EPJ Web of Conferences **269**, 01059 (2022) https://doi.org/10.1051/epjconf/202226901059
EFM 2019

Experimental Investigation of Unsteady Static Pressure Field Behind a Circular Cylinder

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Abstract. In this paper a measurement of a static pressure in the wake behind a circular cylinder for the different Reynolds numbers is presented. For this purpose, a static pressure probe with built-in pressure transducer was used. The main goal is to describe the unsteady pressure field behind the cylinder and determine a frequency of the generated Von Kármán vortex street. The measurement was conducted in a low speed wind tunnel for a cylinder with 110 mm in diameter. The results were compared to an unsteady RANS simulation.

1 Introduction

The wake of a circular cylinder has been investigated by many researchers. The static pressure field behind the circular cylinder can be value source of information about the effects caused by the cylinder in the airflow. It is known, that the periodically shedded vortices called Von Kármán vortex street are responsible of generating tonal noise. [1] This can be considered as one of the best examples of aerodynamically generated sound. For the further research in the tonal sound generated by the cylinder in airflow it is necessary to know a frequency at which the vortices are shedded. This paper evaluates simple approach to determine this frequency by measuring the static pressure fluctuations behind the circular cylinder. To support this approach a CFD simulation using Ansys Fluent was also performed. Validation of this approach is necessary for the future aeroacoustical study of the generated tonal sound.

1.1 Von Kármán vortex street

The relation between Strouhal and Reynolds numbers for a circular cylinder was investigated for example by Lienhard [2]. For the Reynolds number between $3 \cdot 10^2$ and $3 \cdot 10^5$ the Strouhal number is close to 0.2 depending on the cylinder surface and other factors of the airflow. This also means that in this range the frequency of shedding vortices depends on velocity linearly.

For the experimental measurement presented in this paper a cylinder with 110 mm in diameter was chosen. The measurement are conducted in the range of Reynolds numbers approx. 75 000 - 390 000, and Reynolds number is defined as:

$$Re = \frac{vD}{\nu} \tag{1}$$

in which D is the diameter of the circular cylinder, v is the free stream velocity a ν is the kinematic viscosity of air.

Strouhal number is defined by a formula:

$$St = \frac{fD}{v} \tag{2}$$

in which f is the vortex shedding frequency. Strouhal number can be considered as a non-dimensional representation of the frequency.

2 Experimental setup

The experimental measurement was performed in the wind tunnel of Department of Fluid mechanics and Thermodynamics, FME CTU in Prague. This circulation wind tunnel has the test section of dimensions 450 x 950 x 1200 mm and the maximum airflow velocity is 60 ms^{-1}.

The static pressure is measured using a static pressure probe with a built-in pressure transducer Kulite LQ-125, see the figure 1. This probe is designed according to Russo [3] to measure small and fast fluctuations of static pressure of the parallel flow. The diameter of this probe is 6 mm and the diameter of pressure holes is 0.5 mm. The pressure holes are placed 18 mm behind the leading half-sphere of the probe. The pressure transducer itself is placed inside the probe near the pressure hole. The pressure transducer Kulite LQ-125 is a miniature pressure transducer with full Wheatstone bridge sensing principle.

The circular cylinder is placed between two parallel planes and cross to the flow, so 3D effects would be minimal. As a data acquisition device for this measurement National Instruments cDAQ-9174 with an analog input voltage module (NI-9215) is used. The absolute error of this measurement platform is according to the manufacturers' calibrations ±57 Pa. Measurements are taken using National Instruments LabView software and 1000 Hz

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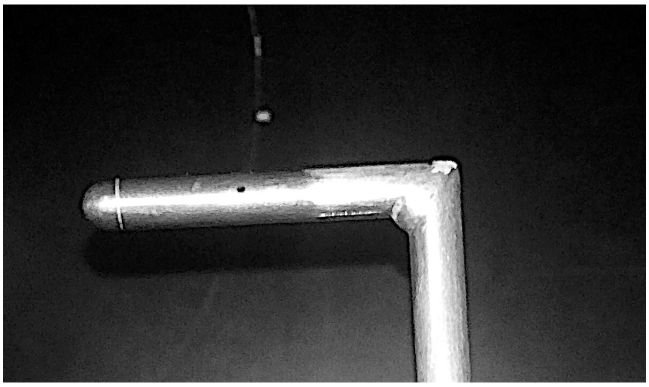

Fig. 1. The static pressure probe.

sampling frequency for 10 seconds. The data is taken separately for each position. The evaluation of the measured data is conducted using MathWorks MATLAB. The main issue of the data evaluation is transformation from the time domain to the frequency domain. For the transformation is used Welch's method to compute the power spectral density and from the power spectral density is then estimated the values of amplitudes. The evaluated pressure data are normalized by dynamic pressure p_d of the free stream.

