VIV AND UNSTEADY PRESSURE LOADS MEASURED ON A FULL SCALE CHIMNEY

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ABSTRACT. 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 mechanical design is done in order to obtain 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 one of lock-in. The lock-in is obtained with a Strouhal number of 0.225.

Unsteady wall pressure measurements were performed on the circumference of the chimney. These signals are analysed with the bi-orthogonal decomposition technique which appears to be very efficient. Mean pressure distribution is provided for a Reynolds number of 1.1 million. Moreover, the unsteady pressure distribution resulting from vortex shedding is identified, with a Strouhal number of 0.21-0.24.

1. PRESENTATION OF THE FULL SCALE EXPERIMENT

The chimney shown in Figure 1 is a steel tube with 35.5 m high and 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.

Figure 1 Views of the chimney and the wind mast

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

A mast of 40 meters high is erected at the distance 55 meters from the chimney in the west direction. It is equipped with 4 anemometers at 10 (cup), 18 (propeller), 25 (3D sonic) and 35 (propeller) meters of height. Three wind vanes complement the cup and the propeller anemometers. All records are organized in sequences of 10 minutes. The wind characteristics of the selected sequences are given in Table 2. On the whole, 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).

2. VIV MEASUREMENTS

Four single component accelerometers are mounted for the chimney motion measurement (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 20.4 meters of height 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.

Table 2. Measured wind characteristics

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

Table 3. Measured top amplitude

Date	Time	Name	CHIMNEY MOTION	
			Reduced frequency	Maximum top displacement
			fr	Ym/D
19-juil.-21	16h50	A	0.2203	0.2418
	17h00	B	0.2216	0.3630
	17h10	I	0.2183	0.3372
	17h20	J	0.2304	0.2516
20-juil.-21	14H00	C	0.1681	0.0431
	14h10	D	0.1700	0.0788
	14h20	E	0.1654	0.0638
	14h30	F	0.1840	0.0874
	14h40	G	0.1930	0.0256
	12h40	K	0.1703	0.0641
	12h50	L	0.1745	0.0537

The results are numerically given in Table 3 and plotted in Figure 2 versus the reduced frequency $f_r = \frac{f\,D}{\bar{U}}$. There are 4 sequences which are close to the “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.

3. UNSTEADY WALL PRESSURE MEASUREMENTS

Synchronized wall pressure measurements are performed by using 32-channel pressure scanners. The global accuracy is about ±1 Pa, but practical difficulties in setting the zero value (the no wind response of the sensor) lead to much higher errors on the mean component. So the classical time-averaged values of the pressure are not used and the mean pressure distribution will result from a data processing detailed hereafter. The records have a sampling frequency of 16 Hz and stored in sequences of 10 minutes long.

We present here the results obtained with the 32 taps around the chimney at 26.75 meters of height with a motionless chimney (thanks to 3 stayed cables). The taps are located at mid-span of the 2 m diameter section, 10 m or $5D$ from the top and the diameter reduction. They are uniformly distributed around the circumference and spaced by 11.25° of the azimuth angle θ. The value $\theta = 0°$ is referred to the wind direction as in a wind tunnel test section, so the data shown further in natural wind have been rotated in order to reach a "symmetrical" result which is of course imperfect due to the natural scatter of these observations. More detailed can be found in (Manal & Hémon 2024).

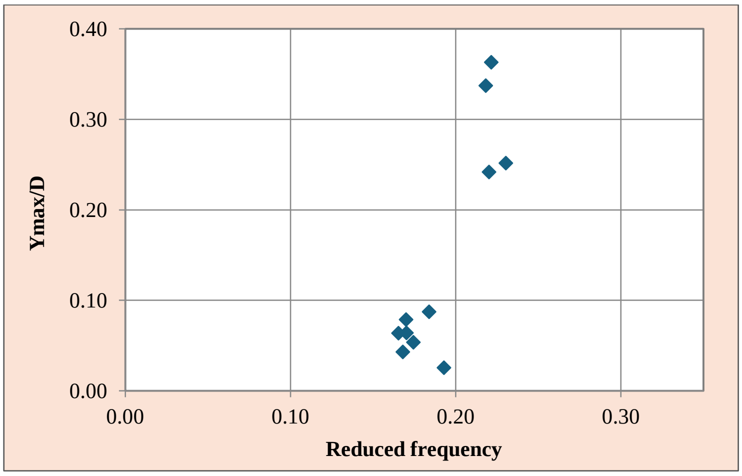

Figure 2. Maximum amplitude during sequences of 10 minutes

Due to the experimental difficulties, the pressure signals are processed with the bi-orthogonal decomposition (BOD) technique which was first introduced by (Aubry, Guyonnet & Lima 1991). The idea of the BOD is to decompose the spatio-temporal signal $Cp(\theta, t)$ in a series of spatial functions $\phi_i(\theta)$ named further as "topos", coupled with a series of temporal functions $\psi_i(t)$ named "chronos". The BOD can be written as

