Vortex-induced vibrations measured on a full scale chimney

Agathe Schmider[1] & Pascal Hémon[2]

[1]LadHyX, CNRS-Ecole Polytechnique, IP Paris, France, agathe.schmider@polytechnique.edu
[2]LadHyX, CNRS-Ecole Polytechnique, IP Paris, France, pascal.hemon@polytechnique.edu

SUMMARY:
We present the measurements performed on a full scale flexible chimney with a height of 35.5 m and a diameter of 2 m in its main part. The chimney is designed to have a low first frequency of bending and a small Scruton number. The site of the setup is supposed to be of type II of the Eurocode and wind measurements are also performed with four anemometers on a 40 m mast. At moderate wind the velocity gradient and the turbulence intensity are lower than expected.
VIV events were observed and measured during a short term campaign. At lock-in the amplitude at the top reaches 36 % of the diameter while the amplitude is much lower when the velocity deviates from the lock-in speed. The lock-in is obtained with a Strouhal number of 0.225. These data are useful for the study and the validation of prediction models of VIV in natural wind conditions.

Keywords: vortex shedding, full scale measurements, circular cylinder

1. PRESENTATION OF THE FULL SCALE EXPERIMENT

The goal of the paper is to report the measurements performed on a full scale vertical cylinder subject to natural wind. The setup shown in Figure 1 is an experimental chimney erected at Bouin (France) near the Atlantic seashore, in order to measure vortex shedding excitation (Manal & Hémon, 2024). Typical Reynolds number is around 1.1 million. The chimney is 35.5 m high steel tube with an external diameter of 1 m in the lower part, from 0 to 12 m, and 2 m in the upper part above 15 m. From 12 to 15 m the diameter linearly increases from 1 to 2 m. The upper part has an aspect ratio L/D equal to 10. The chimney is clamped at the bottom in a concrete mass properly designed. Structural properties of the chimney are given in Table 1. The Scruton number $Sc = \frac{4\pi m\eta}{\rho D^2}$ is 1.53.

Table 1. Structural parameters of the chimney

Parameters	Symbol	Value	Unit
Linear mass	m	322.6	kg/m
Reduced damping	η	0.185	%
First bending frequency	f	0.848	Hz

Four single component accelerometers are mounted to measure the chimney motion (type PCB 3741). They can measure in the frequency range [0-70 Hz] up to ±2 g with an accuracy better than ±0.04 g. Accelerometers #1 and #2 are fixed at a height of 20.4 meters and #3 and #4 at the top, ie 35.5 meters. The record is continuous with a sampling frequency of 16 Hz. In the following, only the top accelerometers are used, providing the amplitude of the motion which is based on the first bending mode.

