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Simulation of Influence of Mechanical Elements on Karman Vortex Street Parameters

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***Abstract*—This work presents the results of numerical modeling of Karman vortex street generation performed with ANSYS/FLUENT package application. The influence of the mechanical elements located downstream of the bluff body on the vortex frequency has been found during earlier laboratory investigations. Five various geometrical configurations have been tested. Considerable differences in pictures of distributions of pressure, horizontal and vertical velocities have appeared for various configurations. Qualitative as well as quantitative results are presented in the paper. They confirm the significant dependence of the Karman vortex street parameters on the meter configuration.**

***Keywords*—Karman vortex street, bluff body, vortex frequency, numerical modeling**

I. INTRODUCTION

NUMERICAL modeling of the phenomena appearing in the vortex meter is a useful tool for the knowledge of cognition and finally – for the meter optimization. Ancient researchers of the vortex meter had not the possibility to carry out theoretical considerations, although the Navier–Stokes equations were known. Unfortunately, the analytical solution of these equations remains one of the unsolved mathematical problems. Hence our older colleagues used ‘try and error technique' relied on laboratory investigations and observation of measuring the signal. Despite such non-effective research method, quite rich achievements in this area have been noticed. Nowadays, however, we have sophisticated software and numerical simulation of the phenomena used in the vortex meter is feasible. In the paper, the results of simulation gained with the application of ANSYS/FLUENT software are presented. The simulations have been focused on the influence of mechanical elements located downstream the bluff body on von Karman vortex street parameters.

II. VORTEX METER

The vortex meter principle of operation is based on the eddies generation on the bluff body. Vortices should be strong and regular. Such properties ensure easiness of the measuring signal detection. Due to vortices processing into the electrical signal, the flow rate being the linear function of the signal frequency can be determined. It should be underlined that the vortex frequency does not depend on the physical properties of the fluid. More, the frequency is the same for liquids and gases.

The vortex signal quality strongly depends on the bluff body geometry and dimensions. Numerous articles were dedicated to this problem. Especially significant progress has been occurred due to Cousins work [1]. He formulated general requirements for the bluff body design. He tested three basic shapes of the bluff body: circular cylinder, triangular cylinder, and rectangular cylinder. He got experimental confirmation of the significant role of pipe walls in the vortex street stabilization. Hence he determined an optimal characteristic dimension of the bluff body to pipe diameter ratio for each tested shape.

Although vortices are generated on the circular cylinder, numerous researchers pointed out the requirement for the existence of sharp edges in the bluff body [1]-[4]. Laboratory investigations confirm the relationship between sharp edges existence in the bluff body and regularity of generated vortices

As it appeared, an introduction of the slit to the bluff body causes considerable improvement of intensity and regularity of generated vortices. Considerations concerned the relationship between the slit existence and the stagnation region appearing downstream the bluff body was presented in [5].

The separate problem in the vortex meter design is the detection of generated vortices. Each vortex represents the local disturbance of pressure and velocity. In compressed fluids also fluctuations in density are observed. Additionally, vortices generation causes a temporary appearance of lift on the bluff body – being the force perpendicular to the flow direction. Hence velocity, pressure, density and force sensors can be used for vortices processing into the electrical signal.

III. HISTORY OF THE BLUFF BODY WITH SLIT

Investigations carried out by Igarashi [6]-[8] resulted in a new class of vortex generators – bluff bodies with slit. It should be underlined, however, that the initial experiments were done by Tsuchiya at al. and presented already in 1970 [9]. The bluff bodies with slit were investigated and also optimized by other researchers: Olsen, Rajagopalan [10] and by the author of this paper [11].

The considerable contribution to the design of this type of bluff bodies was assumed by Popiel, Turner, and Robinson [12-14]. As it results from laboratory investigations, insertion the slit into the bluff body causes radical enhancement of intensity and regularity of generated vortices. Flow visualization pictures performed by Igarashi [8] show the appearance of the flow along the rear side of the bluff body. On the flow visualization pictures, it can be observed, that sucking and blowing of the shear layer from the bluff body surface appears alternately on both sides of the bluff body.

The calculations were performed at the Interdisciplinary Center for Mathematical and Computational Modeling (ICM) of the University of Warsaw as part of the computational grant No. G68-10.

