H03

UNSTEADY PRESSURE MEASUREMENTS ON CYLINDRICAL SURFACES

1. Aim of the measurement

- To get acquainted with computerised data acquisition, recording and processing of unsteady pressure signals.
- Determining the mean pressure coefficient distribution on square and circle based cylinders and locating the separation point.
- Commenting on near-wall turbulent fluctuations based on pressure RMS (Root Mean Square) values.
- Investigation of pressure spectra obtained from FFT (Fast Fourier Transform), detection of vortex separation frequencies, calculation of Strouhal numbers and examining the dependence between Str and Re numbers.

2. Description of measurement setup

The measurement setup is based on the setup M03 prepared for the BSc level Fluid Mechanics course. Its sketch is shown on **Figure 1**. A radial fan is placed in the box that moves the air. Air velocity is set by suction side throttling. The maximum velocity is about 32 m/s in the outlet cross section, whose size is 150x150 mm. The calibration formula placed on the setup connects the reference pressure drop (Δp_{ref}) and the outlet velocity.

A closed, vertical channel with a square cross section is attached onto the outlet, into which the cylinders are placed for the measurement. After the measurement, the velocity-pressure drop calibration formula has to be checked by measuring outlet velocities using a Pitot-static probe.

A part of the measurement channel is prepared so that the different sized cylinders can be places into it. This allows the reposition of the cylinders perpendicular to their axes with the help of a long bolt. Cylinders can also be moved along their axes. On the surface of each cylinder, there is a small diameter pressure hole that allows the measurement of local static pressure. On the channel walls there are four pressure holes connected together by tubing. This way the average static pressure in the channel can be measured. These two pressures are to be measured to be able to determine the pressure coefficients.

