A light sculpture element under wind load – numerical FSI analysis and an experiment in a wind tunnel

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Abstract. The article introduces a numerical and experimental work to analyse the behaviour of a specific light sculpture element in a wind-load. It starts with a static analysis, which moves to a simplified unsteady analysis followed by a real experiment in a wind channel. The numerical part was not able to provide all necessary information about the light sculpture element behaviour. The experimental part was done to determine the real behaviour of the sculpture element under specified wind conditions.

1 Introduction

Fluid-structure-interaction computations get over the last years a higher level of importance. It allows predicting in a certain degree the mutual interaction between mechanical parts, parts in complex systems and fluid environments. Things becoming much more complex if unsteadiness and vibrations will appear in the analysis. For a proper analysis were often necessary parameters which hardly could be guessed and an experiment had to be done to obtain the requested data.

The investigated object here was a light sculpture concept depicted in fig. 1. The major diameter of the whole sculpture is around 8 m and it consists from more than 500 parts. The sculpture will be mounted at a ceiling of a pool bar on a beach. It will be permanently exposed to the actual wind situation. To ensure the safety of the artwork it was necessary to evaluate deflections of the light sculpture elements from the original position due to wind.

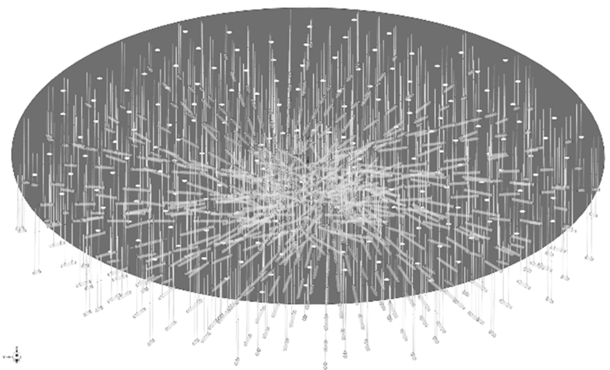

Fig. 1. Model of the whole light sculpture.

Because of the high complexity of the sculpture, it was chosen to investigate only the light sculpture elements with expectantly the highest deflections. One of the chosen elements, which will be investigated during this article in fig. 2 is the one with the largest surface area, which is exposed to the wind and has the longest support rods.

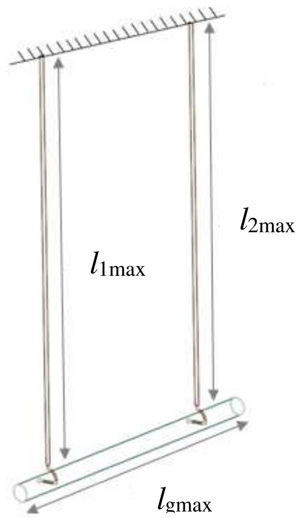

Fig. 2. Model of the whole light sculpture.

The analysis started with a one way FSI computation for the highest static deflection. The reason why the interaction that means, the flow field simulation was done, was given partially by the customer to catch quite accurately the flow, with potential disturbances etc. During this analysis was found that there could be some risk of vibrations of the sculpture elements at natural frequencies excited by vortex shedding behind the support rods or glass element. Such a proper numerical analysis would request quite high computing power and additional parameters like damping factors. Especially correctly, evaluated damping factors of the given system will influence the results significantly. For that, reason was executed an experiment in a wind channel of VZLÚ. It provided real measured data to evaluate the deflections and compare them with the numerical approach and

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started a future work of investigations of tuning vibrating systems.

2 Numerical analysis of the sculpture element

The problem was for the numerical simulation approach quite complex and so this part was divided in two sections. First a steady static analysis of the element was done and later a try to simulate the unsteady behavior, at least in partial steps. The analysis was done with a specified element depicted in fig. 2 and named as sample 1 (s1). A real sample with the same geometry was later used in the experimental part.

