortices are shedded thus forming the vortex street propagating through the wake over the cylinder.

## Verification

The Strouhal number has been used here as a verification parameter for Tdyn solver. In this way, the experimental measurements of S are presented in the following graph (see reference [1]), together with the present Strouhal numbers of Tdyn, for a wide range of Reynolds numbers.




Strouhal number against Reynolds number over the circular cylinder.

It should be emphasized that Tdyn offers an excellent agreement with the measurements given in reference [1].

The following table shows the pressure values associated with the numerical solution for the given mesh, of the current Tdyn software package version versus the reference Tdyn result, at two points P1 (-2.0,0.0,0.0) and P2 (2.0,0.0,0.0) of the domain.

| Re = 20 | Pressure (Pa) Ref. Value | Pressure (Pa) Curr. Value | Error ( %) |
|---|---|---|---|
| P1 | 0.82937 | 0.82937 | 0.0 |
| P2 | -0.31396 | -0.31396 | 0.0 |

| Re = 10 0 | Pressure (Pa) Ref. Value | Pressure (Pa) Curr. Value | Error (% ) |
|---|---|---|---|
| P1 | 0.64404 | 0.64404 | 0.0 |
| P2 | -0.39421 | -0.39421 | 0.0 |

| Re = 30 0 | Pressure (Pa) Ref. Value | Pressure (Pa) Curr. Value | Error (% ) |
|---|---|---|---|
| P1 | 0.60881 | 0.60881 | 0.0 |

| P2 |
|---|

## References

[1] A. Roshko. On the development of turbulent wakes from vortex streets. NACA report 1191. 1954.

[2] H. Schlichting. Boundary layer theory.

## Validation Summary

| CompassFEM version | 15.1.0 |
|---|---|
| Tdyn solver version | 15.1.0 |
| RamSeries solver version | 15.1.0 |
| Benchmark status | Successfull |
| Last validation date | 27/11/2018 |