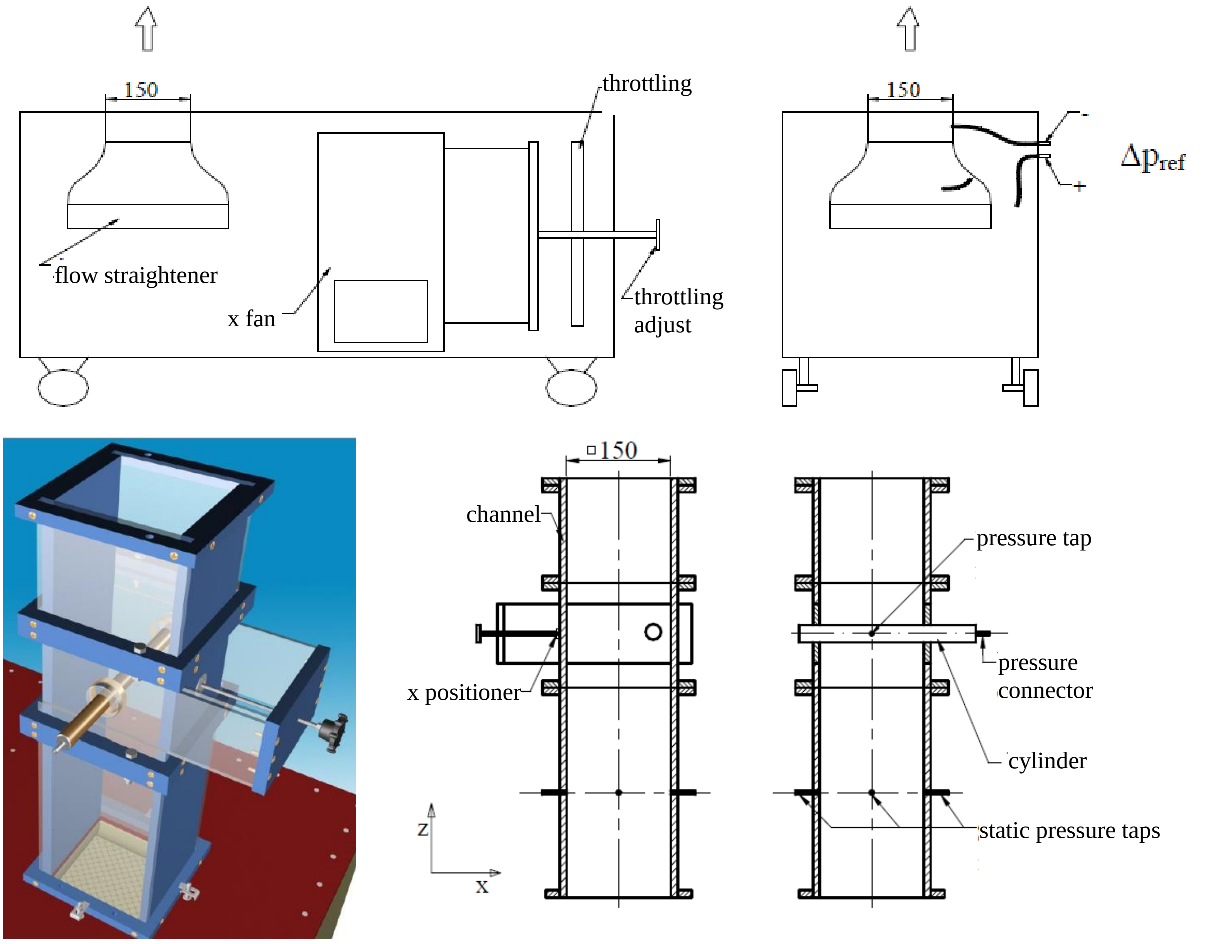


Figure 1. M03 measurement setup

To get information about the time-dependent, dynamic behaviour of pressure, the signals have to be recorded using a sufficiently high temporal resolution. The pressure probes are to be located to the holes as close as possible, because the tubing has frequency-dependent impedance characteristics that modifies the amplitude and phase of the signals propagating inside it.

To fulfil these requirements, a miniature piezo-resistive ENDEVCO pressure transducer is used attached directly into the cylinder (**Figure 2**). This sensor is appropriately small and has a wide frequency range with a nearly constant transfer function.

On the front part of the sensor the membrane is found. Behind that there is a cavity connected to the reference pressure by small tubing. The sensor is placed into a cylindrical Plexi support in which there is a perpendicular hole connecting the inside to the surface (**Figure 3**). Both ends of the Plexi cylinder are sealed by a ring. This piece can be inserted into the inside of the measured cylinder by the help of a small stick. This way the membrane is only a few mms away from the surface, therefore it can record pressure fluctuations very well. The measured pressure is converted into an electric signal by the sensor and wiring connects it to the acquisition computer.

