

The response of aeroelastic models of circular cross-sections to wind action

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ABSTRACT: This paper presents results obtained for vertically placed cylinders of circular cross-sections during wind tunnel tests. All models are considered as aeroelastic ones and can represent real chimneys. Accelerations in two perpendicular directions in horizontal plane (along and across wind tunnel) were measured at the tops of 27 cylinders. An attempt to research along-wind as well as across-wind responses with respect to different approaching flows was taken up.

KEYWORDS: circular cylinder, wind tunnel, aspect ratio, wind structure, along-wind response, across-wind response, vortex excitation.

1 INTRODUCTION

Cylinders of circular cross-sections were investigated in wind tunnels by many researches, who carried out experiments in order to obtain pressure distributions on the surface, the lift force and the drag force coefficients, Strouhal number, the correlation coefficient of the load, etc. In general research tasks can be gathered in specific groups: the study on motionless cylinders (measurement of forces and pressures), aeroelastic models (study of dynamic behaviour), vibrating cylinders (f.e.: lock-in). Experiments were performed mainly on stationary cylinders.

Pantazopoulos (1994) collected and characterized the majority of wind and water tunnel studies carried until 1992, which were focused on measurements on fixed cylinders in connection with: rms of lateral force coefficient, the dependence of Strouhal number (St) on Reynolds number (Re), load correlation length coefficient. Changes of St values with Re were presented by Schewe (1983) (smooth cylinder, $H/D = 10$, H = height, D = diameter), who also studied the change of lateral force based on direct measurements of forces and by Leung et al. (1997) (smooth and rough cylinders). Ribeiro (1991, 1992), for steady and unsteady flow, suggested an empirical relationship for estimating the standard deviation of the local fluctuating lateral force caused by vortices, and based on the knowledge of the distribution of the pressure fluctuations and the correlation coefficient of fluctuating lateral force.

Recently circular cylinders were investigated by: Sumner and Heseltine (2004) and Sumner et al. (2004) who investigated the vortices forming near the free-end of the cylinder ($H/D = 3, 5, 7, 9$), at $Re = 6 \cdot 10^4$. Velocity fields were measured in the excitation area and averaged in time, and then strength of vortices in every measuring point was estimated. General conclusion was that the vortex excitation for the model with the free-end occurs only in certain areas along the height of the model. In the next paper by Sumner and Heseltine (2008) detailed information about the tip vortex structures and their streamwise development were provided. The turbulent wake of cylinders was investigated at $Re = 6 \cdot 10^4$ by Adaramola et al. (2006) and was similar for cylinders of aspect ratios of 5, 7, 9 whereas distinctly different was for the cylinder of aspect ratio of 3. More details about the flow around the model of aspect ratio of 9 are presented in the paper by Adaramola et al. (2010). Cao et al. (2007) studied experimentally and Cao and Tamura (2008) studied experimentally and numerically the flow around cylinders ($H/D = 2.22, 4, 8$) in linear

shear flows, at $Re = 1.7 \cdot 10^4 - 3.6 \cdot 10^4$. Vortex shedding was investigated by examination of Strouhal number and base pressure variations with respect to shear parameter. Also the mean pressure distributions around cylinder as well as drag and lift forces were studied. The 3D effect of the flow passing over the free-end on vortex shedding in the case of cylinder of small aspect ratio of 3, at $Re = 6 \cdot 10^4 - 11 \cdot 10^4$ was investigated by Iungo et al. (2012). Pressures, forces and velocities measurements were conducted during tests. Pressure measurements on the surface of the cylinder at $Re = 4.0 \cdot 10^4 - 1.64 \cdot 10^5$ were conducted by Lee et al. (2011) in order to investigate the difference of aerodynamic characteristics between non-accelerated and accelerated flow. Pressure and hot-wire measurements for two cylinders of aspect ratios of 8 and 8.6 and different surface roughness at $Re = 1.73 \cdot 10^5 - 5.86 \cdot 10^5$ were conducted by Miao et al. (2011). Particular attention was paid to the flow behavior in the near wake region.

Many papers are devoted to the vibrating cylinders. The results of studies on the relation between St and Re numbers at various intensities of turbulence of the approaching flow in the case elastically mounted model were described by Cheung and Melbourne (1983). The standard deviation of local lift caused by vortex excitation, obtained in studies in turbulent flow in dependence on Re number and turbulence intensity were also examined in that research. Novak and Tanaka (1975) found that the correlation length of the load increases rapidly with the amplitude of vibrations, and the increase is higher for steady flow than for turbulent flow. Howell and Novak (1980) studied the global force acting on cantilever, rigid cylinder, mounted elastically. The authors measured correlation coefficient of pressures as the function of the distance between the reference point and the location of the second point moving along the height. The experiment was performed in steady and turbulent flows, with the model oscillating transversely, at Re number $7.5 \cdot 10^4$. The study showed an increase in lateral force coefficient with increase of the vibration amplitude to 0.1D.