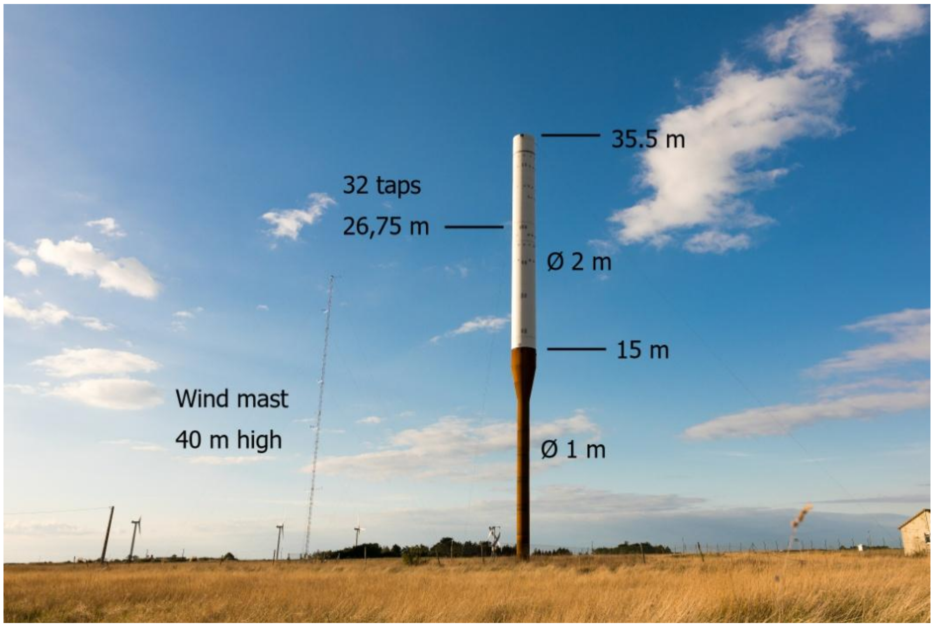

Figure 1. Photo of the Bouin chimney with its dimensions.

2. MEASUREMENTS OF WIND CONDITIONS

A 40 meters high mast is erected 55 meters west from the chimney. It is equipped with 4 anemometers at heights of 10 (cup), 18 (propeller), 25 (3D sonic) and 35 (propeller). Three wind vanes complement the cup and the propeller anemometers. All records are organized in sequences of 10 minutes.

Table 2. Measured wind characteristics

Date	Time	Wind data from sonic anemometer at 25.5 m					Data from cup anemometers		
		Mean velocity m/s	Turbulence intensity %	Wind direction ° ref MN	RMS of wind direction °	Integral Scale Lu m	Mean velocity at 10 m m/s	Mean velocity at 20 m m/s	Mean velocity at 35 m m/s
19-juil.-21	16h50	7.70	16.30	72.1	6.3	34	7.21	7.67	8.32
	17h00	7.65	16.20	66.5	7.6	60	6.80	7.55	7.78
	17h10	7.77	14.20	58.9	8.9	35	6.94	7.19	7.81
	17h20	7.36	16.50	59.7	7.3	33	7.00	7.26	7.87
20-juil.-21	14H00	10.09	13.50	76.3	8.0	45	7.70	8.40	9.12
	14h10	9.97	12.96	69.3	8.9	44	8.90	9.60	10.14
	14h20	10.25	13.50	73.0	7.0	46	8.93	9.50	9.85
	14h30	9.22	15.05	82.9	6.89	41	9.11	9.69	10.29
	14h40	8.79	13.42	85.4	9.14	39	8.05	8.69	9.42
	12h40	9.96	13.17	67.5	8.1	50	9.47	9.95	10.58
	12h50	9.72	10.57	73.09	7.55	50	8.43	9.31	9.98

The wind characteristics of the selected sequences are given in Table 2. Overall, while the site is supposed to be of type II in the Eurocode, the measurements show a lower velocity gradient and a lower turbulent intensity than expected. Preliminary results were presented in (Ellingsen et al. 2022, Manal & Hémon 2022).

3. MEASURED OSCILLATIONS

The statistical results are given in Table 3 and plotted in Figure 2 as a function of the reduced frequency $f_r = \frac{f\,D}{\bar{U}}$. Four sequences approach a "perfect" lock-in, with an amplitude that reaches 36 % of the diameter. The corresponding Strouhal number is 0.225.

The other sequences present much lower amplitudes, lower than 10 % of the diameter. In these cases, the chimney response is certainly due to the turbulent excitation with a small participation of the vortex shedding.

Table 3. Measured top amplitude

Date	Time	Reduced frequency f_r	Maximum top displacement Y_{max}/D	RMS top displacement Y_{RMS}/D	Peak factor g
19-juil.-21	16h50	0.2203	0.2418	0.0543	4.45
	17h00	0.2216	0.3630	0.0961	3.78
	17h10	0.2183	0.3372	0.1006	3.35
	17h20	0.2304	0.2516	0.0630	3.99
20-juil.-21	14H00	0.1681	0.0431	0.01337	3.22
	14h10	0.1700	0.0788	0.02210	3.59
	14h20	0.1654	0.0638	0.02463	2.60
	14h30	0.1840	0.0874	0.03430	2.56
	14h40	0.1930	0.0256	0.00380	6.76
	12h40	0.1703	0.0641	0.02638	2.43
	12h50	0.1745	0.0537	0.01724	3.12

