MŰEGYETEM 1782

GÉPÉSZET 2010

PROCEEDINGS OF THE SEVENTH CONFERENCE ON MECHANICAL ENGINEERING

May 25-26, 2010
Budapest, Hungary

COMPACT disc
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ISBN 978-963-313-007-0

Budapest University of Technology and Economics
Faculty of Mechanical Engineering

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PROCEEDINGS OF THE 7th CONFERENCE ON MECHANICAL ENGINEERING

Budapest University of Technology and Economics
Faculty of Mechanical Engineering
May 25-26, 2010, Budapest, Hungary

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Gépészet 2010. Proceedings of the 7th Conference on Mechanical Engineering. Budapest University of Technology and Economics, Faculty of Mechanical Engineering, Budapest, 2010

ISBN 978-963-313-007-0

Budapest University of Technology and Economics, Faculty of Mechanical Engineering, Budapest, 2010

FOREWORD

It was 12 years ago when the Faculty of Mechanical Engineering at the Budapest University of Technology and Economics started the conference series 'Mechanical Engineering'. Each conference of the series had defined a special topic in mechanical engineering, in this year our focus is the 'Advanced Technologies'. According to the goal and the desire of the organizer this conference provides a forum for presenting new scientific results in different fields of mechanical engineering and possibility for young scientists to introduce their work. In this year the organizers tried to open the conference inviting prominent members in the IPC and more foreign authors and participants. Keeping this track the actual conference the 7th 'GÉPÉSZET 2010' is a new starting point which retains the original goals and moves to the direction of the recognized international conferences.

Parallel this conference the Industrial Design Education celebrates its 15th anniversary. A special workshop was organized in the frame of GÉPÉSZET 2010 as a simultaneous program of the conference. Other activity in the frame of this conference the 'Precision Glass Manufacturing' training program organized by the Production4micro network of the EU supported Integrated Project.

Professor Gábor Stépán
Dean, Faculty of Mechanical Engineering

GÉPÉSZET 2010

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Budapest University of Technology and Economics, May 25-26, 2010

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COMPUTATION OF LOW-REYNOLDS NUMBER FLOW AROUND A STATIONARY CIRCULAR CYLINDER

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Abstract: The two-dimensional flow around a stationary circular cylinder at Reynolds numbers $50 \le Re \le 200$ is investigated numerically using two different CFD methods. The effect of resolution and computational domain size on the drag, lift and base-pressure coefficients further the dimensionless frequency of vortex shedding (Strouhal number) are investigated. The computed Strouhal number versus Reynolds number is compared with existing experimental and numerical data. Comparisons include time-mean values of the drag and the base-pressure coefficients and root-mean-square values of the lift coefficient. The results of both methods agree well with available data in the literature.

Keywords: *circular cylinder, domain size, Strouhal number, lift and drag coefficients*

1. INTRODUCTION

The laminar, two-dimensional flow around a stationary circular cylinder placed in a uniform stream has been of continuous interest to researchers involved in basic fluid mechanics. Extensive studies have been performed on resolution as well as blockage effects. Examples of analyses of the influence of computational domain extensions on the drag at low Reynolds numbers can be found in Posdziech and Grundmann [1], Stalberg et al. [2] and Kang [3]. Kang concentrated on one Reynolds number ($Re = 100$), and varied the time step and domain extension. While the free-stream velocity varies linearly across the cylinder, computations were also carried out for constant velocity [3]. In the study of Posdziech and Grundmann [1] different computational domains were used to obtain asymptotic solutions in the steady and unsteady flow regime at different Reynolds numbers.

The main aim of the present study is to compare the results from two very different CFD methods for simulating flow past a stationary circular cylinder at low Reynolds numbers. The first author has used the commercial software FLUENT, based on the finite volume method. The second author has developed a finite difference method using boundary-fitted coordinates. Both methods analyse flow properties such as drag, lift and base-pressure coefficient and Strouhal number by varying the extent of the domain and the Reynolds number.

2. NUMERICAL SOLUTION

For both methods (FLUENT and the in-house code) the computational domain is characterized by two concentric circles: the inner represents the cylinder surface with diameter D, the outer the far field with diameter D_∞. Blockage B is expressed as ratio of the cylinder diameter D to height H of the computational domain. In our case the height of the domain corresponds to the diameter of the outer circle ($H = D_\infty$), meaning that blockage is the ratio of cylinder diameter to outer diameter. In this paper, we use the reciprocal value of the blockage ratio, *H/D*, for convenience. The origin of the coordinate system is in the center of the cylinder. The positive *x*-axis is in the downstream direction.