More recent researches on vibrating cylinders were made by Gupta and Arun (2003) who performed measurements of the wind velocity fields around cylinders of different cross-sections, in which oscillations caused by vortices were observed. The dependence of Strouhal number on Reynolds number was formulated. Pastò (2008) analysed the behavior of freely vibrating model in laminar and turbulent flows. Studies were focused on the influence of mass-damping parameter of circular models and Reynolds number on lock-in phenomenon, on the response amplitude and on wake correlation. Measurements of unsteady pressure distributions on the surface of oscillating cylinder were presented by Zasso et al. (2008). Studies were focused on vortex shedding and on integral forces on the cylinder and their correlations with motion. The effect of free-stream turbulence on vortex-induced vibrations of an elastic cylinder ($H/D = 20$) in a cross-flow and the associated fluid forces were investigated experimentally at Re number $5 \cdot 10^3 - 4.1 \cdot 10^4$ by So et al. (2008). Belloli et al. (2012) investigated vortex induced vibrations of the cylinder ($H/D = 10$) of low structural damping and high mass ratio at $Re = 5.4 \cdot 10^4$. Tests showed the clear correlation between wake and force changes during cylinder vibrations.

2 RESEARCH DESCRIPTION

2.1 Models

The experiments were carried out in the boundary layer wind tunnel in Wind Engineering Laboratory in Cracow, Poland. Circular cylinders were placed vertically in the working section of the wind tunnel (Fig. 1). The basic geometrical characteristics of the 27 models are collected in Table 1 together with measured frequencies. All models were made of carbon fiber in order to assure particular stiffness, which was necessary to fulfil similarity criteria. The applied material has got the following characteristics: elastic modulus $E = 105$ GPa, density: $\rho = 1455$ kg/m³.

The following parameters are settled in Table 1: geometrical characteristics of the models (D – diameter, H – height, λ – aspect ratio), f = natural frequencies of vibrations calculated from power spectral density functions of top accelerations. There are distribution of natural frequencies with respect to case number and aspect ratio in Figure 2.



Figure 1. View of the wind tunnel with the model place on rotational table and one of the models.

Table 1. Geometric and dynamic characteristics of models.

No	D	H	λ	f	No	D	H	λ	f	No	D	H	λ	f	V_{crit}
	[mm]	[cm]	[-]	[Hz]		[mm]	[cm]	[-]	[Hz]		[mm]	[cm]	[-]	[Hz]	[m/s]
1	16	50	31.25	50.66	10	20	30	15.00	193.12	19	34	80	23.53	54.50	10.295
2	16	40	25.00	73.67	11	24	60	25.00	54.32	20	34	70	20.59	66.17	12.499
3	16	30	18.75	110.72	12	24	50	20.83	77.40	21	34	60	17.65	85.50	16.150
4	18	50	27.78	63.51	13	24	40	16.67	105.04	22	34	50	14.71	107.65	20.334
5	18	40	22.22	89.18	14	24	30	12.50	235.96	23	50	90	18.00	54.77	15.214
6	18	30	16.67	132.10	15	27	70	25.93	50.07	24	50	80	16.00	67.00	18.610
7	20	60	30.00	51.16	16	27	60	22.22	65.07	25	50	70	14.00	82.03	22.785
8	20	50	25.00	65.94	17	27	50	18.52	81.43	26	50	60	12.00	100.73	27.981
9	20	40	20.00	89.89	18	27	40	14.82	136.03	27	50	50	10.00	121.68	33.799

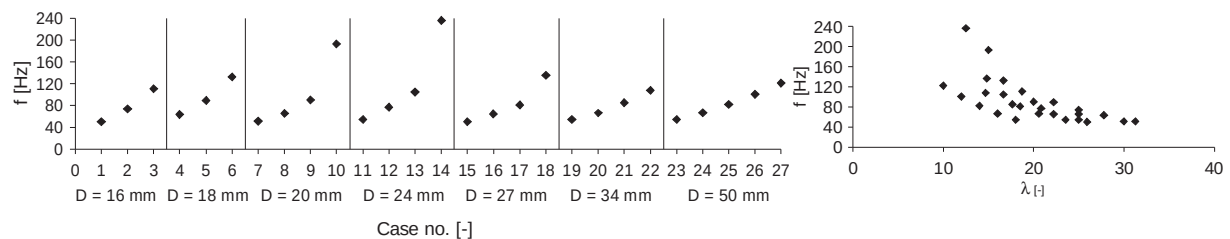


Figure 2. Distribution of natural frequencies against case number and aspect ratio.