2.1 Steady static analysis

fig. 3 shows the simple configuration of the boundaries for the one-way FSI simulation. This approach was chosen because the deflections of the element were quite low in the comparison to the main sizes so that the deformation had negligible influence on the flow. During the first step the whole geometry was modeled. Later was prepared a one-way FSI coupled system in Ansys-workbench.

The CFD part consists of the outer limit brick-shaped surroundings around the sculpture element. It has one inlet, one top wall (ceiling) and four pressure outlets. The solid is represented only as walls ie. obstacles in the flow.

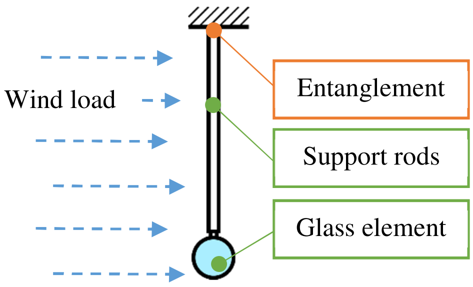

Fig. 3. Configuration for the computation.

The mechanical part was computed by a static structure analysis. It includes all analyzed solids with a defined anchoring of the light sculpture element. The pressure load is evaluated from the flow computation (fig. 4). The pressure field on the whole light sculpture surface is interpolated to the surface boundary in the mechanical computation (fig. 5). The gravity was taken in account too, because the weight of the element was relevant for the results.

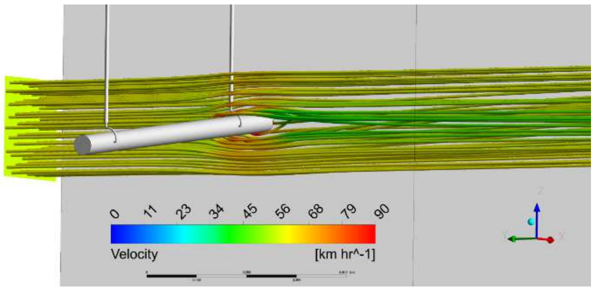

Fig. 4. Stream lines around a part of the light element.

Computations were made for a wind flow range from 20 km/h, which is a common breeze in the location of the sculpture [3], up to 80 km/h, which is aproximatelly 20 km/h higher then the observed common extreme situation at the location. The flow was handled like incompressible flow due the relative low velocity. For turbulence modeling was used the k-omega SST model.

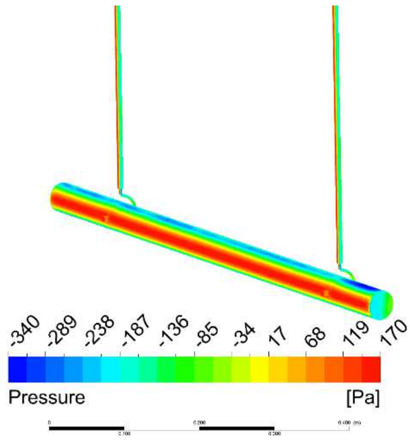

Fig. 5. Pressure load from one-way FSI simulation.

A representative result from the computation shows fig. 6. The geometrical deformation scaling is overestimated for the evaluation but the red color shows the correct maximum deformation eq. deflection of 12.4 mm. To get a wind-velocity, deflection dependence few points were computed and result in a plot in fig. 7. Like expected the dependence of deflection is aproximately quadratic on the wind velocity. It is given simply due to the fact that pressure is lineary dependent on the flow stream energy but the energy of the flow is quadraticaly dependent on the velocity.

