Wind-Induced Vibration of an Irregular Pentagon Lamella

Norbert Jendzelovsky 1*, Roland Antal 2

1 STU in Bratislava, Faculty of Civil Engineering, Radlinskeho 11, Bratislava 810 05, Slovak Republic
2 STU in Bratislava, Faculty of Architecture and Design, Namestie slobody 19, Bratislava 812 45, Slovak Republic

norbert.jendzelovsky@stuba.sk

Abstract. At present, there are increasingly encountering the use of lamellar structures, for example on the roofs of buildings, which, in addition to their visual function, also fulfill the function of reducing the flow of wind into the roof space. These structures are often designed as long and subtle structures and therefore their very common problem is unwanted vibration. In this article, the main focus is to show the methodology of the determination of the effects of wind on the lamella of a shape of an irregular pentagon. A real-size model made of steel with a total length of 2 m and a weight of 7.4 kg was used. Its size and shape were influenced by several factors which are specified in more detail in the paper. In the wind tunnel experiment, it was very important to ensure the exact position of the model and also to secure both ends of the model against shifting (to replicate fixed ends). Dynamic response of the structure in two directions together with wind speed were measured simultaneously. To investigate the wind effects by numerical analysis, fluid-structure interaction software simulation (FSI) on a full-size model was used. The main pitfall of the software solution was to get as close as possible to the conditions of the wind tunnel. The actual wind speed measured under laboratory conditions was used as the input wind speed for FSI simulation. The material of the model and the shape of the model was set in software simulation to be as close as possible to the real structure. Subsequently, other boundary conditions were set and the solution process was executed. The biggest problem, especially in terms of comparing the results of both approaches which greatly affected the results, was the very high stiffness of the model. Due to the extent and interconnectedness of results, findings are presented in more detail in the conclusions of the paper. The methodology of setting up a relatively complex FSI simulation, its results, as well as new findings that we came up with if the measurement of the dynamic effects of wind is the matter of interest are presented in this paper.

1. Introduction

The main focus of this paper is to show the methodology of the determination of the effects of wind on the lamella in the shape of an irregular pentagon. Design, light-weight, subtle, irregularly shaped structures of roof commonly called lamella are now widely used. Structures of this type are directly exposed to wind and this fact should be also taken into account in their design. In contrast to flexible cable-type structures, which are still given a lot of attention [1, 2], the effects of wind on the lamellas are often overlooked. Lamellar structures are not given sufficient attention and dominate studies that examine the effects of wind on the building as a whole. An example is [3]. Lamellar structures are stiffer compared to cables, therefore the fatigue failure is a very common type of damage. Empirically it is...
almost impossible to determine the range of the oscillation of the irregularly shaped lamella and thus greater emphasis should be placed on the other methods of analysis of wind-induced vibration.

Wind-induced vibration can be investigated experimentally, by software simulations or by empirical relations. Each of these methods has its advantages and disadvantages. This paper builds on our research and our previous work presented in [4].

If we want to analyse wind-induced vibrations in a wind tunnel, it is important to maintain dynamic properties of the model and the real structure. It mostly leads to the need to examine the model in real scale with real material properties. Therefore, examined structure is limited by the size of the wind tunnel. As in the previous case, the research is very often limited to flexible cable-type structures whose shape is most often a circle [5].

FSI software analyses are slowly growing in popularity. Some examples are [6, 7, 8, 9]. As mentioned in [10] “the solution of the aerodynamic task is a very complex issue.” Two-way FSI software simulation, can evaluate the time-history of the structural response together with the time-history of wind flow. The analysis works on the recurring principle. First computational fluid dynamics (CFD) analysis calculates results of wind pressure acting on analysed structure. This result in the form of a wind load is taken over by structural analysis module where variables e.g., deformation and acceleration are calculated. The whole process repeats and the deformed structure is subjected to CFD analysis again. Empirical relationships have been used mostly in the past for vibration analysis. There are methodologies in [11, 12, 13] for analysis of wind-induced vibrations of basic geometric shapes such as rectangle, circle etc. These relations have been derived from many experiments, however as mentioned they are only applicable to specific geometric shapes for which they were derived and in this age of modern architecture, their use is declining.

2. Experimental and numerical model shape
The task was to choose a model of the lamella that could be subjected to both a wind tunnel test and numerical analysis. The idea was to create a closed profile with the minimum size and weight where the accelerometers could be fitted inside. As a model – an irregular pentagon shown in figure 1 was chosen.