2.2 Wind conditions

The influence of wind characteristics – wind mean speed profiles, turbulence intensity profiles and PSD functions – on the mean pressure coefficient distributions were examined. Over 40 configurations of barriers, spires and blocks generating boundary layer were taken into account. Three (six in case of pipes of the diameter $D = 16$ mm) flows were chosen for further measurements. The mean wind speed profile (power-law formula), intensity of turbulence, and PSD function (similar to Davenport's function) were described by respective equations:

$$v(z) = k \cdot z^\alpha \quad \text{for } z > z_{min}$$

$$I_v(z) = \frac{\sigma(z)}{\bar{v}(z)}$$

$$G(f) = \frac{bf^2}{(1+cf^2)^d} \quad (1)$$

where: z = height [cm], z_{min} = minimum height [cm] for which all profiles have the same value at 70 cm, k and α = values selected by the least squares method, $\bar{v}(z)$ = mean wind speed, $\sigma(z)$ = standard deviation of wind speed, b, c, d = coefficients selected by the least squares method. Respective plots are collected in Figure 3.

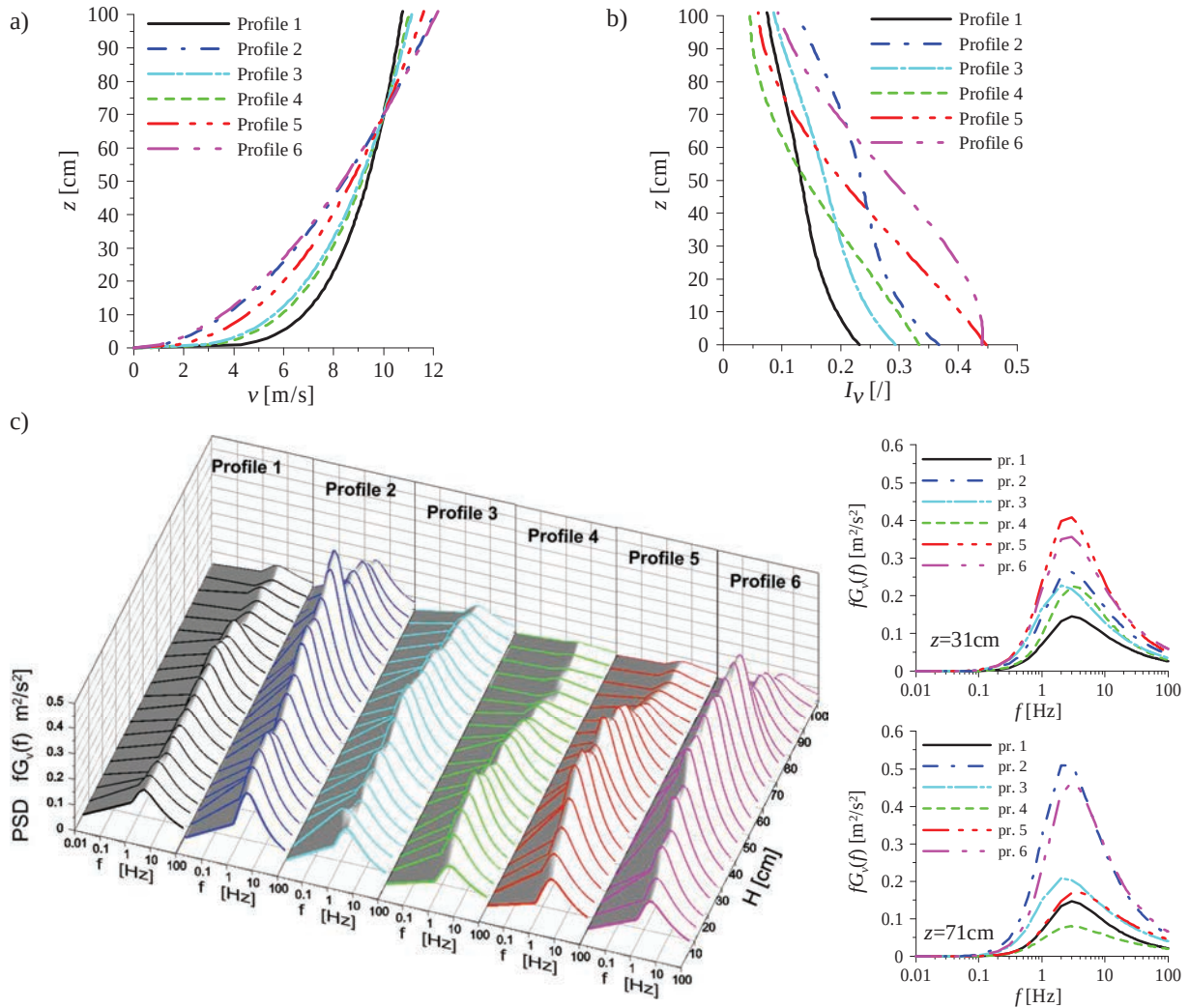


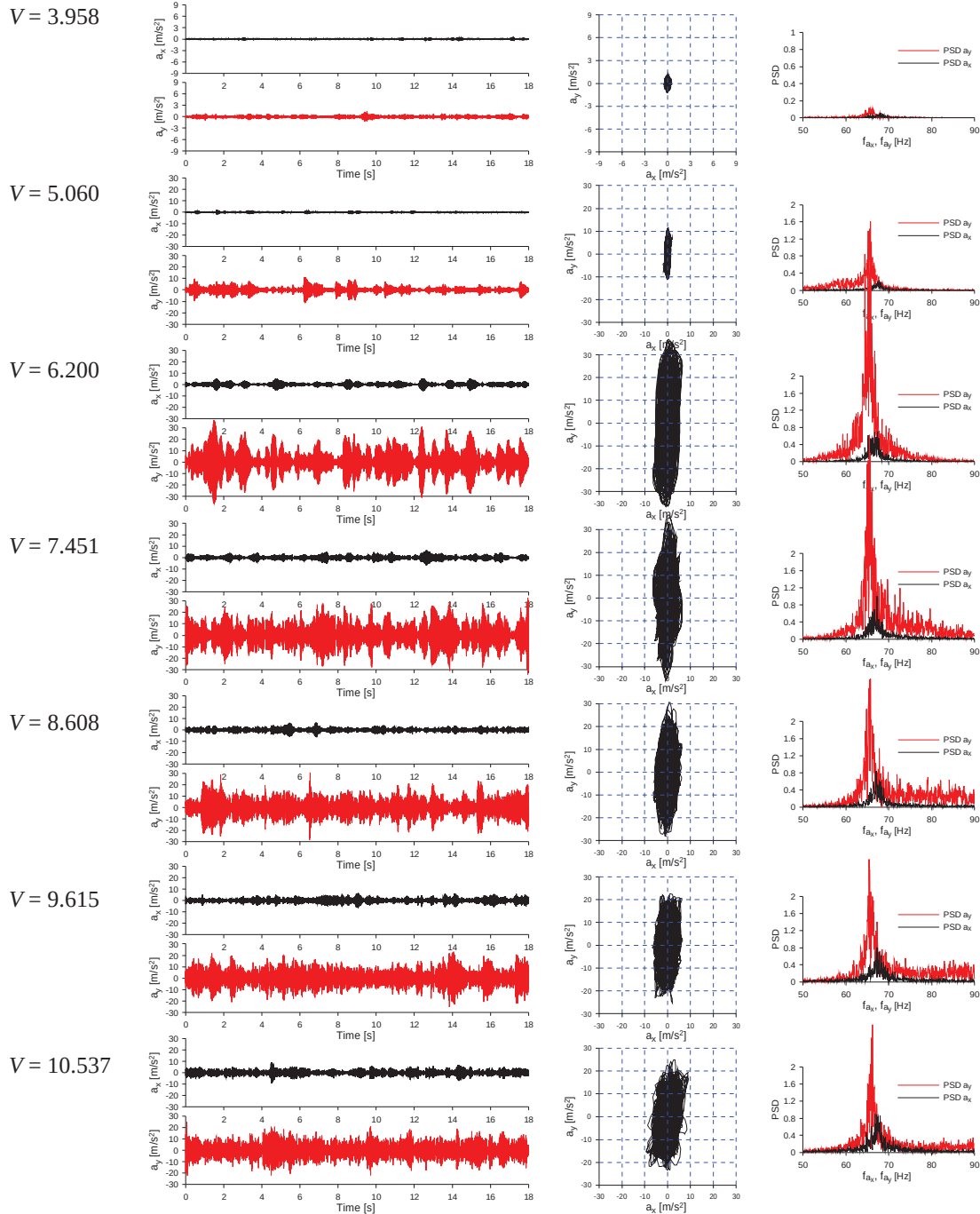
Figure 3. Wind characteristics: a) profiles of mean wind speed, b) profiles of intensity of turbulence, c) PSD functions: spatial distributions and examples at two levels.

2.3 Experiment

Two Brüel&Kjær accelerometers were installed at the top of each model. The data was gathered with PULSE system. Time series of accelerations in two perpendicular direction: along and across wind tunnel were measured. The view of a model with installed accelerometers in wind tunnel is presented in Figure 1. The wind speed was changing from 0 m/sec to about 20 m/sec during measurements.

3 RESULTS AND ANALYSIS

Statistical data handling has allowed to define wind speeds at which vortex excitation could take place. Top accelerations in two perpendicular directions and PSD functions of time series with respect to increasing wind speed are presented in Figure 4 in the case of the model No. 8 ($D = 20$ mm, $H = 40$ cm) and profile 1. Amplitudes of top accelerations for wind speeds at which vortex shedding occur in cases of the same pipe and profiles 3 and 6 are presented in Figure 5 in order to compare results. The same analysis was carried out for all cases of models and wind structures.



