# A BENCHMARK ON THE AERODYNAMICS OF A RECTANGULAR 5:1 CYLINDER


## REQUESTS FOR COMPUTATIONAL SIMULATIONS

International Association for Wind Engineering

Associazione Nazionale per l'Ingegneria del Vento

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## 1. Introduction

In the following sections, the data are described which are necessary to allow comparisons to be carried out of the results obtained by all the researchers involved in the benchmark.
The data are subdivided in *required* and *encouraged*: while the former are mandatory for all the researchers participating in the benchmark, in order to assure that a minimum amount of information is always available, the latter are strongly recommended to allow as many data as possible to be compared. Of course, every researcher is free to include any *additional* data that are considered significant from a scientific point of view.

## 2. Physical model:

a. Reynolds Number (with respect to dimension *D*) (required)
b. Mach number (if incompressible M=0) (required);
c. state law (if compressible) (encouraged);
d. approach to turbulence: unsteady RANS, LES, DES, DNS, ... (required);
e. closure turbulence model (required);
f. wall treatment (wall functions, damping functions, …) (required).

## 3. Model Geometry (see Figure 1 for notations):

a. shape of the boundary of the computational domain in the *xy* plane (rectangular, circular, …) (required);
b. dimensions $\mathcal{D}_x$, $\mathcal{D}_y$ , $\mathcal{D}_z$ of the computational domain in all directions ($\mathcal{D}_z = 0$, 2D domain)(required);
c. maximum distance $\Lambda_x$ in the *x*-direction of the input boundary from the leading edge (required);
d. radius of curvature of the model cross section edges (R=0, sharp edges) (required).