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Analyzing this phenomenon it can be stated that the slit constitutes a special kind of information channel. Hence the conclusion that such a transmission medium like an oscillating tail (stagnation region) from Birkhoff model [15] turn out as unnecessary and finally disappeared.

Later works carried out by Igarashi [16] on the bluff body called by him as "triangular semi-cylinder" consisting of the slit between both its parts resulted in further enhancement of signal quality and meter linearity. Considerable reduction of pressure loss on the bluff body was also attained.

On the basis of Igarashi's experience, Popiel, Turner, and Robinson proposed a new type of the bluff body consisting cylindrical cavity in its rear part. This way matching the bluff body shape to fluid flow has been attained.

IV. PROBLEM OF METER OPTIMIZATION

Vortex meter optimization should be recognized as a multi-level problem. The most fundamental item is generating strong and regular vortices on the bluff body. As it results from the rich literature, energy and regularity of vortices strongly depend on geometrical parameters of the bluff body – more precisely – on their ratio to the pipe diameter. On the other hand, the bluff body shape and existence of sharp edges determine the signal quality. It should be underlined, that proper bluff body design causes requirements to decrease towards the secondary device as well as the signal processing system.

As it occurs, in the optimization process of the vortex meter, also issues related to the secondary device design should be considered. Laboratory tests and analyses carried out by the author of the paper prove, that the vortex, after generation, increases its energy at some distance from the bluff body and then scatters. So the most effective is vortices detection in the area of maximum energy appearance. Of course, this demand fulfillment strongly depends on the vortex detector type and design.

The methodology of vortex meter optimization proposed by the author of this work consists in cognition of the phenomena in every aspect. The Karman vortex shedding phenomenon is very complex and is sensitive to numerous factors. Hence the cognition requires various methods application like flow visualization, investigations of velocity area using hot-wire probes, measuring signal analysis and numerical modeling. The results obtained due to these methods should be consistent and complementary.

V. MOTIVATION

Vortex meter design tested by the author of the paper is based on the circular cylinder with the slit as the bluff body and strain gauge sensors glued to the beam as the secondary device. This way the secondary device appeared as the separate part of the meter. As it was found during the laboratory tests the vortex frequency has been changed when the distance between the bluff body and the secondary device has been changed.

Experimental investigations carried out by the author of the paper and reported in [17] show that mechanical elements placed in the flowing fluid downstream the bluff body influence the vortex shedding frequency. This effect has been observed in water being the medium as well as in the air. Also, some other researchers noticed this phenomenon but they couldn't interpret it properly [18]-[19].

The investigations reported in this paper were aimed at confirmation of the author's interpretation of the observed effect, that even small disturbances (mechanical elements placed in the stream) can influence the vortex frequency.

Due to feasibilities of ANSYS/FLUENT software, additional information concerned the phenomenon has been attained: time of instability, the stability of vortices amplitude, C_L, C_D, the dependence of the signal amplitude on the point of observation.

VI. NAVIER-STOKES EQUATIONS

Already in 1755, Leonard Euler proposed [20] system of partial differential equations describing the fluid motion. There were based on assumption that fluid can be treated as a body of the continuous structure. In such body there appear the forces proportional to mass elements of the fluid (mas forces) and forces proportional to surface elements (surface forces). It is worth to mention, that Euler introduced the pressure term. So Euler applied Newtonian mechanic for the description of phenomena appearing in fluids. He also developed mathematical methods for the solution of a mechanic of fluids problems.

Several dozen years later M. Navier in [21] and G.G. Stokes in [22] completed Euler's equations taking into account the fluid viscosity. Hence the name "Navier – Stokes equations". In literature, these equations can be found in various forms. In the most common approach for non-compressed fluids, they may be presented as:

$$\rho \cdot \frac{dV}{dt} = \rho \cdot F - grad(p) + \mu \cdot V \qquad (1)$$

and for compressed fluids:

$$\rho \cdot \frac{dV}{dt} = \rho \cdot F - grad(p) + div(\mu \cdot \Delta M) \qquad (2)$$

where:
ρ – fluid density
V – velocity vector
F – mass force vector
P – pressure
M – viscous strain tensor
μ – dynamic viscosity

It should be underlined that Euler equations and Navier-Stokes equations originate from the principle of conservation of energy, the principle of conservation of momentum and principle of conservation of mass applied for moving the fluid. Because of the fact, that in the equations the number of unknowns exceeds the number of equations, it was necessary to add the relations among the chosen unknown functions. They describe the fluid properties resulted from its inside structure and are called as constitutive equations.