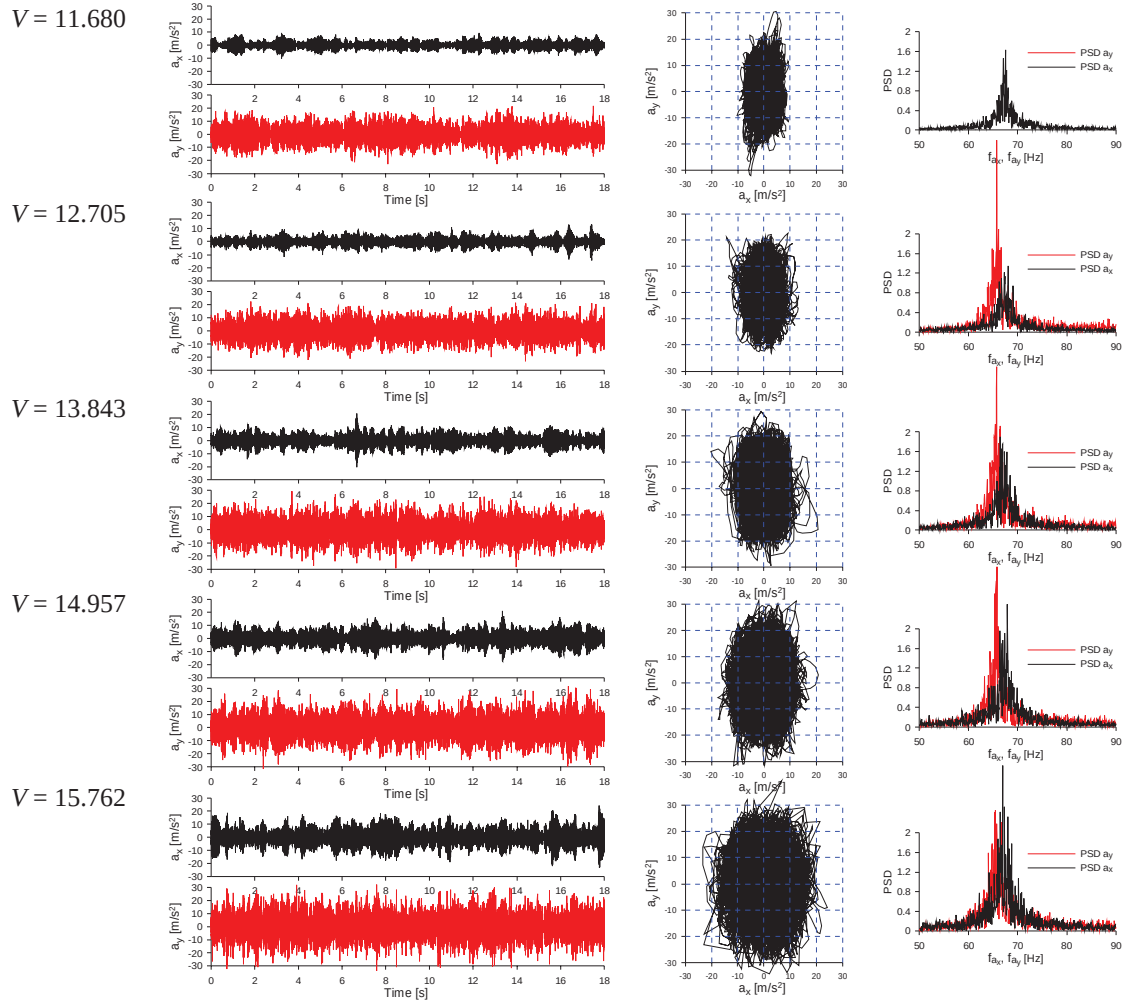


Figure 4. Time histories of accelerations (a_x , a_y), trajectories of top accelerations and PSD functions of along and across-wind components for consecutive wind speeds, for wind profile no. 1, for pipe no 8.

