Fluid-Structure Interaction Analysis and the Detection of Wind Induced Vibration of Triangular Lamella

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Abstract. The use of very thin, subtle and light structures as an external part of buildings causes many problems related to wind induced vibration. Constructions of this type occur mostly as a part of roofs or design facades. The principal idea of this paper is to show dynamic response of triangular lamella exposed to wind gusts, which frequency is equal to the first natural frequency of the lamella. By the two-way software fluid-structure interaction (FSI) analysis, oscillation of the lamella was detected. The solution of two-way FSI analysis requires co-simulation between computational fluid dynamics and structural mechanics. In the simulation, it was essential to simulate conditions that if met, create resonant vibration of the lamella caused by vortex shedding on the leeward side of the structure. If the frequency of vortex shedding matches the resonance frequency of the structure, the structure begins to resonate and vibrates in harmonic oscillations driven by the energy of the flow. In this case, vibration rises and structure can be damaged or deformed permanently. For the long-term vibration, fatigue stress and subsequently fatigue failure is significant. By the usage of empirically derived equations, input data for the software simulation were obtained. It was important to consider mainly natural frequency of lamella, frequency of vortex shedding behind the structure and also correct properties of air such as wind speed, frequency of wind gusts, density of air and Strouhal number. As a conclusion, dynamic response of lamella in the form of deformation and wind stream pattern depending on time is shown. It has been also shown that if the inputs are specified correctly to software simulation it is possible to analyse time history of many variables such as deformation, wind speed, and acceleration. By this method, it is possible to determine not only the maximum variables such as deformation or wind speed, but also its entire time history. In practice, it is therefore possible to create different design situations and, on their basis, design the lightweight non-bearing structures exposed to the wind.

1. Introduction
The main purpose of this paper was to analyse non-bearing hollow triangular lamella exposed to the wind gusts, which frequency causes periodic vibration of the structure caused by wind turbulence (vortex shedding) behind the object. Due to very thin, subtle and light design, these structures are at the risk of oscillation caused by many factors. In sources [1, 2], it states that, if certain conditions are met, wind turbulence pattern behind the object become periodic and therefore when the frequency of vortex shedding tunes to the natural frequency of the structure it causes unwanted and dangerous periodic vibrations of the structure. Vortices behind the structure arise from the wind flow past an object, where vortices at high angular velocities compared to the wind flow velocity are produced on both sides of the object. On one side clockwise rotating vortices and on the other side counter-clockwise rotating vortices
separate periodically as shown in the figure 1. If the frequency of vortex shedding matches the resonance frequency of the structure, the structure begins to resonate and vibrates in harmonic oscillations driven by the energy of the flow. Subsequently, vibrations rise and structure can be damaged or deformed permanently. For the long-term vibration, fatigue stress and subsequently fatigue failure is significant.

**Figure 1.** Example of flow visualization with periodic vortices behind the object, [3]

The wind turbulence pattern shown in the figure 1. resembles Von Karman effect, which causes transverse resonant vibration of the structure [2, 4]. Creation of so-called Von Karman vortex street shown in figure 1. is overwhelmingly associated with flow behind cylinder or other cylinder-like structures. It is necessary to say that wind flow past the triangular, rectangular or any other sharp edged objects can also create periodic vortices behind the structure, however, without simulation it is hard to predict in which direction the resonance vibration will develop and whether the object would oscillate in the transverse direction or in the longitudinal direction.

The purpose of this paper is to show software simulation and dynamic response of triangular lamella exposed to the wind gusts at which it was expected that resonance vibration of the structure occur.

2. Analysed model
For the dynamic response analysis, triangular hollow cross-section was selected as shown in the figure 2. It is very common shape of cross-section used as a non-bearing structure. Material of the analysed model was selected as a structural steel S235 with Young’s modulus E= 210 GPa. Lamella was modelled as a both sides clamped, due to the assumption that, structures of this type are most time both sides welded to a rigid structure. As shown in the figure 2, total length of the lamella is 2 m. Structure was modelled as a 3D solid with cross-section of equilateral triangle with the edge length of 65 mm and the thickness of 1.5 mm.

**Figure 2.** Analysed model with structural supports, dimensions and wind flow direction

3. Input data for software analysis
Before running the software analysis, it was necessary to determine wind data which according to [1, 2] creates periodic vortices behind the object which subsequently cause resonant vibration of the structure.