The most important one describes proportionality tensions tensor appearing in the fluid to the deformation tensor. Finally, for various assumptive models of fluids, we have various equation systems describing the motion. For instance, for the viscous liquid of constant density we receive the following system of equations:

$$div(V) = 0 \qquad (3)$$

$$\rho \cdot \frac{dV}{dt} = \rho \cdot F - grad(p) + \mu \cdot \Delta V \qquad (4)$$

Problems with the solution of proposed equations had been already noticed by Euler [20], but the introduction of new elements by Navier and Stokes additionally it complicated. Researchers tried to solve the Navier-Stokes equations presenting two tendencies. The first one assumed simplification of the equations, the other relied on approximated methods of solution of differential equations. In this assumption, we can find also the application of numerical methods.

The lack of the possibility of using simplified Navier-Stokes equations was the reason for the delay in its application in the analysis of von Karman vortex street. It should be underlined, however, that in the vortex generation and development, numerous factors may influence the process. Only after the fact development in computer technology in the 90s of XX century, the more effective solution of the Navier-Stokes equations with numerical methods was feasible.

It is worth to mention, that Navier-Stokes equations are the object of particular interest from the purely mathematical point of view. Clay Mathematics Institute found the problem of analytical solution of these equations as one of seven most important open problems in mathematics. The award of 1 million $ for its solution is waiting.

VII. NUMERICAL MODELING

Investigations have been carried out for five configurations shown in Fig. 1.

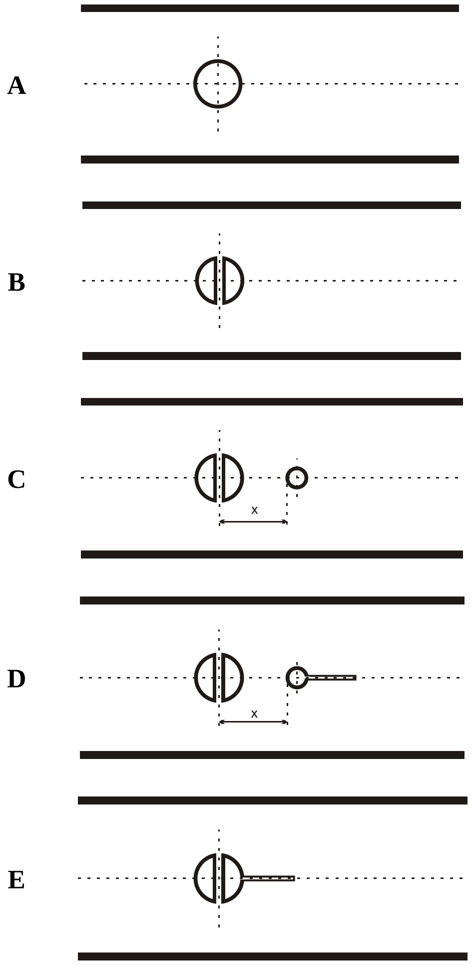


Fig. 1. Tested configurations: A - circular cylinder, B - circular cylinder with the slit, C - circular cylinder with the slit and the small cylinder downstream, D - circular cylinder with the slit and the small cylinder with beam downstream, E - circular cylinder with the slit and with a glued beam

Following parameters of the models have been assumed:

- pipe diameter: 40 mm
- pipe length: 150mm
- bluff body diameter: 12 mm
- small cylinder diameter: 5mm
- location of the bluff body: 50 mm downstream the pipe inlet
- slit width (in the bluff body with the slit): 1,2 mm
- beam length: 20,5 mm
- flow velocity 3 m/s
- medium: water

The mesh for calculations divided the flow area into ca 170000 elements using ca 100000 nodes. The k-omega viscous SST model has been chosen. The time step was equal 4ms. 1000 steps for each modeling were performed.