Figure 1. Cross-section of the analysed model

Total length of the model was 2 m and its weight was 7.4 kg. The structure was welded of sheet metal of thickness of 2 mm. An important role in choosing and designing the model played the size of the model - because it was limited due to the size of the wind tunnel space and the transport possibilities, weight was also kept as low as possible using steel as a material, the thickness of the sheet metal used for model walls was based on the requirements of the welder so that the sheet do not bent due to the high temperature during welding.

Model shape for numerical analysis was created by computer software with exactly the same dimensions as shown in figure 1.
3. Study of wind-induced vibration in the wind tunnel

3.1. Methodology of the study

Prior to the installation of the model into the wind tunnel, the uniaxial accelerometers were mounted in its place inside the model. A total of 6 accelerometers were installed inside. Four of them were placed on both ends of the model as close to the tunnel walls as possible to capture vibrations in the connection between the model and wooden reductions (clamp). The remaining two were mounted in the centre of the model to record horizontal and vertical accelerations at the centre. The layout diagram of accelerometers with the numbering is shown in figure 2.

![Figure 2. Location of uniaxial piezoelectric accelerometers inside the model and its numbering](image)

Subsequently, the model was mounted into the front space of the wind tunnel where it was subjected to examination. An important task was to ensure that both sides of the model were connected properly to the tunnel walls (fixed connection was expected). The connection of the model to the walls of the tunnel was made by wood beams and steel threaded rods as shown in figure 3. Due to fixed connection of the model to the tunnel walls the entire measurement was performed for only one direction of wind flow.

![Figure 3. Model located and positioned in the wind tunnel – ready for examination](image)

In order to measure the wind speed, the hot wire sensor of anemometer miniCTA type 54T42 (Dantec Dynamics) was attached to the centre of the model. The wind speed was measured 12 cm in front of the model.

The data of wind speed and acceleration were stored at a frequency of 3000 Hz (every 0.00033 second). The wind tunnel of Slovak University of Technology (STU) in Bratislava is not primarily
intended for measuring the dynamic effects of wind and such an experiment was the first of its kind to be carried out here. In view of the above, this tunnel is not equipped with a synchronizing device that would perfectly synchronize the measurement of the acceleration of the structure with the wind speed measurement. Therefore, the synchronization of the measurements was performed only approximately - by an instruction / call to start the measurement (two persons tried to start the measurement of two quantities at the same time as synchronously as possible). Additional manual resynchronization of both measurements had to be taken into account on the basis of mutual comparison of results. Subsequent shift of time axes so that the results correspond at least approximately to each other must be done.

During the experiment, it was found out that the model was too stiff and greater excitation must be performed. The wind speed was gradually increased and the presented results are for one of the highest wind speeds that can be simulated in the STU wind tunnel. Figure 4 shows how the wind speed changes depending on time as a result of turbulence (\( \text{It} \approx 8.3\% \)).

![Figure 4. Wind speed measured 12 centimetres ahead of the model](image)

Figure 4. Wind speed measured 12 centimetres ahead of the model

Figure 5 shows the horizontal and vertical acceleration of the structure measured at both ends of the model. Accelerometers no. 5, 6, 10 and 11 show acceleration of the structure in close proximity to the tunnel wall. Theoretically, this acceleration should be equal to zero (fixed connection).

![Figure 5. Acceleration of both ends of the model (accelerometers no. 10, 11, 5, 6)](image)
It is clear from figure 5 that there are significant vibrations at the connection of the steel structure to the wooden blocks. These vibrations are associated with the total vibration of the wind tunnel caused by the rotations of wind turbines. Therefore, it was not possible to reduce these vibrations by better fastening of the structure to the tunnel walls. The influence of the stiffness of the connection between the model and tunnel walls on the size of vibration is negligible - vibrations of the whole tunnel were transmitted directly to the analysed structure. Negative effect of vibrations transfer on results cannot be removed within the available possibilities.

Horizontal acceleration measured in the centre of the model is shown in figure 6. Vertical acceleration measured in the centre of the model is shown in figure 7. In both cases, the figures show not only the acceleration of the structure but also the wind speed depending on time. In order to make the results clearer, they are presented as filtered (averaged within a time interval of a 0.005 sec = 200 Hz).