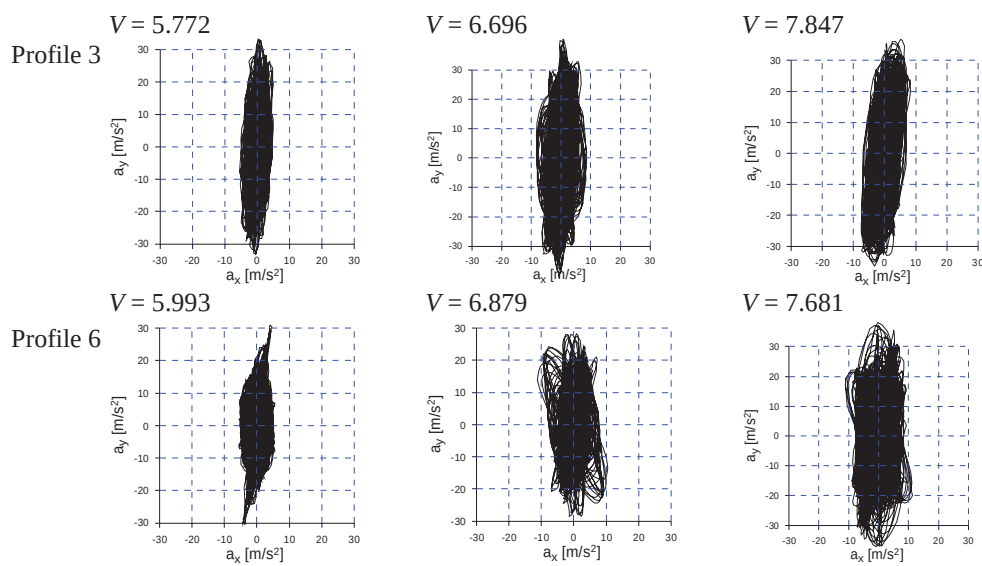


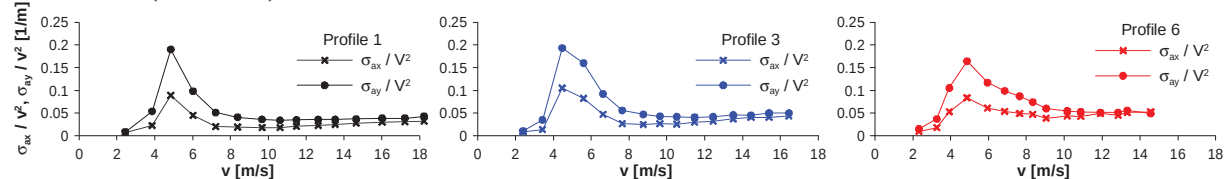
Figure 5. Top trajectories of accelerations at the range of wind speeds at which vortex shedding occur.

Vortex excitation is clearly visible on time histories of accelerations (higher amplitude of the acceleration in direction perpendicular to the flow) as well as on power spectral density functions (higher peak value). Increasing amplitude of the accelerations in both directions are caused by the increasing wind speed.

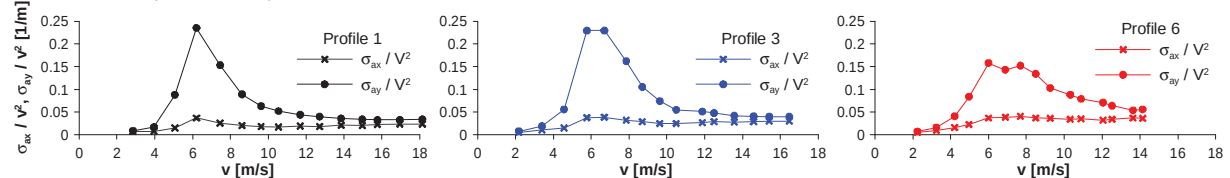
The reduced standard deviations of top accelerations respectively along and across mean wind speed (σ_{ax} , σ_{ay}) were assumed as results, which allow to compare two components of the cylinder response to the wind action. Examples of normalized standard deviations (σ_{ax}/V^2 , σ_{ay}/V^2) and their ratio (σ_{ax}/σ_{ay}) are presented in Figures 6 and 7. As it can be seen in these figures – the range of wind speeds in which vortex excitation appears could be recognized with a good approximation. Some more cases of the ratio σ_{ax}/σ_{ay} are enclosed in Figure 8 and 9 for pipes of the smallest and the largest diameter equal respectively to 16 mm and 50 mm.

Critical wind speed values obtained in the research were evaluated from maxima at plots of standard deviations or their ratio as shown in Figures 6-9. It should be emphasized that values obtained in the studies are approximated and only shows the range of wind speeds close to which vortex excitation can appear. The way of attaching accelerometers at the top of the model pipe causes flow disturbances and then differences in values of measured and calculated critical wind speeds. Vortex excitation appears in the range of wind speeds different in particular cases of flow. There was no excitation for pipes 18, 22, 26, 27 in considered wind speed range. From the other hand an exact critical wind speed could not be estimated (there are no maxima on plots) but only the beginning of vortex excitation was determined in some cases of pipes. Evaluated and calculated critical wind speeds are collected in Table 2 with respect to case of wind structure. Theoretical value was calculated from $V_{cr} = fD/St$, where $St = 0.18$

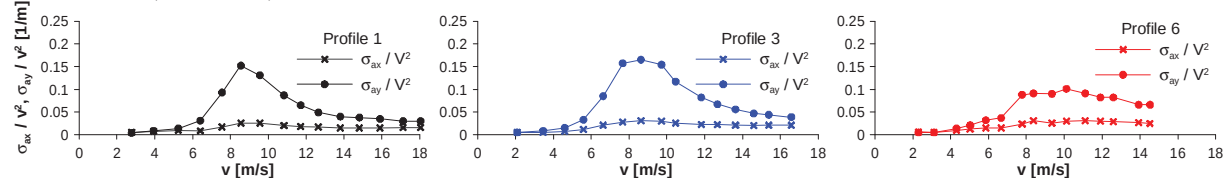
Model No. 7 ($D = 20$ cm)



Model No. 8 ($D = 20$ cm)



Model No. 9 ($D = 20$ cm)



Model No. 10 ($D = 20$ cm)