VIII. RESULTS

Results of simulation for all 5 tested configurations are presented in Fig. 2. Distributions of pressure were obtained for t = 4s, so in the steady state.

We can observe, that the obtained pictures differ each other considerably. Introduction, a slit to the bluff body, enhances the phenomenon - the vortices are stronger and are visible even in long distance downstream to the bluff body. But insertion any mechanical element downstream to the bluff body (configurations C, D, and E) considerably changes the picture of the phenomenon. Changes in the frequency of generated vortices are also observed.

We can formulate similar conclusions on the base of analysis of distributions of vertical and horizontal velocity for all configurations.

A. Influence of the additional obstacle on the vortex frequency

The main part of the research were simulations of the influence of mechanical elements placed downstream the bluff body (vortex generator) on the frequency of vortices. This effect was observed during extensive experimental investigations carried out at measuring stands for calibrating flow meters, both in the case of gases and liquids, and described in [17]. In order to determine the vortex frequency, the FFT option was used. Two configurations were tested: C and D for different distances between a bluff body and a mechanical element disturbing the flow. The value of parameter x means the distance between the axis of the bluff body and the front edge of the mechanical element located downstream (see Fig.1.).

In Tab. I. and Fig. 3 the results obtained for both configurations vs x-parameter are presented. As can be easily seen, in the case of the C configuration, only for the smallest value of the parameter x, the frequency of vortices generated is clearly lower, although the difference is significant. In the case of the D configuration up to x = 25mm, the influence of the mechanical elements introduced into the stream on the frequency of generated vortices can be seen.

Comparison of the frequency of generated vortices shows that the introduction of a mechanical element behind an obstacle significantly affects the process of generating vortices. In the case of the introduction of a cylinder with a diameter of 5 mm (configuration C), the significant effect is visible only at the