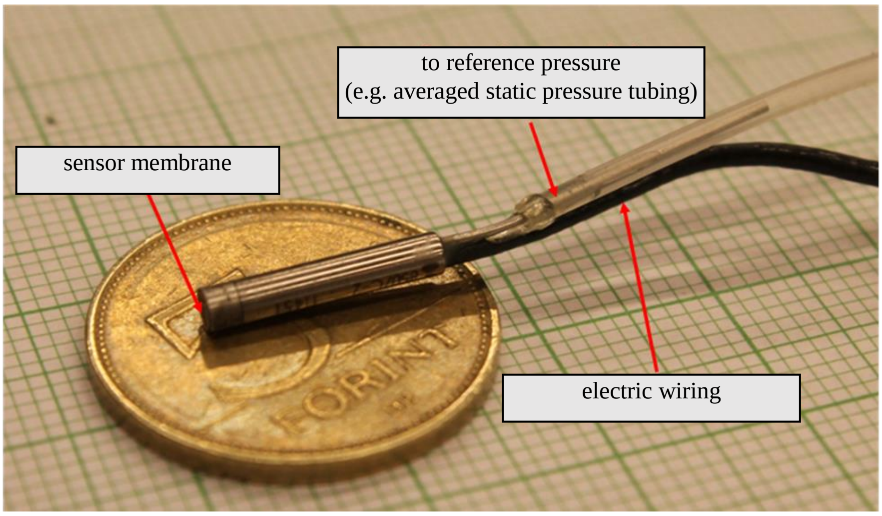


Figure 2. The ENDEVCO pressure sensor

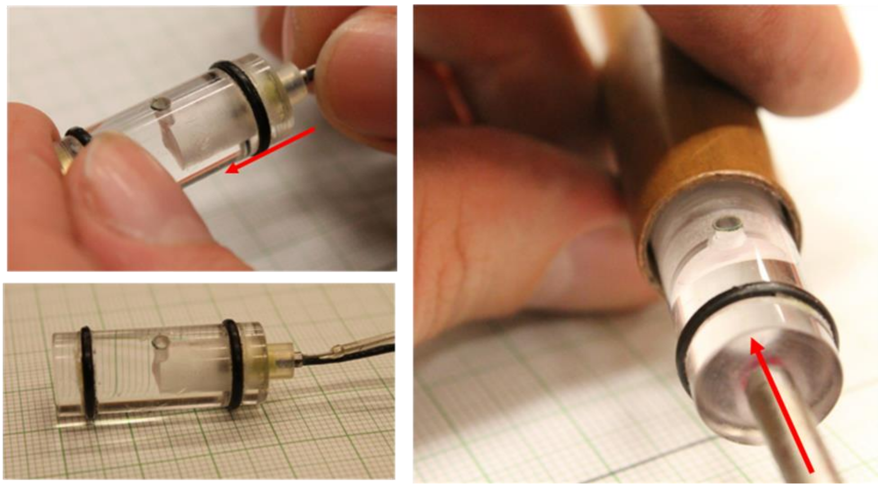


Figure 3. Inserting the pressure sensor into the Plexi support and into the cylinder

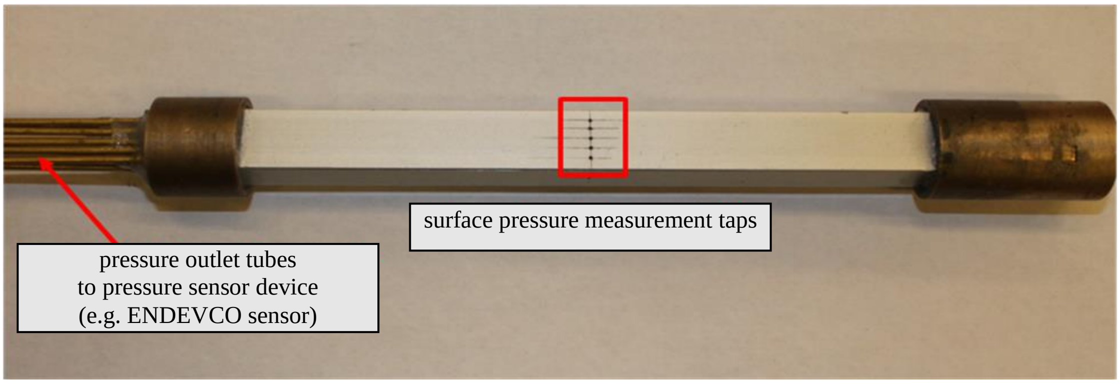


Figure 4. The rectangular cylinder and its pressure holes

Besides the circular one, rectangular cylinder can also be measured (**Figure 4**). In this case the sensor cannot be placed into the body, the pressure is led to it by the small copper tubes on the end of the piece. These have to be connected to the reference pressure port on the ENDEVCO sensor. In this case, the other side is connected to the ambient pressure, therefore a digital manometer has to be used to record the static pressure inside the channel.

A so-called splitter plate, a thin aluminium plate can also be inserted into the channel behind the measured body, parallel to the flow direction (**Figure 5**).

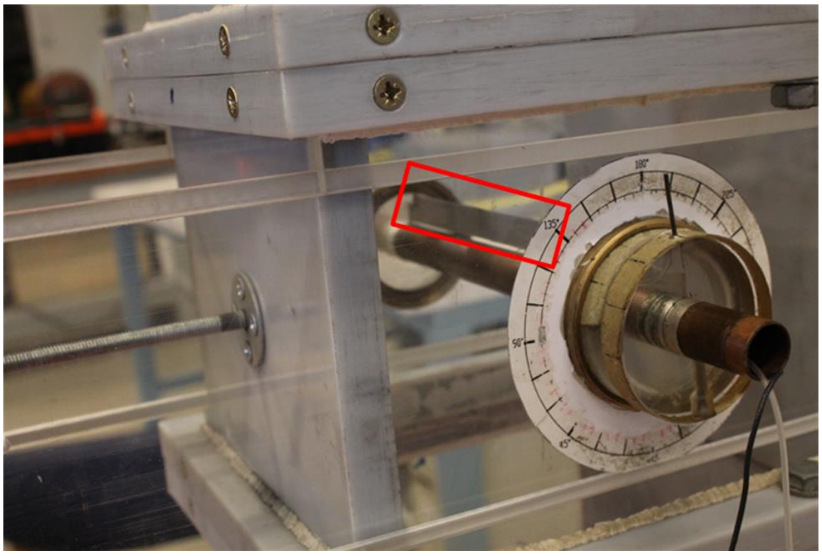


Figure 5. The splitter plate behind the cylinder

The data processing system belongs to the measurement setup. This consist of an analogue-to-digital converter that samples the voltage signal from the sensor, encodes it digitally and transforms it to a pressure signal according to the pre-defined calibration formula. The digitized pressure signal can be processed using the in-house developed software *Pressure and Force*. Sampling frequency can be increased up to the order of magnitude of 10 kHz, but for this measurement 1-5 kHz is sufficient.