For the simulation of resonant vibration, it is important to consider natural frequency of the lamella, frequency of vortex shedding and properties of air.
3.1. Natural frequency of the lamella

The natural frequency of the structure depending on the stiffness of the structure and on the mass, which participates with the structure (in this case self-weight). First natural frequency of the analysed model corresponding to the mode shapes shown in the figure 3. was calculated by the software “ANSYS workbench modal”. In this case, first natural frequency in both directions (longitudinal and transverse) is the matter of interest. It is assumed, that higher frequencies of wind gusts are very rare and thus it is not necessary to calculate higher natural frequencies for this type of analysis.

\[ f_{1, \text{TRANSVERSE}} = 82.005 \text{ Hz} \]
\[ f_{1, \text{LONGITUDINAL}} = 82.008 \text{ Hz} \]

**Figure 3.** First mode shape and first natural frequency in transverse and longitudinal direction

As it is shown in the figure 3., natural frequencies corresponding to the first mode shape in transverse direction and in the longitudinal direction are very close to each other. For the calculations of input variables, rounded value of 82 Hz. was used. It was monitored whether the resonance begin to develop in the transverse direction or in the longitudinal direction.

3.2. Vortex-shedding frequency and excitation frequency of the lamella

In order to create the conditions stated in [1, 2] which causes resonant vibration it is necessary to calculate variables which are directly involved in the creation of periodic vortices behind the structure.

A vortex street (figure 1) will only form at a certain range of flow velocities, specified by a range of Reynolds numbers [5]. Reynolds number is a dimensionless quantity used to help predict flow patterns in different flows. Reynolds number is defined by equation (1), [5].

\[ R_e = \frac{v \cdot d}{\nu} \]

(1)

Where:
- \( v \) is the wind speed with the respect to the object [m/s],
- \( d \) is the characteristic dimension of the object [m],
- \( \nu \) is the kinematic viscosity of the fluid [m²/s].

In the sub-critical zone, Reynolds number is smaller than \( 2 \cdot 10^5 \) - \( 3 \cdot 10^5 \). Vortices are separated alternately on both sides of the object. Two stable, rotating vortices are created with the frequency of vortex separation defined by equation (2), [1, 2].

\[ n = \frac{v \cdot St}{d} \]

(2)

Where:
- \( v \) is the wind speed with the respect to the object [m/s],
- \( St \) is the Strouhal number [-] obtained by experimental measurements, for the triangular cross-section it was taken from [6],
- \( d \) is the characteristic dimension of the object [m].
For the determination of excitation frequency of the lamella it was necessary to calculate critical wind speed \(v_{\text{crit}}\). It was calculated as follows: Instead of calculation of the frequency of vortex separation \((n)\), it was replaced by the first natural frequency of the lamella \((f_1)\). By modifying the equation (2) - critical wind speed \(v_{\text{crit}}\) was subsequently calculated by equation (3).

\[
v_{\text{crit}} = \frac{f_1 \cdot d}{St} = \frac{82 \text{Hz} \cdot 0.065 \text{m}}{0.24} = 22.208 \text{m/s}
\]

Reynolds number of the flow was calculated by the equation (1)

\[
R_e = \frac{v_{\text{crit}} \cdot d}{\nu} = \frac{22.208 \text{m/s} \cdot 0.065 \text{m}}{15.1 \cdot 10^{-6} \text{m/s}^2} = 0.96 \cdot 10^5
\]

It was demonstrated that it is subcritical flow [2, 4] where vortex street occurs with periodic vortex separation defined by the frequency of separation, which could be calculated by equation (2).

Previous calculations were used to quantify input variables for software simulation. The most important input variables are shown in the table 1.

| Table 1. Calculated input variables for software simulation |
|-----------------------------------------------------------|
| Strouhal number \(St\) | Critical Wind Speed \(v_{\text{crit}}\) [m/s] | Reynolds Number \(Re\) [-] | Vortex Shedding Frequency \(n\) [Hz] | Frequency of Wind Gusts [Hz] | Period of Wind Gusts [s] | Simulation Time Step [s] |
|------------------------|---------------------------------|-----------------|-----------------|-----------------|-----------------|------------------------|
| Input value            | 0.24                            | 22.208          | 0.96 \(\cdot 10^5\) | 82.0            | 82.0            | 0.012195               | 3.89107 \(\cdot 10^{-4}\) |

4. Fluid-structure interaction (FSI) analysis

Fluid-structure interaction (FSI) analysis is used when simulation of the fluid flow, which causes deformation of the structure, is needed. Due to the extent and complexity of the FSI analyses, only the basic assumptions and variables used in the calculation are given. The solution of the two-way fluid-structure interaction requires co-simulation between computational fluid dynamics (CFD) and structural mechanics (Mechanical). The principle of program operation is displayed on the figure 4.