![Figure 6. Horizontal acceleration measured in the middle of the model (accelerometer 9)](image)

![Figure 7. Vertical acceleration measured in the middle of the model (accelerometer 9)](image)
In the observed time period of 2 seconds, the acceleration values were within ± 0.67 m/s², respectively ± 0.5 m/s². Greater acceleration (± 0.67 m/s²) was achieved in the vertical direction due to lower stiffness of structure in this direction. During the observed time period, the wind speed was in the range of 13.6 m/s to 16.5 m/s. During the measurement no aerodynamic instabilities occurred, which would lead to excessive vibration of the structure or to the resonance vibration.

4. Study of wind-induced vibration by FSI software simulation

4.1. Methodology of the study

Two-way FSI analysis is used when it is required to determine the dynamic response of the structure to time-varying wind load. Because the scope and complexity of the whole simulation far exceeds the required scope of the contribution, only the basic assumptions are given. The solution is based on the exchange of solved variables between CFD module and structural (mechanical) module.

CFD simulation was performed by the ANSYS CFX software. The discrete environment was divided into 3 million hexahedral final volumes. The mesh layer closest to the object was created with a thickness of 0.1 mm and another 60 mesh layers were created around the object until the thickness of 300 mm were reached, representing the largest edge of the final volume.

![Figure 8. Discrete environment and generated mesh near to the object](image)

Inlet wind speed was used the same as the measured one in wind tunnel experiment with a sampling rate of 200 Hz shown in figure 4. The pressure at the outlet was defined as static pressure of 0 Pa. Walls around discrete environment were set as a “free slip” walls and the model itself was set as a “no slip” wall with the roughness of brushed steel. Mathematical model Shear Stress Transport (SST) was used to solve wind pressure, wind velocity and other flow related variables. Due to the scope of the issue, references [13, 14, 15] are given where it is possible to find all the information about the mathematical model of SST and also other information about parameters and methodologies used in CFD simulations. Time step was set to 0.005 seconds and simulation time was set to 0.03 seconds. The structural model of the structure was created with exactly the same dimensions as shown in figure 1. This structural model was divided to 4620 SOLID186 elements. The material of the structure was set as structural steel S235. On both ends, fixed supports were defined. Vibrations of tunnel walls caused by wind turbines were not taken into account because of the considerable complication of the whole task which would lead to insolvability due to hardware possibilities. For orientation - the computational demands for such a simulation are as follows: solution itself (60 time steps) took 2 full days (using seven 3.6 GHz processors Intel i7-7700 and RAM 32 GB).

After the end of the solution and the convergence check, it was possible to proceed with the results and comparison of both methods.
4.2. Results of the study

Averaged dimensionless wind pressure coefficient and wind speed pattern are shown in figure 9.

![Figure 9. Averaged values of dimensionless pressure coefficient, (left) and wind speed in [m/s], (right)](image)

As shown in figure 10, no aerodynamic instabilities occur and wind stream maintains its straight flow pattern. Wind flows from right to left.

![Figure 10. Velocity field depending on time](image)
Subsequently, the shape of deformation of the structure is shown.

\[ \text{Figure 1}. \text{Maximal deformation of the structure } 1.119 \times 10^{-4} \text{ m (only local bulging occur)} \]

Despite the fact that relatively high wind speed was used for structure excitation, the structure does not react by global vibration. As shown in figure 11, only local bulging occurred.

5. Comparison of both methods
First, the wind speed as a function of time obtained by both methods at a point 12 cm in front of the center of the model can be shown.

\[ \text{Figure 12}. \text{Comparison of wind speed obtained by experiment and by software simulation}. \]

It is clearly visible in figure 12 that the values of wind speed are practically the same between both methods – therefore first very crucial criterion (to provide same wind speed between methods) was fulfilled.

In figure 13 and 14 comparison of the horizontal and vertical acceleration obtained by both methods is shown. The results of the acceleration between software and experimental measurements do not match
in this case. It is important to point out that the results of the wind tunnel experiment were highly influenced by unwanted excitation of both ends of the structure. Also, due to lack of synchronization device, it was not possible to precisely synchronize the wind speed and acceleration measurements.

![Figure 13. Comparison of horizontal acceleration in the centre of the model](image13.png)

![Figure 14. Comparison of vertical acceleration in the centre of the model](image14.png)

### 6. Conclusions

The synchronization of measurement of wind speed and acceleration in the wind tunnel was based on the reaction time of two persons. However, to accurately and simultaneously measure two or more variables with the high sampling frequency, it is necessary to resolve synchronization procedure by special equipment. This was one of the things we couldn't do in the wind tunnel experiment.