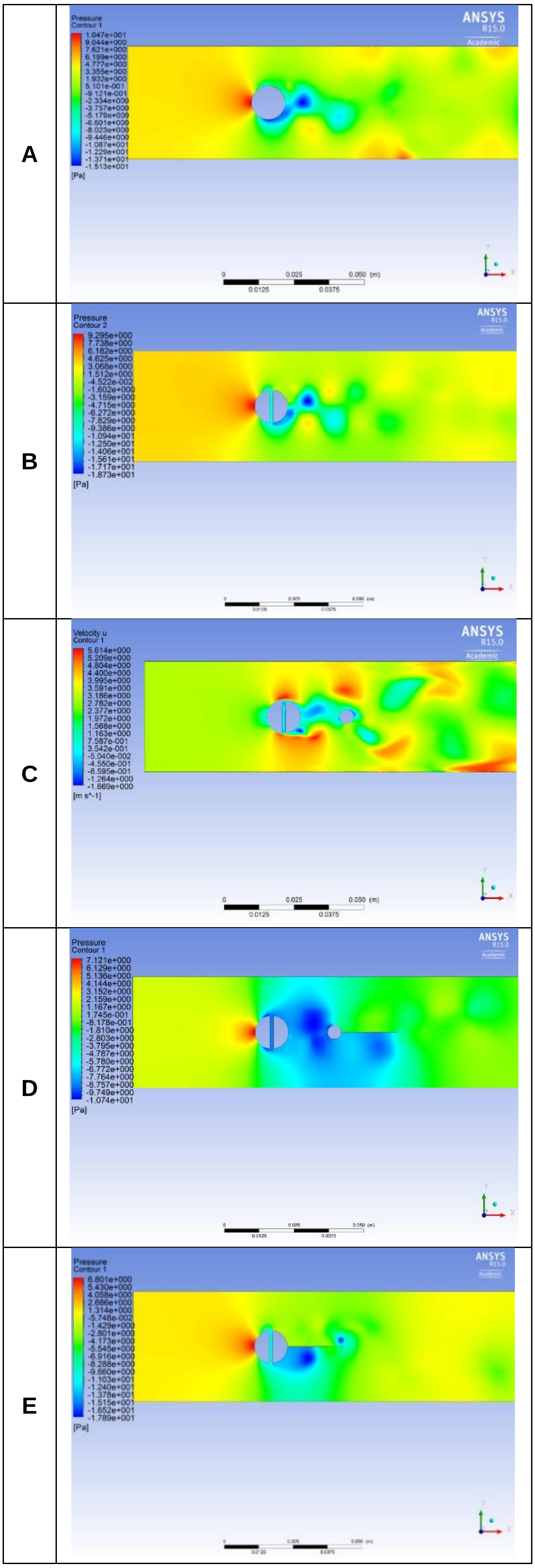


Fig. 2. Distributions of pressures for all tested configurations

TABLE I
VORTEX FREQUENCY VS. X-PARAMETER (f_C – frequency for configuration C, f_D – frequency for configuration D)

x [mm]	f_C [Hz]	f_D [Hz]
8	23,35	17,67
11	39,39	16,91
15	37,37	14,39
20	40,91	13,38
25	37,88	14,64

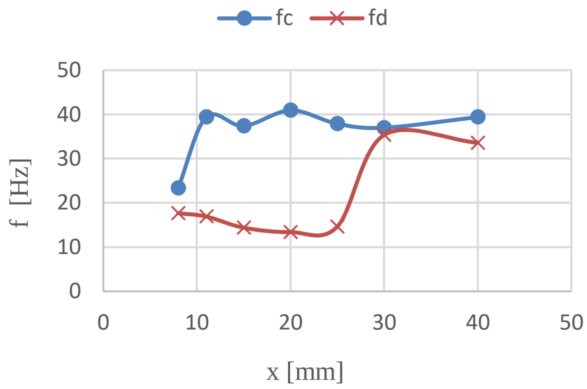


Fig. 3. Frequency of generated vortices vs parameter x – for C and D configurations

shortest distance between the bluff body and the beam. However, putting the beam downstream of the bluff body (configuration D) results in a much stronger effect. As you can see, the frequency of generated vortices is much lower than the frequency obtained for the largest distances from the obstacle. This effect is visible in a relatively large range of changes of parameter x.

In this way, it can be stated that the hypothesis formulated in [17] on the sensitivity of the stagnation zone and the influence of mechanical elements on the frequency of generated vortices has been confirmed. The hypothesis was based on results of experimental investigations carried out on measuring stand for flowmeters calibration.

B. Stabilizing the influence of the obstacle on the measuring signal

In the course of the tests on the measuring stand (carried out with strain gauge sensors glued on a beam), it was also noticed, that the quality of the measuring signal was very high – practically free of amplitude modulation. Comparison of results of simulation obtained for configurations B and D (Fig.6) shows, that – of course – signal obtained for configuration with the beam is hugely better.

It confirms the stabilizing effect of the beam on the measurement signal. The Fig.4. shows the course of transverse velocity at a point 50 mm away from the axis of the obstacle for two cases: the circular cylinder with a slit and for a cylinder with the slit and beam located at x = 8mm downstream the bluff body. It can be seen that the measurement signal in the second case is stable without modulation of the amplitude as can be seen in the case of an obstacle with a slit.