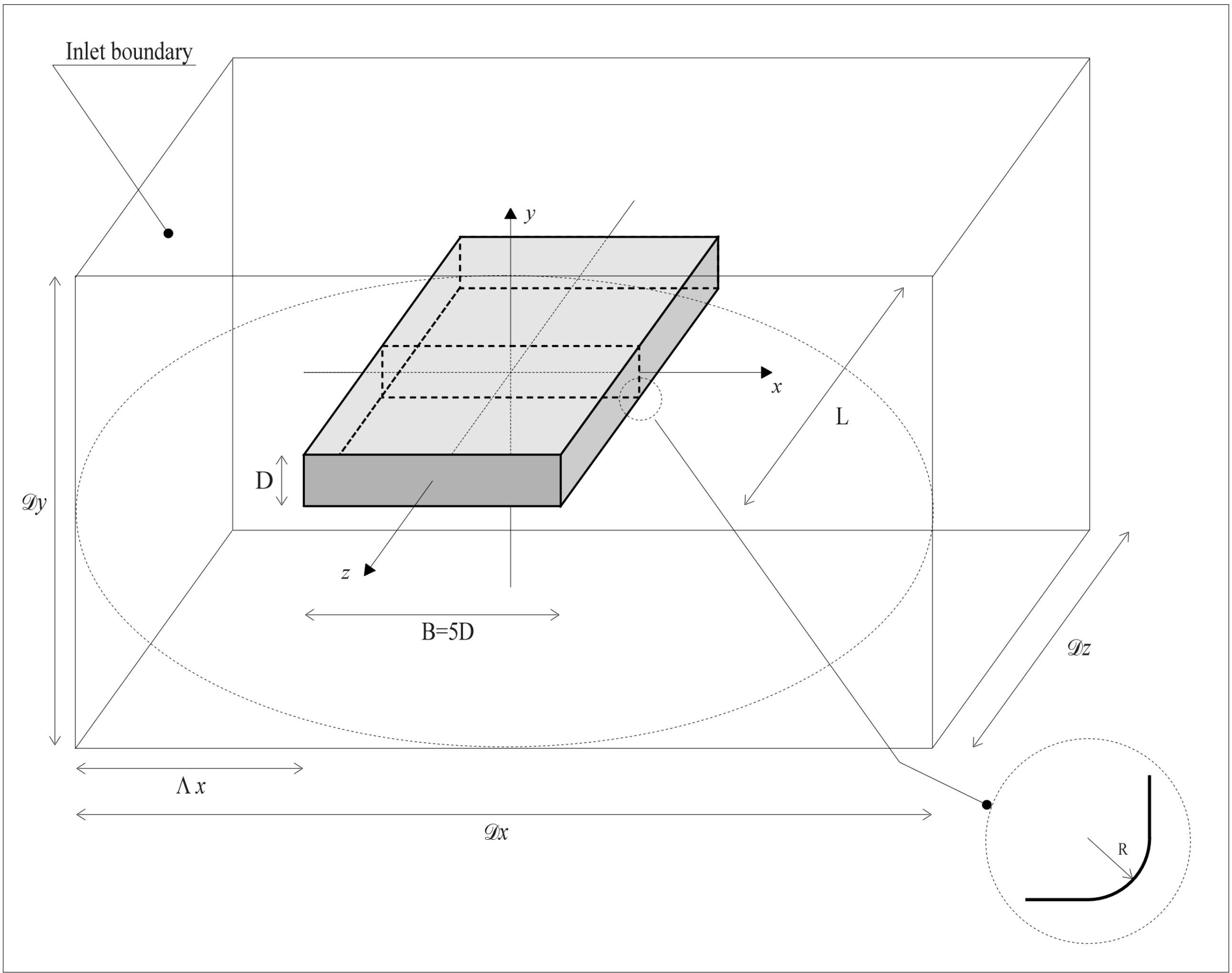


Figure 1 - Model geometry

4. **Space Grid** (see Figure 2 for notation):
    a. grid topology (fully structured, fully unstructured, unstructured in the *xy* plane and structured along the *z* axis, number and types of blocks) (required);
    b. number of nodes (required);
    c. number of cells (required);
    d. maximum, minimum and averaged normal distance *nw* from the wall of the first node layer closest to the wall (non-dimensionalized with *D,* required);
    e. number of cells and growing ratio in the grid boundary layer at wall (if any)(encouraged);
    f. maximum, minimum and average grid element size $\Delta_z$ in the spanwise direction *z* (required for 3D computational domains only);
    g. distribution of the cell volume *Vc* and skewness *Sk* along the straight lines *y/D*=0 and *x/D*=3.5 at *z/D*=0 (encouraged, ASCII file with three columns format: *x* or *y* , *Vc, Sk*).

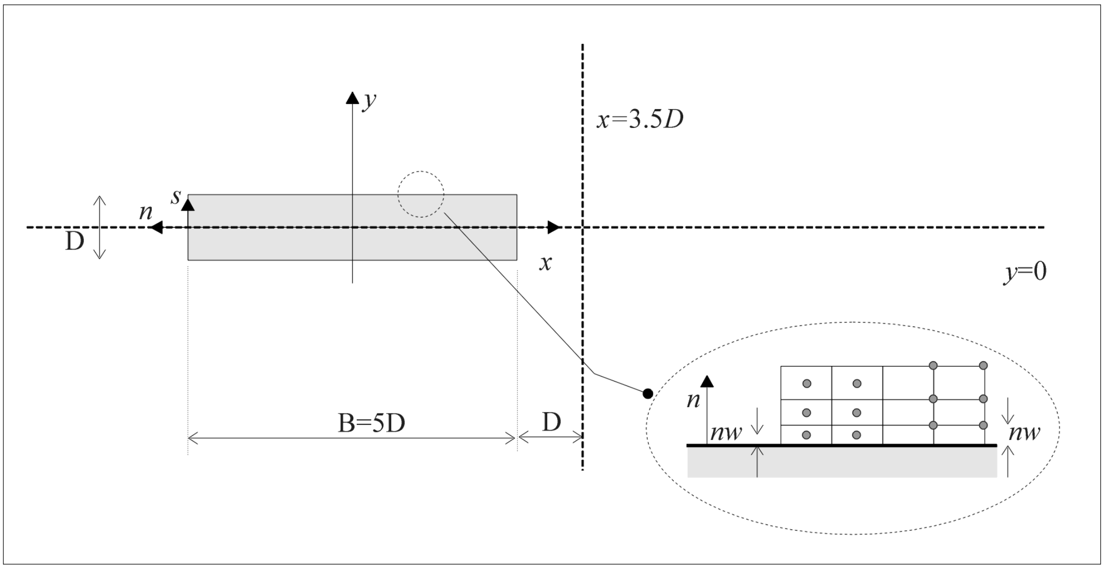


Figure 2 - Space grid conventions (*nw* depends on variables collocation)

5. **Time grid:**
    a. grid topology (fixed or adaptative time-step) (required);
    b. time step size (required);
    c. number of time steps (encouraged).

6. **Initial Conditions:**
    a. type of initial conditions (homogeneous in space, restart from a previous simulation, …) (required);
    b. initial values for all flow variables (if homogeneous, included the additional ones used for turbulence modelling, if any) (required).

7. **Boundary Conditions:**
    a. boundary conditions used for all flow variables (included the additional ones used for turbulence modelling, if any) on all boundaries (required).