Typical boundary conditions are used for velocity and pressure. At the inlet uniform velocity distribution (U) and constant temperature are prescribed. Time-dependent, incompressible Newtonian fluid flow with constant properties is assumed. The computational grid is 360×310 (azimuthal$\times$radial) for *H/D*=220. Logarithmically spaced radial cells are used on the computational plane, providing a fine grid scale near the cylinder wall and a coarse grid in the far field. The minimal dimensionless mesh size in radial direction is 0.00875 for the first method, and is 0.00879 for the in-house code. For the in-house code a time step of $\Delta t = 0.0005$ is used, and for FLUENT $\Delta t = 0.001$.

The first author carried out simulations using FLUENT v6.3.26 commercial software. The two-dimensional, unsteady, laminar, segregated solver is used to solve the incompressible flow on the collocated grid arrangement. The *Second Order Upwind scheme* has been used to discretize the convective terms in the momentum equations. The semi-implicit method for the pressure linked equations (SIMPLE) scheme is applied for solving the pressure-velocity coupling.

The second author used a 2D in-house code based on a finite difference solution. The governing equations are the unsteady Navier-Stokes equations, continuity, a Poisson equation for pressure and an energy equation, all in dimensionless form. The computational method and its validation are described in detail in [4, 5]. Using the mapping functions, not specified here, the governing equations and boundary conditions can also be transformed into the computational plane. The transformed equations are solved by using the finite difference method. For further details see Baranyi [5].

3. COMPARISON OF DETAILED NONDIMENSIONAL COEFFICIENTS

Numerical simulations are conducted by systematically varying *H/D* or Reynolds number in the fairly wide ranges of *H/D* = 60 – 220 and $50 \le Re \le 200$. The accuracy of numerical results is compared by means of integral quantities like drag, lift and the base-pressure coefficients and Strouhal number. The drag and lift coefficients are calculated as

$$C_L = \frac{2F_L}{\rho U^2 A},\ C_D = \frac{2F_D}{\rho U^2 A}, \tag{1}$$

where ρ is the fluid density, U is the free-stream velocity, F_L and F_D is the lift and drag. A frequently considered quantity is the non-dimensional pressure at the rear stagnation point, called the 'base-pressure' coefficient (C_{pb}).The base-pressure coefficient is

$$C_{pb} = \frac{2(p - p_\infty)}{\rho U^2}, \tag{2}$$

where p_∞ is the reference pressure. The Strouhal number, the non-dimensional shedding frequency, is defined as $St = f\,D/U$, where f is the oscillation frequency of C_L. The time-mean and root-mean-square (rms) values of the base-pressure, lift and drag coefficients are written as

$$C_{mean} = \frac{1}{nT}\int_t^{t+nT} C(t)dt,\ C_{rms} = \sqrt{\frac{1}{nT}\int_t^{t+nT} [C(t) - C_{mean}]^2\, dt}, \tag{3}$$

where T is a period of a vortex shedding, n is the number of periods. The general coefficient C stands for drag, lift, and base-pressure coefficients.

3.1 Vortex-shedding frequency

Fig. 1 shows the variations in the dimensionless vortex shedding frequency *St* with the blockage ratio at $Re = 100$. As seen in the figure, for both methods the shedding frequency remains nearly constant from about *H/D* = 140. This agrees with the experimental data of Williamson and Brown ($St = 0.164$) [6]. Kang [3] used the immersed boundary method for computations and resolved the governing equations with the finite volume method. Although a smaller blockage ratio from 10 to 80 was applied, for *H/D* = 80 the same nondimensional value is obtained as in our results. Posdziech and Grundmann [1] investigated the effect of the domain size at Reynolds numbers from 5 to 250 numerically by means of the spectral element method. A rectangular domain was applied, and the blockage ratio was *H/D* = 40 – 8000. Their results fit accurately to the curve from the present work.