Unwanted model excitation due to turbine rotations and subsequent vibrations which were transferred by the tunnel walls to the model ends significantly influenced results. It is necessary to say that the analysed model was very stiff and did not show any significant vibration even at higher wind speed. In case of such a stiff model, even a weak excitation of ends highly influences acceleration of the centre part. If the model would be more flexible (less stiff), the vibration caused by wind would be far
higher and excitation of both ends due to rotation of turbines would have only minimal effect on the results.

If an experiment of a similar task would be carried out in the wind tunnel it is highly recommended based on our experience to test structures whose bending stiffness allows their flexible deformation in bending and thus visible vibration will prevail over shaking respectively tremor of the whole model.

FSI simulation confirmed that it is a very good tool for complex analysis of time-dependent tasks and monitoring of vibration of the structure.

Although a wind tunnel proved to be a possible solution for investigating wind-induced vibrations, too many complications and limitations entered the measurement. Therefore, it is possible to say that for the analysis of wind-induced vibrations it is more appropriate to use FSI simulation, which when inputs are correctly set can provide results of both wind flow analysis and structural analysis.

Acknowledgment
Grant Agency VEGA, project No. 1/0412/18, supported this paper.

References
[1] M. Jafari, F. Hou, A. Abdelkefi, “Wind-Induced Vibration of Structural Cables,” *Nonlinear Dyn* 100, pp. 351-421, 2020.
[2] C. Wen-Li, H. Li, “CFD Numerical Simulation of Vortex-Induced Vibration of a Stay Cable under a Wind Profile,” *Computational Structural Engineering*, pp. 477-488, 2009.
[3] V. Michalcova, S. Kuznetsov, S. Pospisil, “Numerical and Experimental Models of Load on Buildings from the Effects of the Atmospheric Wind,” *Advanced Materials Research*, Volume 969, pp. 280-287, 2014.
[4] N. Jendzelovsky, R. Antal, “Transverse Resonant Vibration of Non-Bearing Structures Caused by Wind,” *IOP Conference Series Materials Science and Engineering* 245(3):032031, 2017.
[5] V. D. Hung, C. H. Nguyen, “Mitigating Large Vibrations of Stayed Cables in Wind and Rain Hazards,” *Shock and Vibration*, Volume 2020, 10 pp., 2020.
[6] N. Di Domenico, C. Groth, A. Wade, T. Berg, M.E. Biancolini, “Fluid structure interaction analysis: vortex shedding induced vibrations,” *Procedia Structural Integrity*, Volume 8, pp. 422-432, 2018.
[7] F. K. Benra, H. J. Dohmen, J. Pei, S. Schuster, B. Wan, “A Comparison of One-Way and Two-Way Coupling Methods for Numerical Analysis of Fluid-Structure Interactions,” *Journal of Applied Mathematics*, pp. 16, 2011.
[8] R. Parameshwaran, S. J. Dhulipalla, D. R. Yenduri, “Fluid-structure Interactions and Flow Induced Vibrations: a Review,” *Procedia Engineering*, Volume 144, pp. 1286-1293, 2016.
[9] I. Kološ, V. Michalcova, L. Lausova, “Numerical modeling of the pressure coefficient of the circular cylinder,” *Mathematical Methods in the Applied Sciences*, Volume 43, pp. 7579-7574, 2020.
[10] J. Dobes, M. Kozubkova, “The Numerical Solution of the Aerodynamic Task Using by CFD Modelling,” *Manufacturing Technology* 15(5), pp. 788-795, 2015.
[11] Eurocode 1: “Actions on structures. Part 1-4 General actions - Wind actions,” pp. 104-120, 2007.
[12] O. Hubova, “Aeroelasticity - Static and Dynamic Effects of Wind on Building Structures,” Department of Structural Mechanics, *STU Press*, Bratislava, pp.46-48, (in Slovak), 2013.
[13] G. Vertes, “Structural Dynamics,” Elsevier Science Publishers, *Developments in Civil Engineering*, vol. 11, pp. 283-287, Budapest, ISBN 963-05-3581-5, 1985.
[14] T. J. Chung, “Computational Fluid Dynamics,” Second Edition, *Cambridge University Press*, New York, 1034 pp., 2010.
[15] F. R. Menter, "Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications," *AIAA Journal*, vol. 32, no 8., pp. 1598-1605, 1994.
[16] M. Kozubkova, “Modeling of Fluid Flow, FLUENT, CFX,” *Technical University of Ostrava - VSB*, pp. 32-63, ISBN 978-80-248-1913-6, (Electronic publication on CD ROM in Czech), 2008.