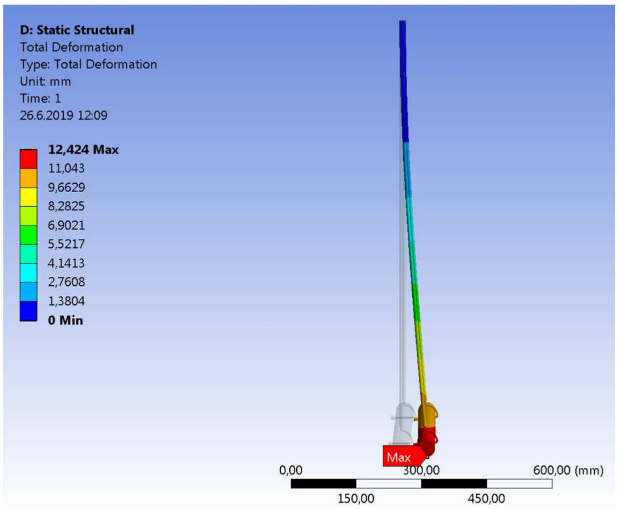

Fig. 6. Computed static deflection by one-way FSI simulation for 60 km/h wind load.

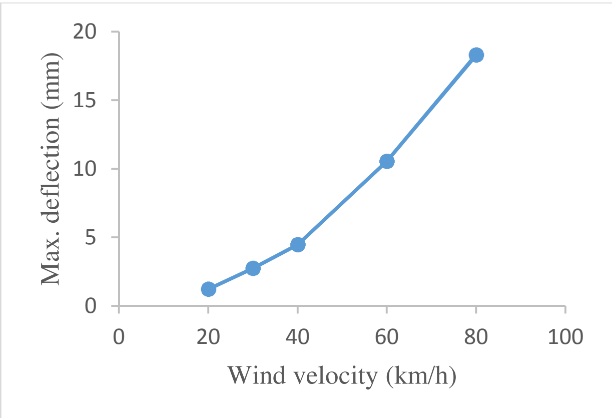

Fig. 7. Numerically evaluated static dependence of deflection ond wind load.

2.2 Unsteady behaviour analysis

The geometry of the sculpture element, which consists from two thin and long support rods, which hold the quite massive glass element, rises an uncertainty about the unsteady behaviour of it for different wind regimes. It was not clear if something like flatter could occur.

A very simplified estimation of the vortex shedding frequencies for the support rods and the glass elements was done together with a modal analysis of the light element. The comparison between the range of the vortex shedding frequencies in fig. 8 and the low mode natural frequencies of the sculpture element in fig. 9 shows some overlaping. That could cause an excitation of the system at quite high deflections.

$$Sr = \frac{fL}{U} \tag{1}$$

To get an idea of the force, which acts on the glass element a simple 2D numerical computation of vortex shedding behind a cylinder was done. The simulation was unsteady and as expected it forms the typical von Karman vortex street, see fig. 10.

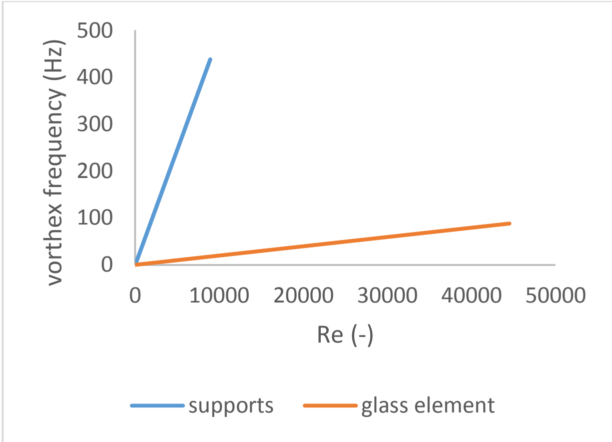

Fig. 8. Rough estimated dependence between Reynolds numbers and vortex shedding frequencies for cylinders of the diameter for the support rods and the glass element.