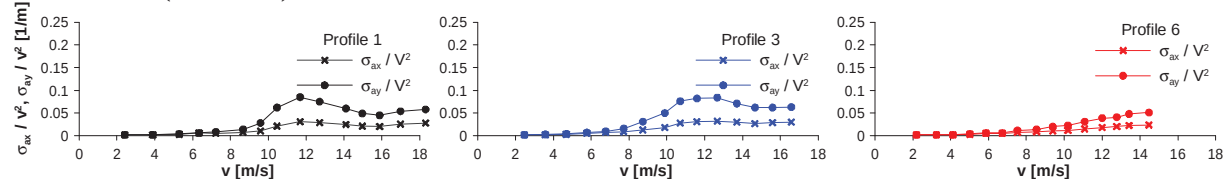


Figure 6. Normalized standard deviations of accelerations (σ_{ay} and σ_{ax}) for three different wind speed profiles against increasing wind speed for four models of the diameter $D = 20$ m (No. 7-10).

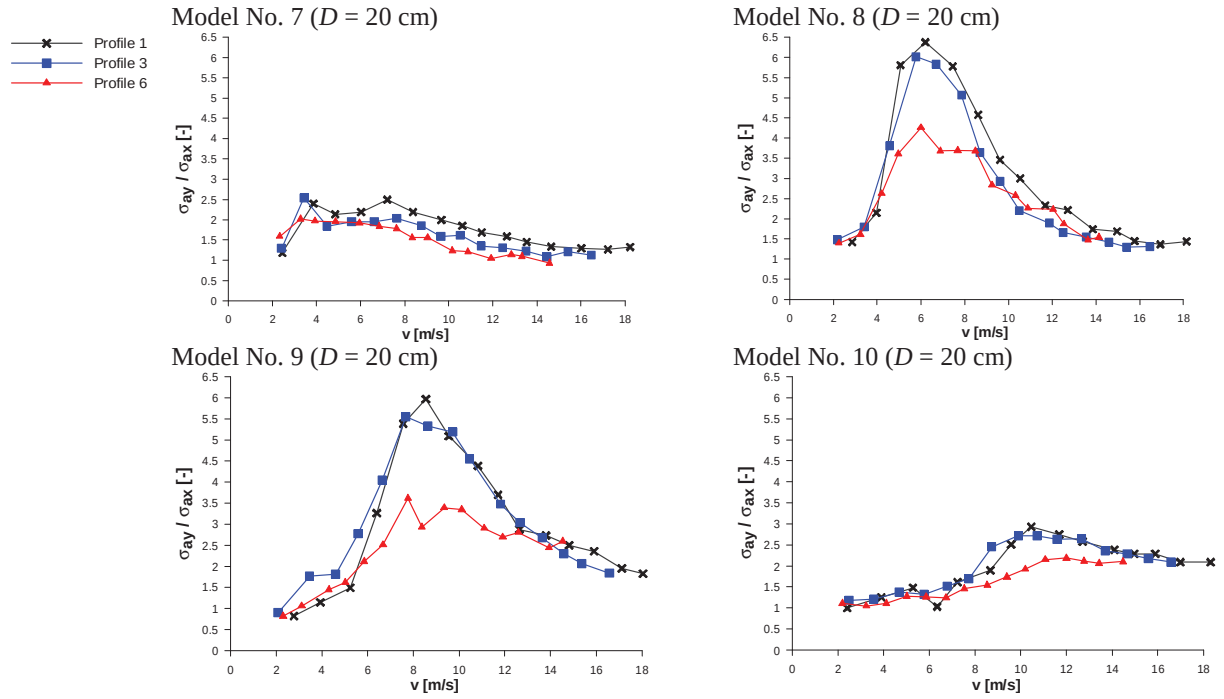


Figure 7. The ratio of standard deviations (showed in Fig. 6) against wind speed for models of the diameter $D = 20$ m (No. 7-10).

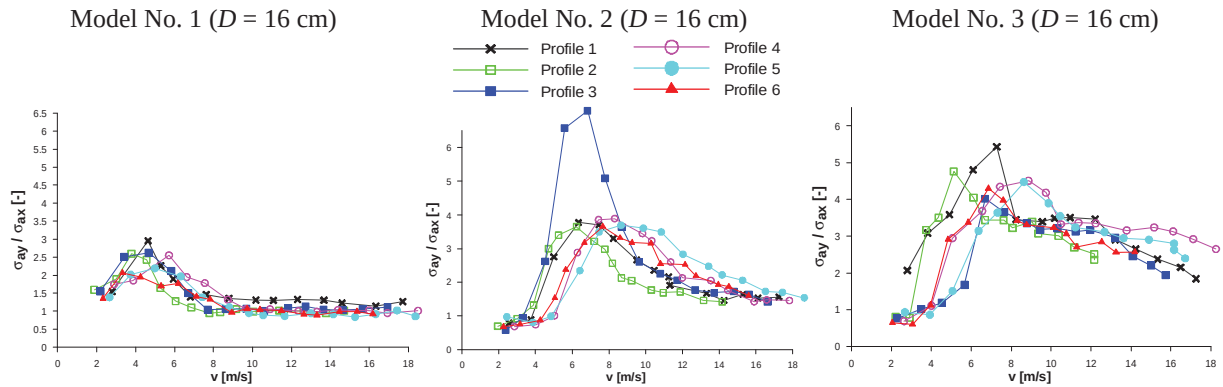


Figure 8. The ratio of standard deviations against wind speed for models of the diameter $D = 16$ m (No. 1-3).