8. **Numerical approach - space discretization:**
    a. space Discretization Method (FEM, FVM, FDM, …) (required);
    b. variable collocation (co-located, staggered,...)(required);
    c. order of accuracy in space (required);
    d. description of the numerical dissipation (none, proportional to grid size, tunable...) (required);
    e. other information characterizing spatial discretization (type of variable interpolation, quadrature rules, shape functions,...) (encouraged).

9. **Numerical approach - time advancing:**
    a. time advancing scheme (explicit, implicit, fractional...)(required);
    b. order of accuracy in time (required).

**10. Numerical approach – solver:**

a. other information characterizing the used solver (coupled or segregated, pressure–velocity coupling method, method used for solution of linear or non linear systems, under relaxation, ...)(encouraged)

**11. Convergence:**

a. residual threshold for each variable at each time step (if an iterative solver is used) (required);
b. mean number of iterations per time step (if an iterative solver is used) (encouraged);
c. under relaxations factors (if an iterative solver is used) (encouraged).

**12. Computation:**

a. computer system:
   i. processor type (required);
   ii. number of processors employed (required);
   iii. RAM (encouraged);
   iv. number of FLOPS (FLoating point Operations Per Second) (encouraged);
b. total CPU time (encouraged).

**13. Results for preliminary check:**

a. maximum, minimum and averaged normal distance from the wall of the first node layer closest to the wall in terms of wall units *y*+ (required);
b. check the mean value of the $Cp = 1$ at the stagnation point *p*0 (required, see Figure 3).
c. check the steadiness of the flow statistics (e.g. mean value, standard deviation and frequency content of the drag coefficient) converge for increasing sampling periods, excluded the initial transient. Indicate the interval in which the (steady) statistics are computed, in terms of non-dimensional time units $t^*=tU/D$ and in terms of vortex-shedding cycles (required).

**14. Results for comparisons** (see Figure 3 and Table 1 for notations).

The results format is given for 3D computational domains and 3D results. Vectors *z*-component should be set equal to zero otherwise (e.g. 2D domains, spanwise averaged results).

a. <u>Integral parameters:</u>
   i. mean value and standard deviation of the aerodynamic force per unit length coefficients ($C_F=F/(0.5\rho U_\infty^2 D)$), $C_x$, $C_y$ and $Cm_z$ (torque is meant evaluated with respect to the origin of the reference system) (required);
   ii. Power Spectral Density of the aerodynamic force per unit length coefficients $C_x(t^*)$, $C_y(t^*)$ and $Cm_z(t^*)$ as a function of the non dimensional frequency $fD/U$ (required, ASCII file with four columns format: $fD/U$, PSD($C_x$), PSD($C_y$) and PSD($Cm_z$));
   iii. time histories of the aerodynamic force per unit length coefficients $C_x(t^*)$, $C_y(t^*)$ and $Cm_z(t^*)$ (encouraged, ASCII file with four columns format: $t^*$ (non-dimensional), $C_x$, $C_y$, $Cm_z$);
   iv. length of the mean recirculation bubble along the side surface of the body the central section (z=0), evaluated based on the friction coefficient (required);
   v. length of the mean recirculation bubble along the side surface, averaged in time and also in the spanwise direction (*z*) if periodic boundary conditions are used (encouraged).

b. <u>Local parameters - statistics:</u>
   i. statistics of pressure (*Cp*) coefficient for all the nodes on the central section of the body (*z*=0) (required, ASCII file with five columns format: $s/D, \overline{Cp}, Cp_{std}, Cp_{skew}, Cp_{kurt}$, where *s* is the curvilinear abscissa defined in Figure 3);
   ii. statistics of pressure (*Cp*) coefficient averaged in the spanwise (*z*) direction if periodic boundary conditions are used (encouraged, ASCII file with five columns format: $s/D, \overline{Cp}, Cp_{std}, Cp_{skew}, Cp_{kurt}$);
   iii. mean value and standard deviation of the friction (*Cf*) coefficient for all the nodes on the central section of the body (*z*=0) (encouraged, ASCII file with three columns format: $s/D, \overline{Cf}, Cf_{std}$);

iv. mean value and standard deviation of the friction ($Cf$) coefficient averaged in the spanwise ($z$) direction if periodic boundary conditions are used (encouraged, ASCII file with three columns format: $s/D, \overline{Cf}, Cf_{std}$);

v. mean values (required) and standard deviations (encouraged) of the $x$-velocity along the straight line $l1$ ($y$=0, $z$=0) (ASCII file with three columns format: $x/D, \overline{u_x}, u_{x\,std}$, $u_{x\,std}=0$ if not provided);

vi. mean values and standard deviations of the $x$-velocity along the straight lines $l2$ ($x/D$=2.5, $z$=0), $l3$ ($x/D$=3, $z$=0), $l4$ ($x/D$=3.5, $z$=0), $l5$ ($x/D$=4, $z$=0), $l6$ ($x/D$=4.5, $z$=0) (encouraged, ASCII files with three columns format: $y/D, \overline{u_x}, u_{x\,std}$).