In order to have a statistically meaningful signal, a signal of at least 10 s length should be recorded at each measurement point. After a single measurement the software saves the time series and automatically calculates the mean pressure and the RMS:

$$p_{MEAN} = \frac{1}{N}\sum_{i=0}^{N} p_i \qquad p_{RMS} = \sqrt{\frac{1}{N}\sum_{i=0}^{N}(\bar{p} - p_i)^2}$$

3. Theoretical background

The force on a body placed into a flow is obtained by integrating the surface pressure and shear stress distributions. The force resulting from shear is orders of magnitude less than the pressure force, its direct effects are negligible. Wall shear does have an important effect however, as it causes the separation of the boundary layer that changes the flow characteristics and creates a large zone of low pressure, the separation bubble. The local surface pressure distribution is characterized by the local pressure coefficient (c_p), calculated as the difference of local and static pressures divided by the free-stream dynamic pressure.

$$c_p = \frac{p_{MEAN} - p_\infty}{\frac{\rho}{2} v^2}$$

In a theoretical, frictionless case the pressure distribution on a cylinder is symmetric to the plane perpendicular to the flow direction (left on **Figure 6,** c_p=1 stagnation point on both sides!), therefore there is no force acting on the body [5]. If friction is present, the pressure coefficient does not grow after a certain circumferential position but stays at an almost constant negative value in the separation bubble. The flow around the cylinder and thus the pressure distribution depends on the Reynolds number ***Re*** calculated using the cylinder diameter:

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

Above a critical ***Re*** number the separation occurs further back at a larger angle (right on **Figure 6**). In this case a turbulent boundary layer is formed instead of a laminar one that initiates more intensive momentum transport perpendicular to the cylinder wall [1]. Thus the decelerated air particles can travel further despite the adverse pressure gradient, since they get additional momentum and kinetic energy transport from the main flow. Uneven surface or a so-called tripping wire can help to initiate the turbulent transition of the boundary layer at lower ***Re*** numbers [2].

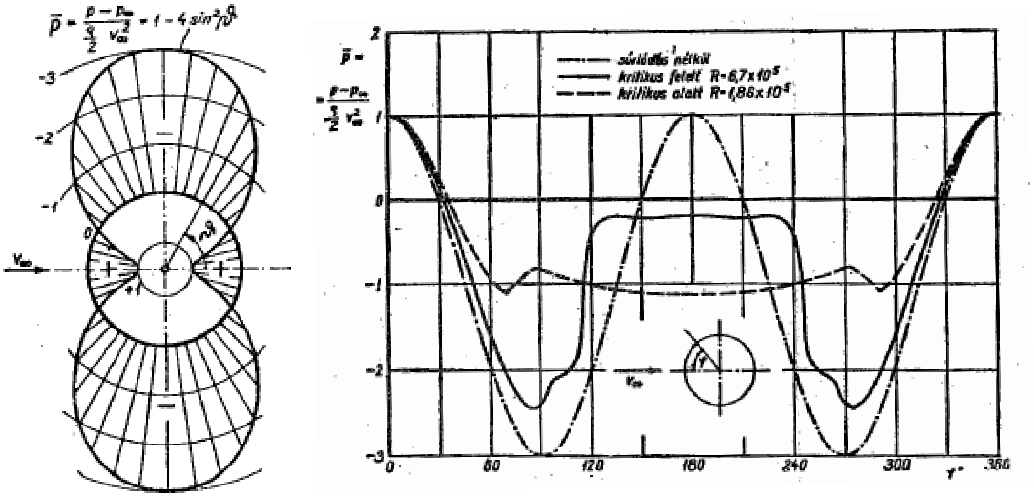


Figure 6. Left: distribution of pressure coefficients on a cylinder in inviscid case.
Right: distribution of pressure coefficients in case of subcritical and supercritical Re numbers