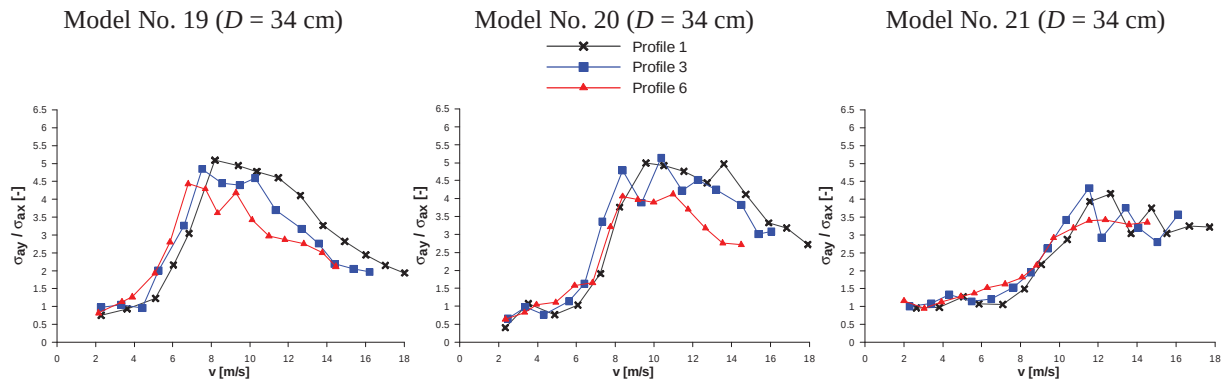


Figure 9. The ratio of standard deviations against wind speed for models of diameter $D = 34$ mm (No. 19-21).

Table 2. Calculated and measured wind speeds.

No.	V_{cr} (theoretical) [m/s]	V_{cr} (wind tunnel) [m/s]					
		Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6
1	4.501	4.643	3.784	4.675	5.717	4.989	3.338
2	6.549	6.345	6.230	6.836	6.278	8.659	7.655
3	9.842	7.278	5.123	6.696	8.866	8.630	6.857
4	6.351	7.545		5.534			7.652
5	8.918	9.528		8.584			10.818
6	13.210	12.255		13.470			12.342
7	5.684	3.853		3.425			3.269
8	7.327	6.200		5.772			5.993
9	9.988	8.547		7.666			7.769
10	21.458	10.459*		12.659*			12.002*
11	7.243	6.267		6.543			6.620
12	10.320	11.743		8.231			7.786
13	14.005	11.463		11.512			11.971
14	31.462	14.259*		12.639*			13.923*
15	7.510	6.091		6.444			6.527
16	9.760	8.701		8.519			7.653
17	12.214	12.904		12.367			12.563
18	20.404	-		-			-
19	10.295	8.189		7.521			6.797
20	12.499	9.584		10.372			10.977
21	16.150	12.630*		11.523*			12.365*
22	20.334	-		-			-
23	15.214	11.420		10.356			11.145
24	18.610	13.622		12.308			11.792
25	22.785	16.755*		15.145*			14.272*
26	27.981	-		-			-
27	33.799	-		-			-

* the beginning of vortex excitation.

4 CONCLUSIONS

Based on the analysis of results it can be stated that the response of aeroelastic models of circular cross-sections depends strongly on the structure of the approaching flow. The response of such models is highly influenced by buffeting load resulting from the turbulence (fluctuations of wind speed and direction) as well as by the vortex excitation load.

It seems that the wind structure have the higher influence on critical speed for models with larger aspect ratios. Perhaps this is related to a combination of wind gusts and vortex excitation. On the other hand, the wind structure has less effect on the critical speeds for smaller aspect ratios (lower differences between calculated and measured values – Table 2).

The standard deviations obtained for the profile 6 are in most cases lower than those obtained for other cases. For most of models, the largest standard deviations and their ratios were obtained in case of profile 1 (the lowest turbulence of the flow), the smallest in case 6 (the largest turbulence of the flow).

The studies provided a range of critical wind speeds (different for various cases of flow), which in general is close to the theoretical values obtained for $St = 0.18$. Differences are caused by the way of accelerometers attachment on the top (disturbance of the flow around). Also the approximated estimation of maxima values on plots in Figures 6-9 causes the difference between

calculated and theoretical values. But it can be clearly noticed that vortex excitation appears in the range of wind speeds almost for each case of the pipe.

It seems that further analyses are necessary to better understand the influence of wind structure on the response of pipes. Numerical simulations of dynamic response taking into account buffeting load as well as vortex excitation is also planned

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