The measured amplitudes are compared to amplitudes estimations obtained from the two methods of Eurocode, using Ruscheweyh's model (method 1) or Vickery-Basu model (method 2), which are plotted at resonance in Figure 2. The Vickery-Basu model overestimates the field observations (0.53 against 0.36), while Ruscheweyh's model underestimates them (0.29 against 0.36).

Surprisingly the linear model based on a harmonic lift force gives an amplitude close to the one given by Ruscheweyh's model. This model reads

$$\frac{Y_{max}}{D} = \frac{1}{8\,\pi^2\,{f_r}^2\,M^*}\,\frac{\sqrt{2}\,C_{lat}}{\sqrt{(1-f^{*2})^2+4\,\eta^2\,f^{*2}}} \tag{1}$$

where the mass ratio is $M^* = \frac{m}{\rho\,D^2}$ and the frequency ratio $f^* = \frac{St}{f_r}$. Here, we use the same lift force coefficient value as in Eurocode, $C_{lat} = 0.2$.

Moreover, the measured peak factors are close to the result obtained with Davenport's formula

$$g = \sqrt{2\, ln(\nu\, T)} + \frac{0.577}{\sqrt{2\, ln(\nu\, T)}} = 3.69 \qquad (2)$$

where the frequency ν=0.848 Hz and the observation time is T=600 s.

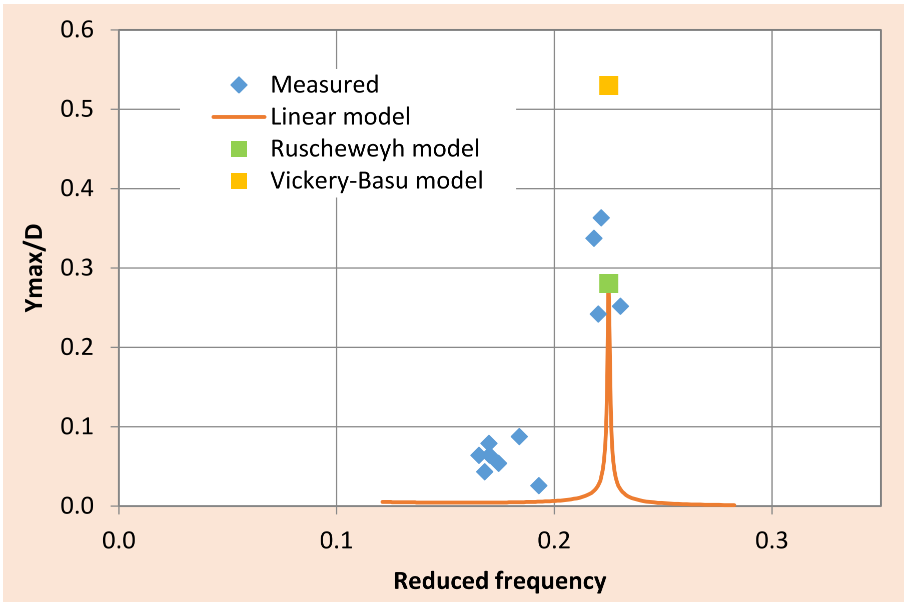

Figure 2. Measured maximum top amplitude versus reduced velocity.

4. CONCLUSION

Wind-induced vortex shedding has been measured on a full scale flexible chimney at Reynolds number of 1.1 million. The upcoming wind at moderate value is turbulent with intensity around 13-16 %. Wind-induced vibrations were observed during a short term campaign with lock-in at the reduced frequency (or Strouhal number) of 0.225. The maximum amplitude at the top was 36 % of the diameter. The presented data are useful for the study and the validation of prediction models of VIV in natural wind conditions.

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