c. <u>Local parameters – time histories and coherence functions:</u>

i. time histories of the velocity components at points $mA$ and $mB$ (encouraged, ASCII files with four columns format: $t^*$ (non dimensional), $u_x$, $u_y$, $u_z$);

ii. time histories of the pressure coefficient at points $p1$ - $p12$ (encouraged, ASCII files with two columns format: $t^*$ (non dimensional), $Cp$).

iii. Coherence functions of surface pressure at positions $x$=0 and $x$=1.5 for $\Delta z_1 = 1/12B$, $\Delta z_2 = 3/12B$, $\Delta z_3 = 5/12B$, $\Delta z_4 = 7/12B$, $\Delta z_5 = 9/12B$ (encouraged, ASCII files with six columns format: $fD/U$, coh($\Delta z_1$), coh($\Delta z_2$), coh($\Delta z_3$), coh($\Delta z_4$), coh($\Delta z_5$)).

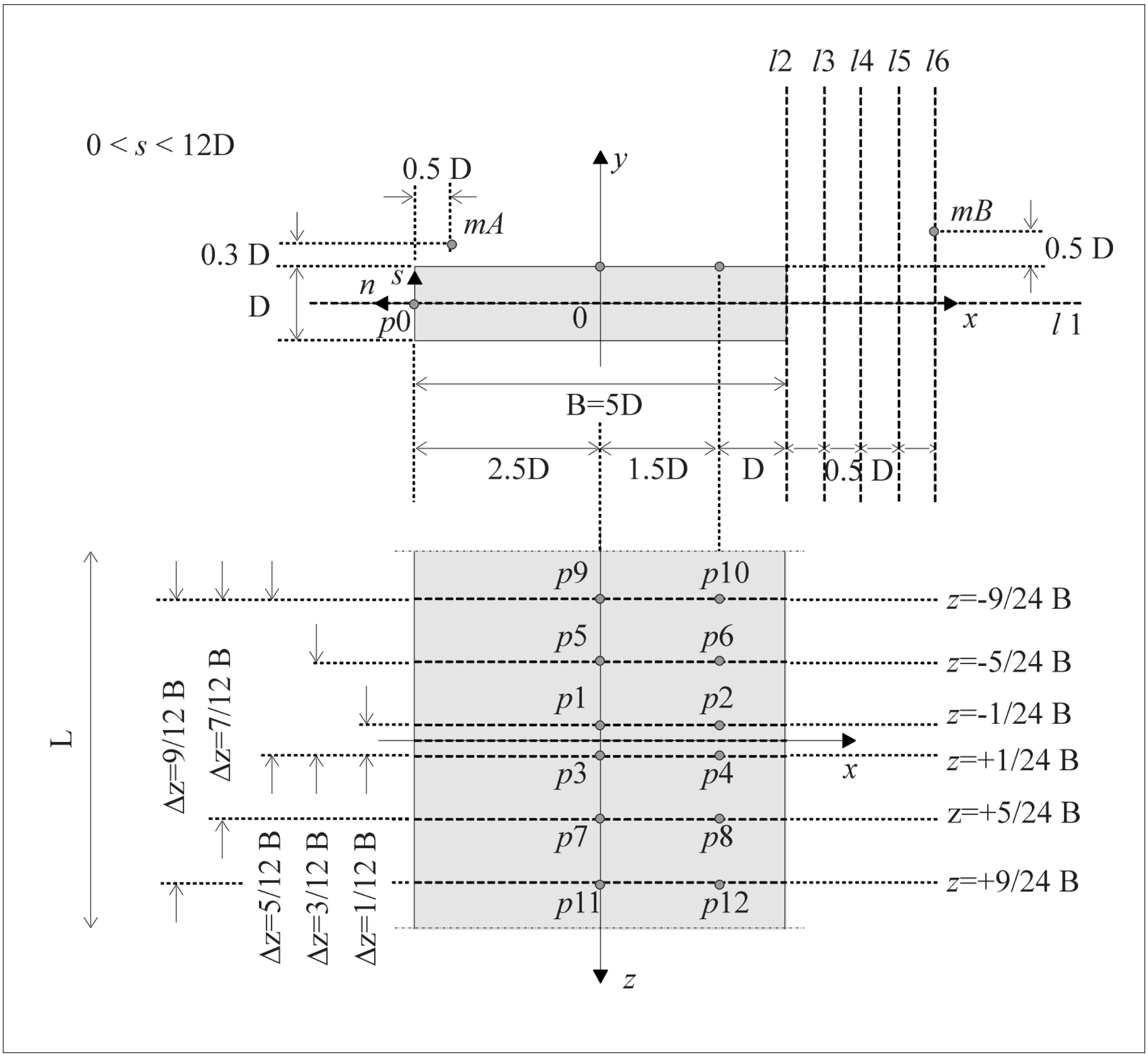


Figure 3 Location of point saving

d. Flow fields:
   i. mean value and standard deviation distributions on the central section of the domain ($z$=0) or averaged in the spanwise direction if periodic boundary conditions are used (encouraged):
      1. velocity (ASCII file with eight columns format: $x/D, y/D, \overline{u_x}, u_{x\,std}, \overline{u_y}, u_{y\,std}, \overline{u_z}, u_{z\,std}$);
      2. $Cp$ (ASCII file with four columns format: $x/D$, $y/D$, $\overline{Cp}, Cp_{std}$);
      3. vorticity (ASCII file with eight columns format: $x/D, y/D, \overline{\omega_x}, \omega_{x\,std}, \overline{\omega_y}, \omega_{y\,std}, \overline{\omega_z}, \omega_{z\,std}$)
   ii. instantaneous distributions, 20 samples during the period corresponding to the main frequency observed in the lift spectrum (encouraged):
      1. velocity (ASCII files with six columns format: $x/D$, $y/D$, $z/D$, $u_x$, $u_y$, $u_z$);
      2. $Cp$ (ASCII files with four columns format: $x/D$, $y/D$, $z/D$, $Cp$);
      3. vorticity (ASCII files with six columns format: $x/D$, $y/D$, $z/D$, $\omega_x$, $\omega_y$, $\omega_z$).

| id. | *x/D* | *y/D* | *z/B* | variable | Addressed phenomena |
|---|---|---|---|---|---|
| *mA* | -2.0 | 0.8 | 0 | $u_x$, $u_y$, $u_z$ | shedding mechanism past the leading edge |
| *mB* | +4.5 | 1.0 | 0 | $u_x$, $u_y$, $u_z$ | vortex shedding in the wake |