The static pressure profile is measured in distance $0.75D$ behind the cylinder. The values of the static pressure are obtained in 10 positions spaced equally 10 mm from the centerline of the test section, see the figure 2. The static pressure profile is supposed to be symmetrical for the time averaging values.

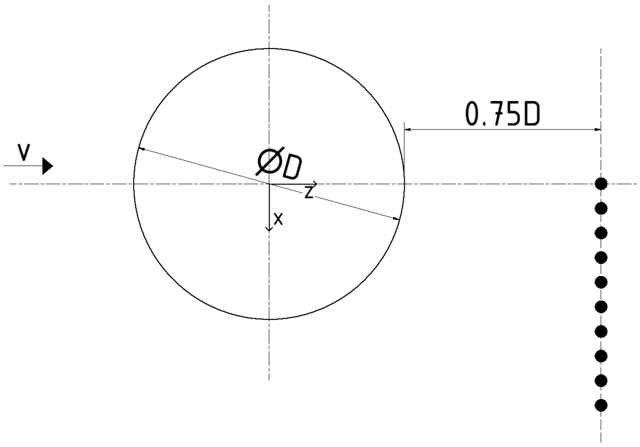

Fig. 2. Scheme of the measurement in the wind tunnel test section.

3 CFD simulation

The Unsteady Reynolds Averaged Navier Stokes (URANS) simulation was conducted using commercial Ansys Fluent Software with non-iterative time advancement method. The computational domain is created with consideration the effects of the closed part of the test section during the experiments. The computation domain is $8.6D$ in width, which is the exactly same ratio as in the wind tunnel test section. For the turbulence model $k - \omega$ SST model is used and the solver is set to use the second order spatial discretization. The boundary condition at the inlet is set to velocity and the outlet is set to the pressure boundary condition. For each simulation the Courant number is below 1 for the most of the cells in the domain.

3.1 CFD prediction

The CFD simulation is calculated for the 9 different inlet velocities, so it can be compared to the experimental results (in the section 4). The vortices are periodically shedded from the two sides of the cylinder. The period of the shedding vortices from one side is the characteristic frequency of the Von Kármán vortex street. The pressure field (in the figure 3) behind the circular cylinder is effected of the shedded vortices from the both sides.

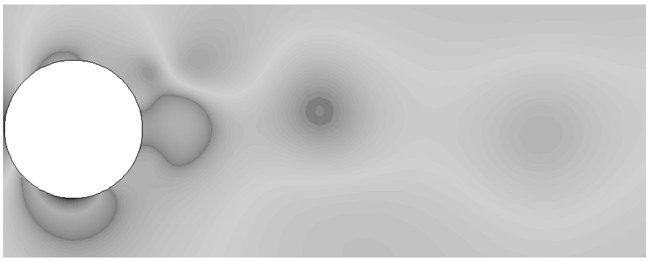

Fig. 3. Prediction of an instant static pressure field behind the circular cylinder for Re = 157 140.

The comparison of the predicted static pressure fluctuations caused by vortex shedding in two positions behind the cylinder is shown in the figure 4. It is evident that the frequency of the static pressure fluctuations in the centerline behind the circular cylinder is double and also that the amplitudes of the fluctuations differ. This is caused by the highest influence of the shedding vortices from the both sides of the cylinder just in the centerline.

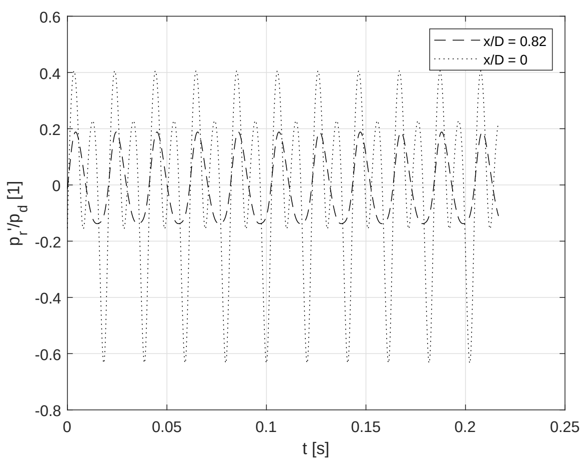

Fig. 4. Prediction of the static pressure fluctuations behind the circular cylinder for Re = 157 140 at two positions.