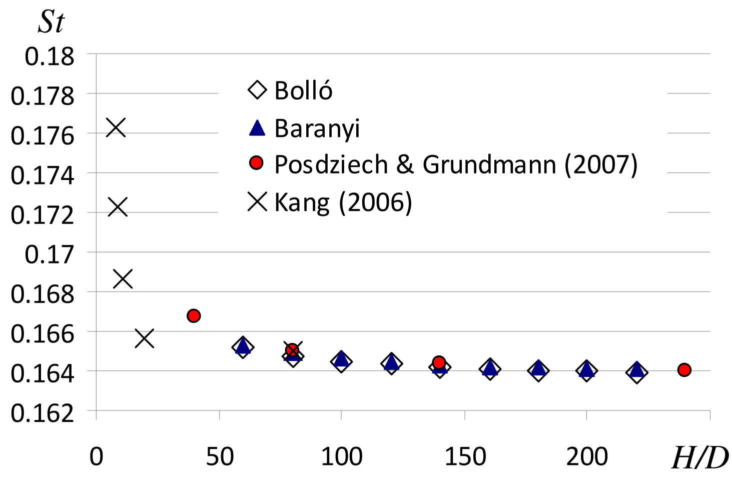

Fig. 1. Vortex shedding frequency versus *H/D* at $Re = 100$

The Strouhal number versus *Re* relationship is shown in Fig. 2, where *H/D* = 220 is used for both methods. Both methods are in good agreement in prediction of the Strouhal number, which varies between $0.12 < St < 0.2$ over the Re range considered. Results were compared to experimental and numerical data from the literature. Several approximate formulas are available for the *St* versus *Re* relationship at low Reynolds numbers. The experimental data that are included in the left-hand side of Fig. 2 are given as polynomial approximations in the literature: $St = 0.2684 - 1.0356/\sqrt{Re}$ in Fey et al. [7], $St = 0.2665 - 1.018/\sqrt{Re}$ in Williamson [6], and $St = -3.458/Re + 0.1835 + 1.51\times10^{-4}Re$ in Norberg [8]. It can be seen that the present results agree very well with experimental data.

Posdziech and Grundmann [1] applied a noninteger polynomial to the asymptotic solution at *H/D* = 8000: $St = 0.278484 - 0.896502\,Re^{-0.445775}$, with the equation being valid for $50 \le Re \le 250$. The data fit perfectly to the curve from the present work. The data of Stalberg et al. [2] and Kang [3] are slightly higher than those in our study, but they applied a smaller domain extension (Stalberg et al. used *H/D* = 40, Kang *H/D* = 80). As Fig. 2 demonstrates, our results match very well with both experimental and computational data.

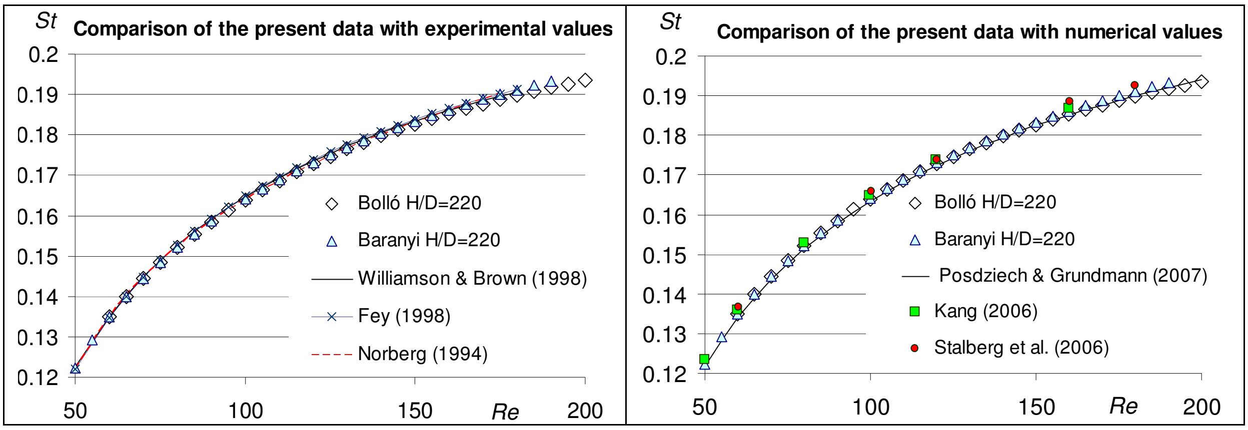

Fig. 2. Vortex shedding frequency versus Reynolds numbers

3.2 Lift and drag coefficients

The rms value of lift-coefficient fluctuations (C_{Lrms}) and the variations of the time-mean values of the drag coefficient (C_{Dmean}) with *H/D* at $Re = 100$ are shown in Fig. 3. The dimensionless coefficients for both of the present methods are extremely similar. The lift coefficient is slightly higher in the data of Kang [3]; blockage ratios below 30 are most likely not reliable. However, the drag coefficient at *H/D* = 80 agrees well with our results. The drag coefficients agree excellently with the data of Posdziech and Grundmann [1].