| *p*1 | 0.0 | 0.5 | -1/24 | *Cp* | spanwise coherence of the surface pressure field |
| *p*2 | +1.5 | 0.5 | -1/24 | *Cp* | |
| *p*3 | 0.0 | 0.5 | +1/24 | *Cp* | |
| *p*4 | +1.5 | 0.5 | +1/24 | *Cp* | |
| *p*5 | 0.0 | 0.5 | -5/24 | *Cp* | |
| *p*6 | +1.5 | 0.5 | -5/24 | *Cp* | |
| *p*7 | 0.0 | 0.5 | +5/24 | *Cp* | |
| *p*8 | +1.5 | 0.5 | +5/24 | *Cp* | |
| *p*9 | 0.0 | 0.5 | -9/24 | *Cp* | |
| *p*10 | +1.5 | 0.5 | -9/24 | *Cp* | |
| *p*11 | 0.0 | 0.5 | +9/24 | *Cp* | |
| *p*12 | +1.5 | 0.5 | +9/24 | *Cp* | |

Table 1- Point data

**15. Sensitivity Studies**

Sensitivity studies are strongly encouraged.

Recommendations about the sensitivity studies on the incoming flow characteristics (angle of attack, Reynolds number, turbulence intensity and length scale) are shared with the experimental approach (see par. *Requirements for further sensitivity studies on the incoming flow* in the *Overview of the Benchmark*).

Recommendations are given in what follows about computational and modelling features:

a. residual convergence by performing the simulation with two or more successively lower residual thresholds, common to every variable at each time step are strongly recommended (if an iterative solver is used);
b. space and time grid convergence by performing the simulation on two or more successively finer grids are strongly recommended;
c. parametrical studies on closure turbulence models (including subgrid models) and wall treatment in the frame of one approach to turbulence are encouraged.

**16. Additional references**

References cited by the author(s) of the study and not enclosed in the benchmark general database should be listed (required, if any).

**17. Contact Information**

Complete address, fax number, telephone number and e-mail of the author(s) of the study should be enclosed.

**18. Upload Data File**

The complete set of the set-up data and the required and recommended results should be provided in the tabular-type file, according to the proposed format for download. The ASCII files with space distributions and time histories should be provided in separated, zipped files *.gz. The whole data set should be provided in an single archive *.tar.