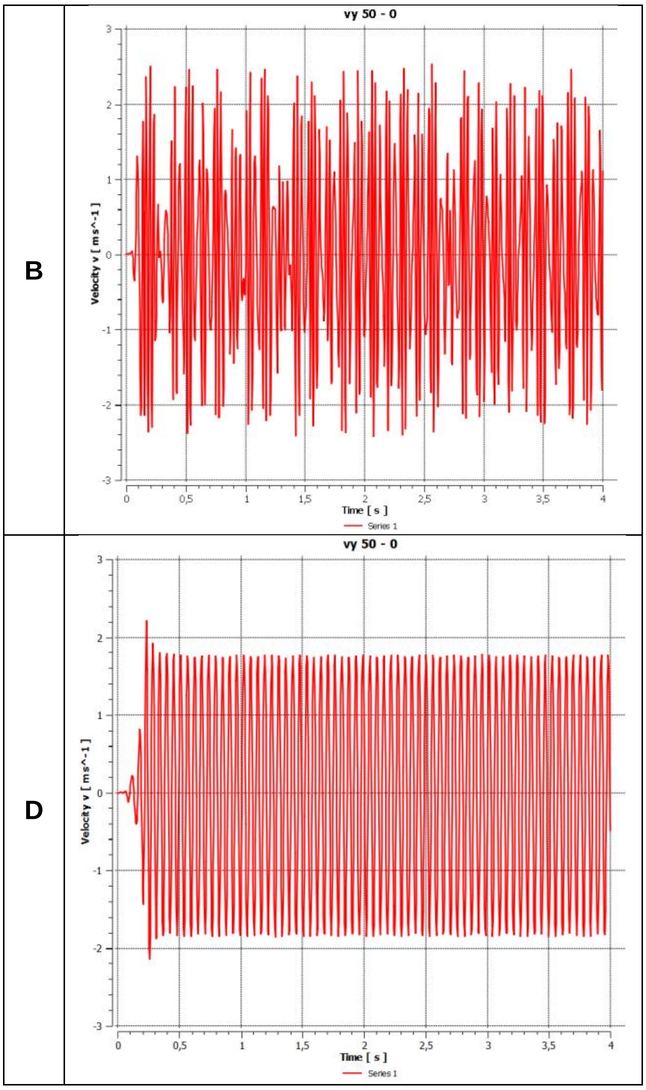
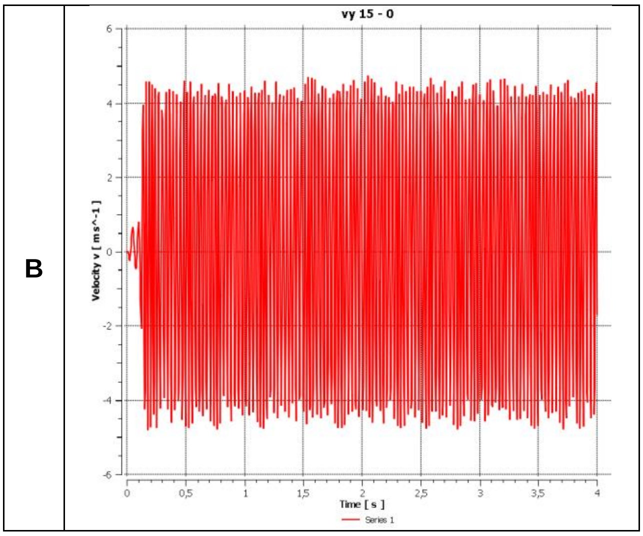


Fig. 4. Vertical velocity for configurations B and D for the point located 50 mm downstream the bluff body



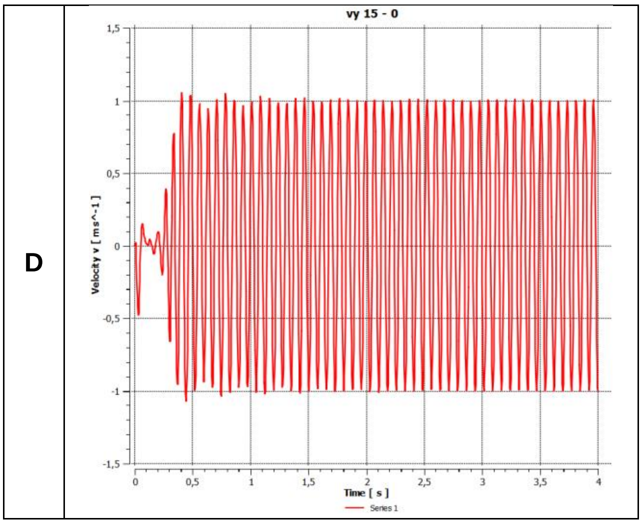


Fig. 5. Vertical velocity for configurations B and D for the point located 15mm downstream the bluff body

For both configurations (B and D), the measurement signal for the point close to the obstacle (15 mm downstream the body axis) was also analyzed (Fig.5.). For configuration D, it means the point between the bluff body and the beam. Also, in this case, the stabilizing effect of the beam on the measuring signal can also be seen.

C. Pressure acting on the beam

In vortex meters designed by the author of the paper, the vortices are detected by strain gauge sensors glued on a beam located in certain distance downstream of the bluff body. Hence significant is the dependence of the signal magnitude and quality on the beam location.