**Figure 4.** Schematic view of the two-way FSI analysis solution
4.1. Computational fluid dynamics (CFD) analysis

CFD simulation was done by ANSYS CFX software module. Calculations in ANSYS CFX are based on a finite volume method (EBFVM) with a cell vertex formulation, [7]. Before running the calculation, discrete environment shown in figure 5. was created with dimensions of 8 x 3 x 2 metres.

![Discrete environment](image)

Figure 5. Discrete environment (left), meshed environment (centre), detailed mesh (right)

Discrete environment was divided by ANSYS mesh component to finite volumes of different sizes. Close to the analysed lamella, fine mesh layers were created. First layer was created with the thickness of 0.1 mm. Subsequently another 60 fine mesh layers were created with the increasing thickness until maximum thickness of 300 mm was reached.

Basic boundary conditions were set as follows: Inlet wind speed was set as sine function with properties based on the fact, that resonant vibration occurs when wind gusts frequency is equal to the frequency of vortex separation and at the same time wind flow velocity is the same as critical wind speed in which periodic vortex separation occurs. The wind load curve is shown in the figure 6.

![Wind load function](image)

Figure 6. Wind load function applied as a wind speed at the inlet of discrete environment

Outlet pressure was defined with constant value of static pressure 0 Pa. Surrounding walls defining the discrete environment were set as a free slip walls. Analysed lamella was set as a no slip wall with the roughness of brushed steel.

Software solution was calculated by the Shear Stress Transport (SST) mathematical model. It is a two-equation eddy-viscosity model belonging to a group of RANS (Reynolds averaged Navier-Stokes) mathematical models. More information about theory of computational fluid dynamics and used mathematical model are listed in [8-10].

Transient simulation time step was set to 3.81097 \times 10^{-4} sec. It is exactly 1/32 of the load frequency period respectively 1/32 of vortex shedding frequency period (table 1). Subsequently analysis was launched. Calculation worked according to the two-way FSI simulation scheme shown in the figure 4.

4.2. Mechanical (dynamic response) analysis

Based on the scheme shown in the figure 4, dynamic response of triangular lamella exposed to wind gusts was calculated. Complete two-way FSI analysis was performed as full transient analysis. Mechanical model of triangular lamella consists of 4620 elements of SOLID186. Material of the
structure was set as structural steel S235. Mechanical and dynamic properties of the structure were obtained from ANSYS material library and generally used guidebooks of steel properties.

5. Results of the analysis
In the following complex figure, time history of the wind flow pattern is shown. Wind flows left to right.

![Time history of the fluid flow pattern - formation of vortices](image)

**Figure 7.** Time history of the fluid flow pattern - formation of vortices
From the figure 7., it can be said that unsymmetrical vortex shedding began approximately at 0.13 sec. After this moment, frequency of vortex shedding matches the resonance frequency of the structure; the structure begins to resonate and vibrates in harmonic oscillations driven by the energy of the flow in the longitudinal direction.

In the figures 8. - 10., shape of deformation and chart of horizontal and vertical deformations of the front tip of the lamella is shown. Results included effect of self-weight. Shape of the curve shown in figure 9., shows that deformation rises logarithmically and variable repeated periodically, what proves that damped resonant vibration was induced. From the results, it can be said that input variables were set correctly and predefined requirement to initiate resonant vibration of the lamella has been met.

Figure 8. Deformation of the lamella (shape of the deformation)

Figure 9. Time history of the horizontal deformation of the front tip of the lamella
6. Conclusions
If the inputs are specified correctly to software simulation it is possible to analyse time history of many variables such as deformation, wind speed, acceleration etc. By this method, it is possible to determine not only the maximum deformation but also its entire time history. In practice, it is therefore possible to create different design situations and, on their basis, to design the lightweight non-bearing structures exposed to the wind.

In the case of analysed triangular lamella, periodic vortices generated on both sides of the structure creates longitudinal resonant vibration of the lamella. For 0.26 seconds lamella was exposed to the wind gusts of frequency equals to the natural frequency of the lamella. This resulted in damped resonance vibration, which would continue until the frequency of wind gusts would change. Consequently, the construction damping would cause re-stabilization of the structure to the original position (provided that lamella was not permanently damaged).

Without proper simulation, for many type of structures it is not possible to say with complete certainty in which direction and if the lamella starts to oscillate in resonance. An example is this case where first natural frequencies (first longitudinal and first transverse frequency) are very close to each other, however periodic vibration has developed in longitudinal direction and not in transverse direction.

Regardless, whether it is transverse or longitudinal vibration, resonance of light structures does not last for a long time, however vibrations are relatively frequent and therefore they are the main reason of fatigue failure.

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