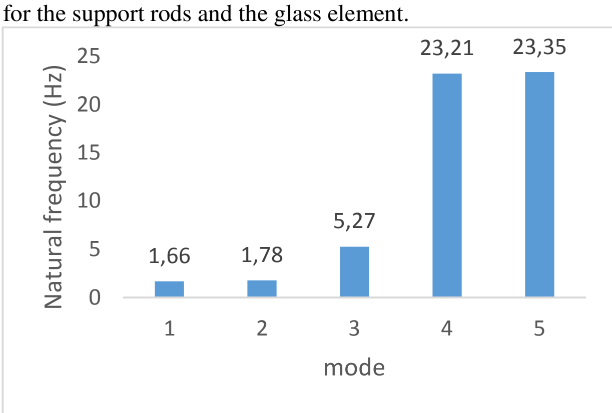

Fig. 9. Natural frequncies of the light sculpture element from a modal analysis in Ansys.

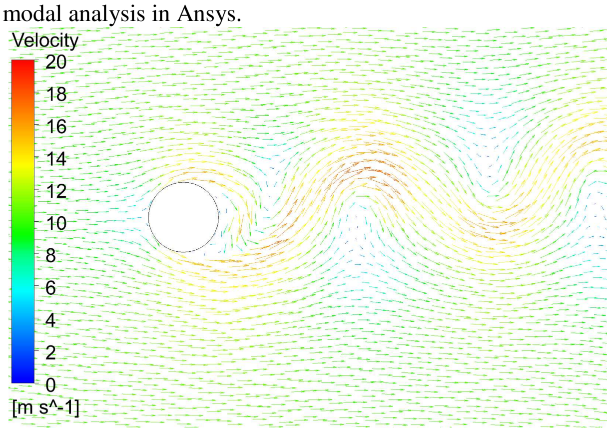

Fig. 10. Vortex shedding behind a cylinder, simple 2D analysis of the glass element cross-section.

During the 2D unsteady computation was recorded the total force acting on the cylindrical surface in the flow and perpendicular direction. The foce-time course for the glass element is in fig. 11 and for the support rod in fig. 12. The forces are directly from the 2D analysis in N for 1 m length. The lengths of the geometrical elements are around 1 m so this value is quite representative. The frequncy of the perpendicular direction is in a reasonable range compared to fig. 8 (around 50 Hz from the equation and 40 Hz from the CFD computation, most likely is the difference given by setting of an average Sr of 21). The highest chance to get in the naturaly oscilation mode of the element is given probably by the glass element, which provides vortex schedding frequencies near to the range of the natural frequencies of the sculpture element.

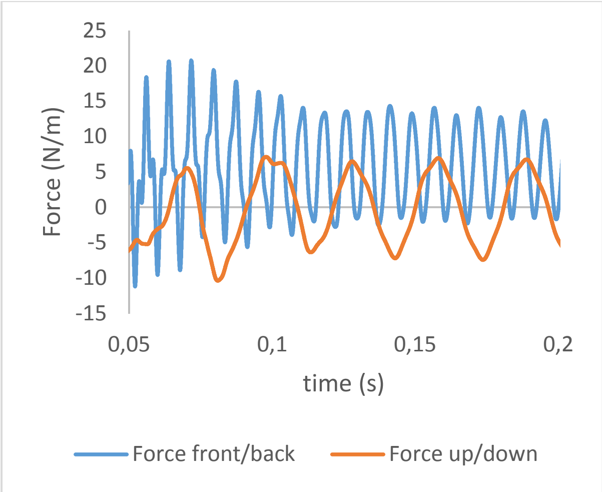

Fig. 11. Force acting on the glass element surface in flow direction and perpendiculatr to it for a flow velocity of 36 km/h.

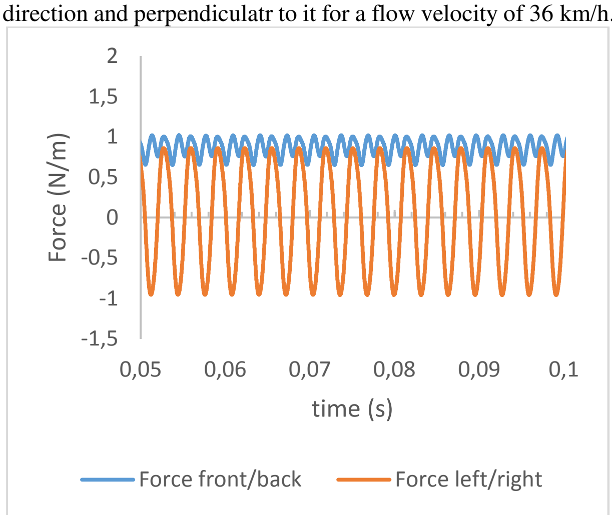

Fig. 12. Forces acting on the suppor element surface in flow direction and perpendiculatr to it for a flow velocity of 36 km/h.