The pressure signal acting on the beam at a point 6 mm from its end was analyzed - for different values of the parameter x. Results are presented in Fig.6. Regarding the quality of the measurement signal for the beam positions for x <20 mm, a stable signal practically devoid of amplitude modulation is visible. For greater distances of the beam from the obstacle, there is evident a significant deterioration of the quality of the measurement signal.

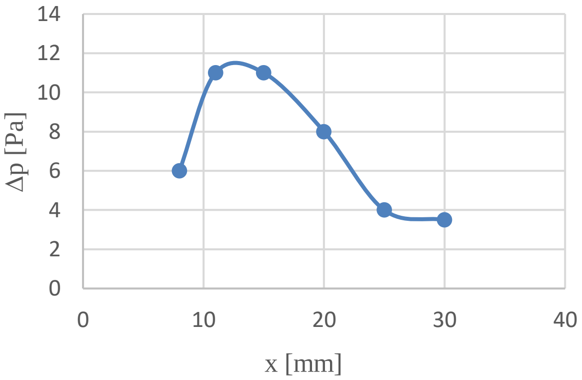


Fig. 6. The amplitude of pressure acting of the beam vs. x-values

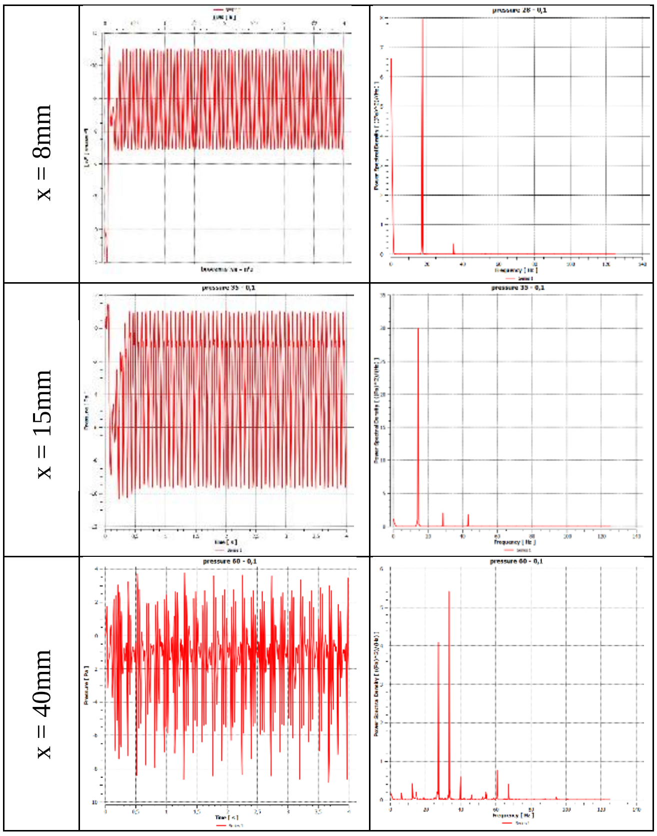


Fig. 7. The pressure acting on the beam at a distance of 6 mm from its end and signal spectrum for different x-values

In the Fig.6 the amplitude of pressure vs. x-parameter is presented. The amplitude of pressure grows for smaller values, achieves maximum for 11mm<x<15mm and then decreases. From presented results it can be stated, that there exists an optimal location of the beam from the point of view of signal amplitude.

It is also seen that Δp decrease is accompanied by considerable deterioration of the signal quality for greater x-values. It is presented in Fig. 7. where we can compare pressure signals and their spectrum for the chosen three distances x.

IX. CONCLUSIONS

The paper presents the problem of influence of the mechanical elements located downstream the bluff body on the Karman vortex street generation and its parameters. Main conclusions from the submitted work are as follows:

1. Insertion of the additional mechanical element into the stream downstream the bluff body influences the vortex shedding frequency.

2. Beam introduction to the flow considerable stabilizes the signal magnitude.

3. Pressure magnitude detected on the beam depends on the beam distance from the bluff body. There exists an optimum beam location. It is essential for meter optimization.

These conclusions are essential for vortex meter designing as well as of clarification unexpected effects appearing during laboratory tests, e.g., investigations of velocity area with hot wire anemometer application.

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