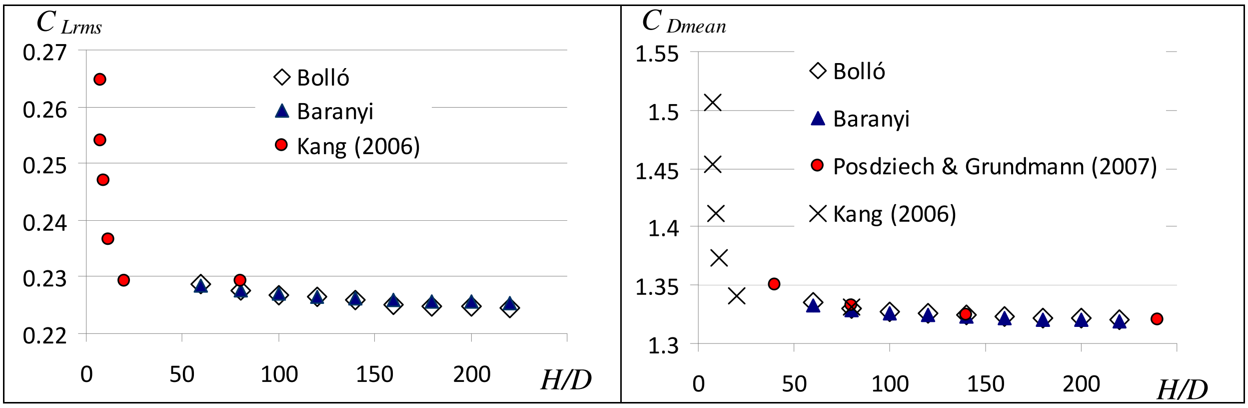

Fig. 3. C_{Lrms} and C_{Dmean} versus *H/D* at $Re = 100$

Since the rms value of the lift coefficient varies slightly with increasing domain size, variations of C_{Lrms} with Reynolds number for only one value of *H/D* = 220 are shown in the left-hand side of Fig. 4. Norberg [9] suggests an approximate formula for the rms lift coefficient: ($C_{Lrms} = \sqrt{\varepsilon/30 + \varepsilon^2/90}\,, \varepsilon = (Re - 47)/47$). The data of [9] and that of the present work are nearly identical, aside from a small difference for $Re < 80$ and $Re > 180$.

In the right-hand side of Fig. 4 it can be seen that the rms drag coefficient increases with increasing Reynolds number. In case of both methods used here the results fit accurately to the curve, and the data of Kang [3] agree perfectly also.

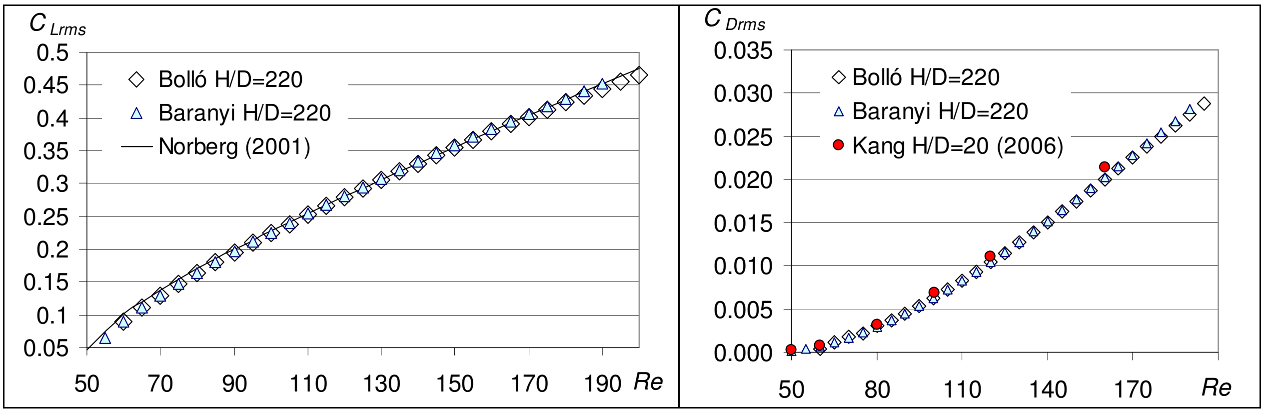

Fig. 4. The rms of lift and drag coefficients versus Reynolds number

3.3 Base-pressure coefficient

The variations of the base-pressure coefficient with *H/D* (at $Re = 100$) and Reynolds number are shown in Fig 5. The results of both Bolló and Baranyi reach the accurate value (a domain-independent solution) at a lower *H/D* value than those of Posdziech and Grundmann [8]. The data of Bolló show only a slight relationship to the blockage ratio. It can be observed that the base-pressure coefficient is nearly constant with increasing domain extension. The values obtained by Baranyi decrease with increasing *H/D* values, and for *H/D*~180 agree perfectly with Bollo's results. The data of Posdziech and Grundmann [8] show a steep curve at lower *H/D* values but by *H/D*~400 a constant value appears to be reached.