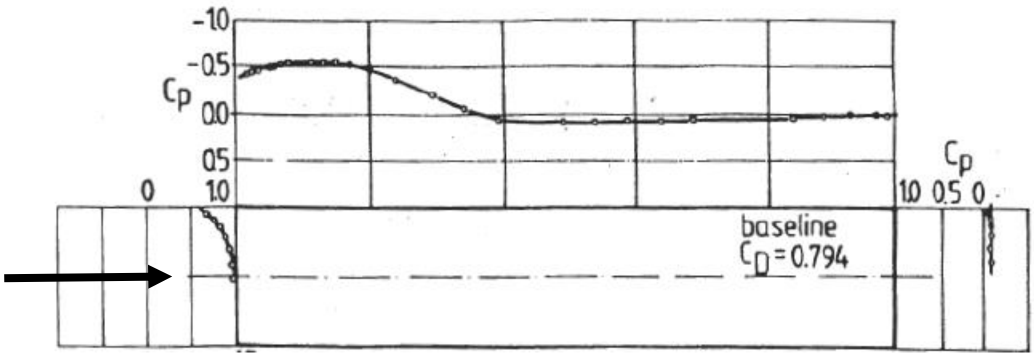


Figure 7. Distribution of pressure coefficients on a square based cylinder

In case of flow impinging on a rectangular cylinder from 90 degrees on the upstream side in the vicinity of the stagnation zone pressure coefficients of about 1 are found (**Figure 7)**. Close to the edges the values of c_p are large negative numbers because of the large curvature of the streamlines. Most of the sides and all of the back side are in the separation bubble, therefore the pressure coefficients are usually nearly constant at a small negative value [3].

In some ***Re*** ranges ($10^3 \leq Re \leq 10^5$) periodic vortex separation occurs on the back side of the cylinder that causes a significant periodic pressure fluctuation [2]. A high RMS value indicates strong fluctuations. Fast Fourier Transform (FFT) can immediately be carried out on the recorded time series in the *Pressure and Force* software. The pressure spectrum can be displayed (amplitude versus frequency) and the results can be saved into text files for further processing. In the spectrum, the highest amplitude usually corresponds to the vortex separation (**Figure 8**), but often other peaks of similar amplitude are found (i.e. fluctuation due to the fan, electric noise of the circuitry etc.).

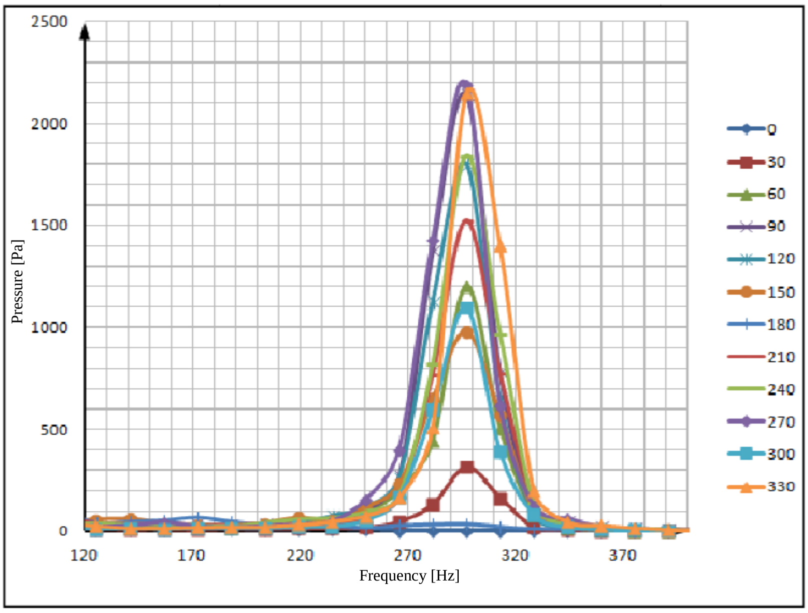
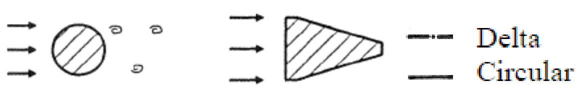


Figure 8. Amplitude spectra of pressure signals recorded at different angles

The periodic vortex separation is characterized by the ***Str*** Strouhal number. For a cylinder of diameter ***D*** (or side length ***L***) placed in a flow with velocity ***v***, if the frequency is ***f***, this is the following:

$$Str = \frac{fD}{v}$$

Experience shows that the Strouhal number of a circular or rectangular cylinder changes only moderately in a certain Re range (**Figure 9**). In these ranges the knowledge of the frequency allows us to calculate the flow velocity. This is the operation principle of vortex shedding flowmeters widely used in the industry [6].