4 Experimental results

The measurements are taken for 9 different Reynolds number matching with the CFD prediction. For Reynolds number between 78 000 and 353 000 the characteristic frequency is present in the static pressure spectra at every measured position. For the Reynolds number about 390 000 there is no dominant frequency present at the positions which are the most distant from the centerline, see the figure 5. The dominant frequency is present at the positions between $0.5D$ and the centerline. This phenomenon can be caused by the transition to the turbulent boundary layer on the cylinder [2] and then by the narrower wake behind the circular cylinder.

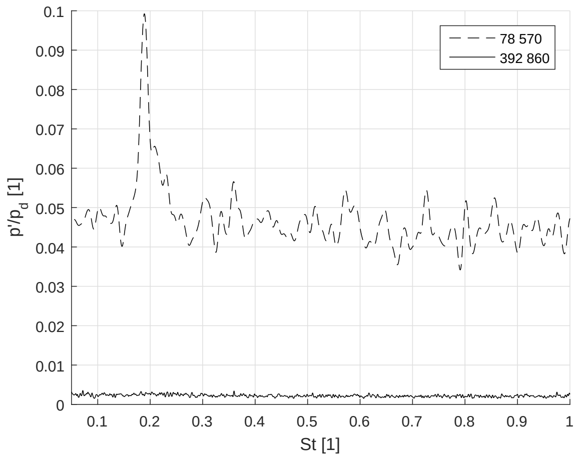

Fig. 5. The measured amplitude spectra normalized with dynamic pressure for the lowest and the highest measured Reynolds numbers at the position $x/D = 0.82$.

The figure 6 shows comparison of normalized amplitudes at the three different measuring positions. The first peak in this spectrum is at St = 0.18 and the second one is at St = 0.37, but this one is perceptible only in positions closer to the centerline. This measurement is in agreement with previously stated theory and predicted periodical values of the static pressure by the CFD simulation, where in the positions closer to the centerline the frequency of the changes in the static pressure is double due to the effect of the vortex at the distant side of the cylinder.

For the measured static pressure for the Reynolds number between 78 000 and 353 000 the dominant Strouhal number was determined. In figure 7 the dominant Strouhal number is presented in the relation to the position x/D, except the centerline, where there is no possibility to undoubtedly determine the dominant frequency because of the effect of the vortex from the opposite side of the cylinder.

The mean values of the Strouhal numbers presented in the figure 7 for different Reynolds numbers are presented in the figure 8 . Using the least square method the relation between Strouhal and Reynolds number can be determined as:

$$St = 0.1897 - \frac{13.9}{Re} \tag{3}$$

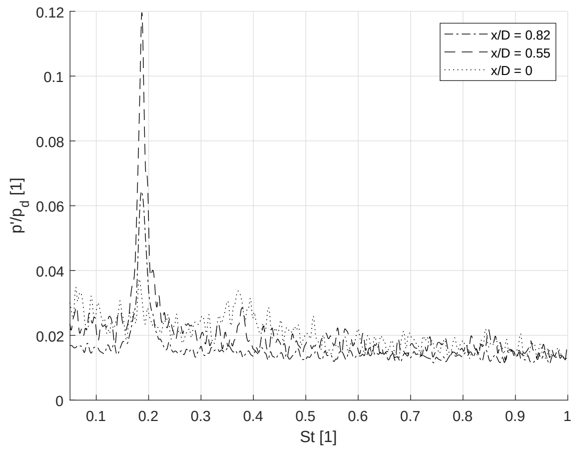

Fig. 6. The measured amplitude spectra normalized with dynamic pressure for Re = 157 140 in the 3 different positions.

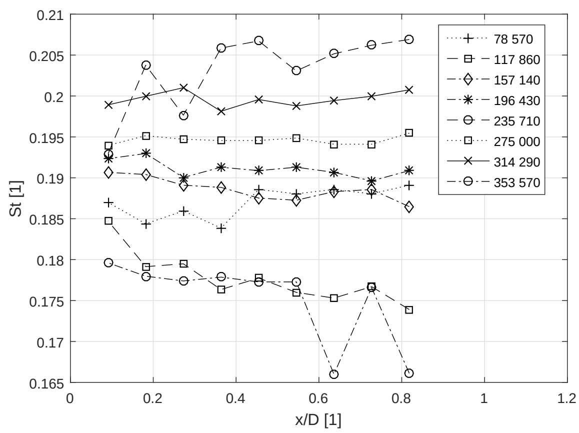

Fig. 7. Dominant Strouhal number of the static pressure fluctuations in relation to position x/D for 8 different Reynolds numbers.

The relation 3 is in a good agreement with the relation proposed by Tyler [4]. This comparison shows that the major fluctuations in the static pressure behind the circular cylinder have the same frequency as Von Kármán vortex street. Also the pressure probe design does not distort significantly the measured frequency.