$$Cp(\theta, t) = \sum_{i=1}^{N} \alpha_i \, \phi_i(\theta) \, \psi_i(t) \qquad (1)$$

where α_i are the eigenvalues of the spatial or the temporal covariance matrix of the signal $Cp(\theta, t)$. N is the number of terms retained for the decomposition. Chronos and topos are orthogonal between them and normalized. Mathematical details can be found in (Aubry, Guyonnet & Lima 1991) and practical applications are presented in (Hémon & Santi 2003).

Thanks to the BOD, the mean pressure distribution is reconstructed with the first 3 terms of the decomposition. It is plotted in Figure 3 where the Reynolds number is 1.1 million. The drag coefficient obtained by proper integration is found to be 0.79 which is higher than commonly found, for instance in the Eurocode.

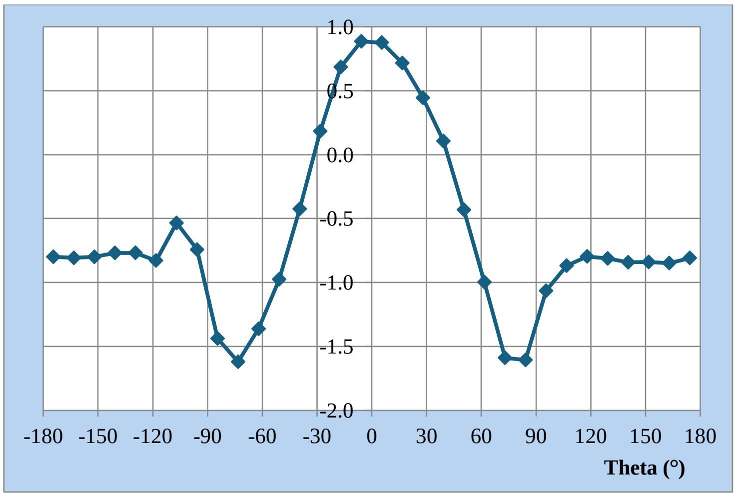

Figure 3. Mean pressure coefficient at 26.75 m, reconstructed with the first 3 BOD terms

The term #4 of the decomposition is responsible of the unsteady lift force due to vortex shedding. By analyzing the corresponding chronos, the Strouhal number is found in the range 0.21-0.24 (Manal & Hémon 2024). The corresponding topos is presented in Figure 4. This distribution leads to the unsteady lift coefficient $C_{lat} = 0.26$ which is higher than the value suggested by the Eurocode.

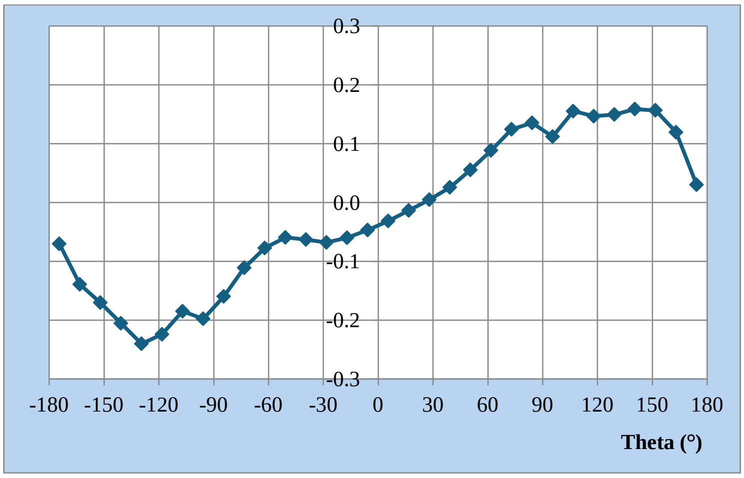

Figure 4. Topos #4 generating the lift force due to vortex shedding

4. CONCLUSIONS

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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