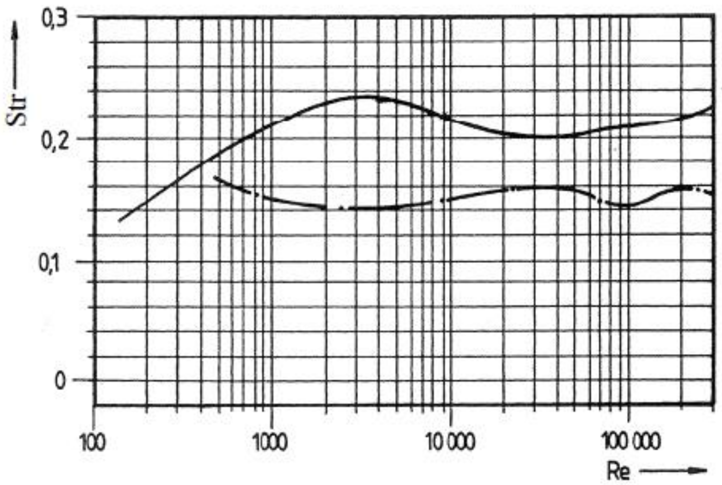


Figure 9. The dependence of ***Str*** versus ***Re*** in case of a cylinder and a delta body

The periodic vortex separation causes a periodic force to act on the body. If the excitation frequency is close to the eigenfrequency of the mechanical system it might cause oscillations with ever increasing amplitudes, resonance. In some cases our aim is to prevent that. It can be achieved by a splitter plate inserted behind the cylinder – a flat plate that will cause two stable recirculation bubbles to form behind the cylinder [2].

4. Possible measurement tasks

Task „A"

Measurement of pressure distribution and unsteady pressure on the surface of a circular cylinder

- Measure the pressures around the cylinder surface by rotating the body by 10-15 degrees. Repeat the measurement at velocities corresponding to 3-4 different Re values.
- Plot the pressure coefficient distribution obtained from the time-averaged values and the RMS values as a function of the rotation angle for each Re value. Compare that to the inviscid case, determine the location of the separation point.
- Show the pressure spectrum for some measurement points calculated by FFT. Show the Str number obtained from the frequency with the highest amplitude versus the rotation angle.
- Show the dependence of Str on Re in some points, where large pressure amplitudes occur.
- Explain the results of the measurement. Do a literature review on flows around cylinders.

Task „B"

Measurement of pressure distribution and unsteady pressure on the surface or a rectangular cylinder

- Measure the pressures on the surface through the tubing at moderate flow velocity! Set the angle to either 45 or 90 degrees! Choose a point, where large pressure amplitude

RMS-s occur. Carry out further measurements in this point at 5-10 different flow Re numbers!
- Plot the pressure coefficient distribution obtained from the time-averaged values and the RMS values as a function of position. Compare the distribution to data from literature (see **Figure 7**).
- Show the pressure spectrum for some measurement points calculated by FFT. Show the Str number obtained from the frequency with the highest amplitude versus the rotation angle.
- Show the dependence of Str on Re in some points, where large pressure amplitudes occur.
- Explain the results of the measurement. Do a literature review on flows around cylinders.

Task „C"

Reducing vortex separation using a splitter plate

- Measure the pressure on the cylinder surface at the point at 90 degree angle. Repeat the measurement at velocities corresponding to 5-10 different Re values. For the further measurements, choose the Re number where the RMS is highest! Plot the Str number calculated from the frequency with the highest amplitude in the spectrum versus Re number.
- Carry out pressure measurements around the cylinder surface on the selected Re number by rotating the body by 10-15 degrees with and without the splitter plate. Plot the pressure coefficient and RMS distribution around the cylinder versus the rotation angle both with and without the splitter plate.
- Show the spectrum of pressure in some angles both with and without the splitter plate (see **Figure 8**).

References

[1] Tamás LAJOS, Dr: Áramlástan alapjai (2004), Chapter 9.3.3
[2] Tamás LAJOS, Dr: Áramlástan alapjai (2004), Chapter 11.1.2
[3] Tamás LAJOS, Dr: Áramlástan alapjai (2004), Chapter 11.2.2
[4] József GRUBER, Dr Miklós BLAHÓ, Dr: Folyadékok mechanikája (1973) pp. 355-357.
[5] József GRUBER, Dr Miklós BLAHÓ, Dr: Folyadékok mechanikája (1973) pp. 279-280.
[6] Dr. János VAD: Advanced Flow Measurement pp. 91-93.