In the figure 9 there is presented relation between the position of the measurement and the amplitude of the static pressure fluctuations. In general the amplitude of pressure fluctuations due to Von Kármán vortex street is lower in the centerline of the wake of the circular cylinder and the maximum of this amplitude is near the projected edge of the cylinder.

The amplitudes for the Reynolds numbers between 117 860 and 235 710 are close to a constant. This similarity can be also seen in the figure 10 where the mean values of the amplitudes are shown.

Between Reynolds number 100 000 and 250 000 the normalized mean values of the static pressure fluctuations amplitudes seem to be almost constant. This can

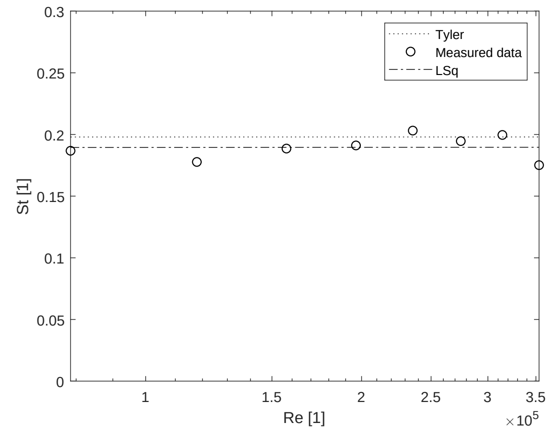

Fig. 8. Relation between Reynolds number and Strouhal number.

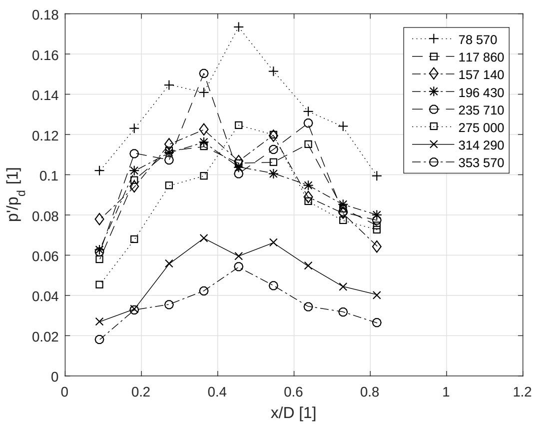

Fig. 9. The amplitude of the vortex shedding frequency in posi-tions x/D for 8 Reynolds numbers.

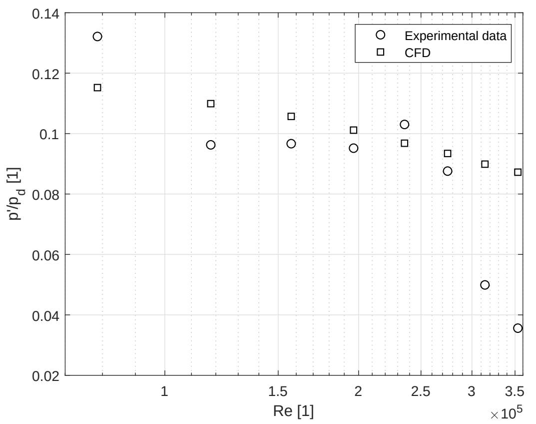

Fig. 10. Relation between Reynolds number and mean static pressure amplitude.

be explained by the almost constant part of Strouhal and Reynolds numbers relation, which was mentioned at the beginning of this paper. In the figure 1 0 t he s tatic pressure fluctuations amplitudes obtained from the CFD simulation is compared to the experimental measurement. The computed normalized static pressure fluctuations amplitudes are for most of the Reynolds number higher than the experimental ones. This can be explained due to lack of noise in the computed results and that the turbulence model is linear. Also in the figure 10 the measured values over Reynolds number $3 \cdot 10^{-6}$ are significantly different, which can be implication of the transition to the turbulent boundary layer on the cylinder.

5 Conclusion

The unsteady static pressure field behind the circular cylinder was measured in 10 different positions for 9 different Reynolds numbers. It was shown that for the most distant measured positions from centerline of the wake behind the cylinder the Strouhal number of the static pressure fluctuations is reliable to determine the frequency of the shedding vortices to the Von Kármán vortex street, however the width of the wake must be considered. It was shown that the wake for Reynolds number over 353 570 is narrower. For this range of Reynolds number between 80 000 and 390 000 the static pressure probe should be placed in the position $0.5D$ from the centerline and $0.75D$ behind the cylinder to be able to measure data for Strouhal number of Von Kármán vortex street evaluation.

Acknowledgements. This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS18/125/OHK2/2T/12 and the Centre of 3D volumetric anemometry - COLA, reg. no. CZ.2.16/3.1.00/21569 - Operat-ing Program Prague competitiveness.

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