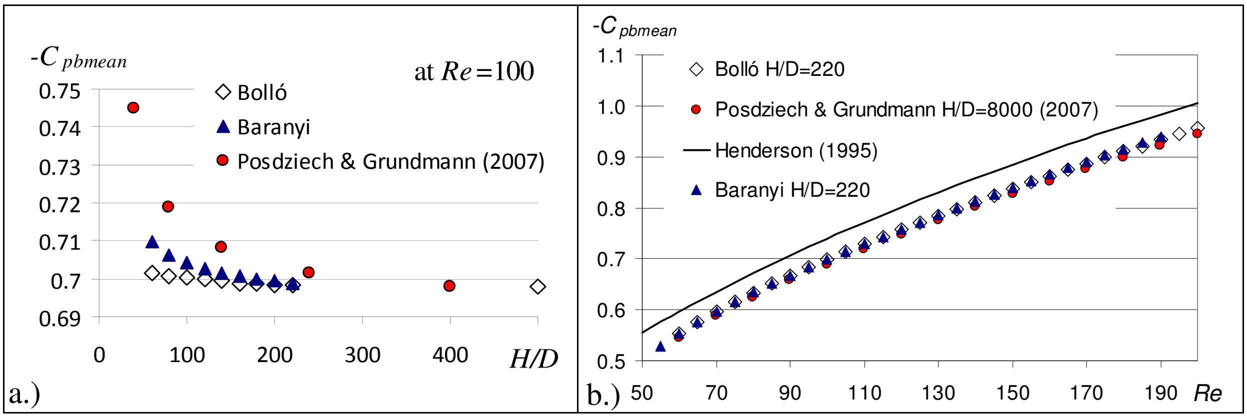

Fig. 5. The C_{pbmean} versus *H/D* (a) and Reynolds number (b)

In the case of both present methods for *H/D* = 220 the time-mean value of base-pressure coefficients are perfectly identical at different Reynolds numbers, as shown in the right-hand side of Fig. 5. The results of Posdziech and Grundmann [1], which was obtained using a very large computational domain of *H/D* = 8000, agree nearly perfectly with our results. If the present results are compared to data of Henderson [10], the shifting of his curve can probably be attributed to the less powerful computational capacity at that time.

4. CONCLUSIONS

Finite volume and finite difference methods were used to compute flow past a stationary cylinder in two dimensions at *H/D* = 60 – 220 at low Reynolds numbers ranging from 50 to 200. Unsteady flow past a circular cylinder was computed and compared with experimental and computational results available in the literature and very good agreement was observed.

For dimensionless coefficients the effect of the computational domain was investigated while keeping the Reynolds number constant. For both present methods the Strouhal number, the rms values of lift coefficient, time-mean values of drag and base-pressure coefficients fit nearly perfectly to each other at $Re = 100$. It was found that the different coefficients are practically constant if *H/D* is over 160. These dimensionless coefficients agree well with the numerical data published by [1] and [3].

For the fixed domain size *H/D* = 220 the Strouhal number, rms values of lift and drag coefficients, and time-mean values of the base-pressure coefficient were investigated over the Reynolds number domain $50 \le Re \le 220$. Both methods are in very good agreement in all investigated coefficients, aside from a small difference for $Re > 180$, at which three-dimensional effects start to occur. The results of both methods agree well with the experimental and numerical data published by [1-3] and [6-9].

The present study shows that a careful validation of the domain size is a necessary step in obtaining grid-independent solutions. To fully confirm a grid-independent solution, the effect of spatial and temporal resolution should also be investigated, although the general agreement with experimental and numerical results in the literature indicates that the time-step and computational mesh used in these two methods are most likely sufficient.

ACKNOWLEDGEMENTS

The support provided by the Hungarian Research Foundation (OTKA project K 76085 and NKTH-OTKA 68207) and the Hungarian-German Intergovernmental S&T co-operation program P-MÖB/836 is gratefully acknowledged by the authors.

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