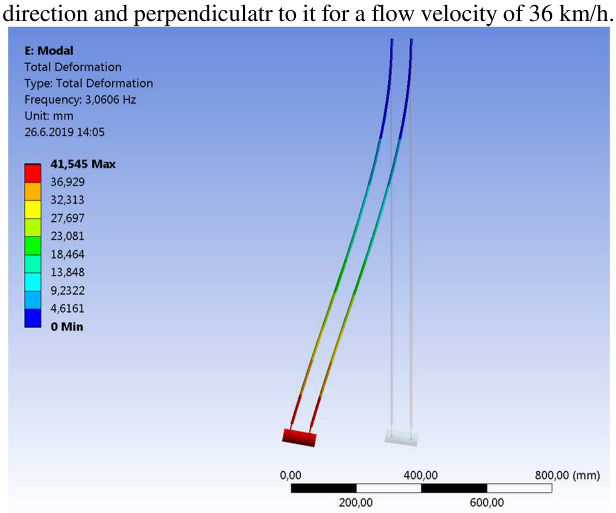

Fig. 13. Maximum deflection from a numerical test for a cyclicali waken system.

In the next step was tried to made a small test where the values of the evaluated forces from the 2D simulation were applied at their frequency on the surfaces. This approach had a lot of limitations. From fig. 11 and fig. 12 is obvious a different frequency of the forces caused by vortex shedding at different parts and also in different directions. The setting in the used software was quite limitting so that it was posible only specify the force definition and one frequency of cycling for all forces. But in the real case all forces on different part act together. Another problem was the definition of the damping factor. This is parameter is given by more factors, like material, geometrical design of the parts (welding/screw connections of parts), how the part is anchored etc. At the actual state was tested only one force applied at a given frequncy with some guesed damping factor and a results of a quite high deflection was obtained (fig. 13).

For a proper prediction of these deflections and in general how the the element would act was not really possible due the lack of input values like main different forces and the damping factor. In the end it was chosen to do an experiment how the light sculpture element would behave in near-reality states.

3 Experiment in the wind channel

The experiment was prepared and performed at the open circuit atmospheric wind channel with continuous operation at VZLÚ Letňany.

The light sculpture element was attached to a present construction beam above the channel. It was mainly tested in the arrangement with the highest surface load from the air stream eq. perpendicular to it like it is visible in fig. 15. A partially rotated configuration was also tested but the results were insignificant. The measurements were done by two approaches. One with two high-speed cameras which recorded the movement of the glass element. The second was based on the use of triaxial piezoelectric accelerometers and uniaxial capacitive accelerometers attached on the glass elements. For powering and read out the sensor was used the Dewetron analyser with the necessary modules. Just before the measurement, was the setup prepared like in fig. 15.

Before the measurement was performed a simple test for the reached airflow velocities in the wind-channel. The velocities from the steering software show the same values like the used hand flowmeter.

A strict procedure of the measurement was performed for every measurement. The airflow velocity in the wind-channel was set to a required value. After the measured velocity had stabilized, the measurement had started. First were measured the acceleration values from the sensors positioned on glass element surface for a specified time. If required, in the next step was taken a record by the cameras for few seconds. The camera record was done only for predetermined velocities or if some more vibrant state had occurred. The reason was a quite time-consuming image set download from the buffer to the storage medium and later data processing for states without "visible" behaviour.

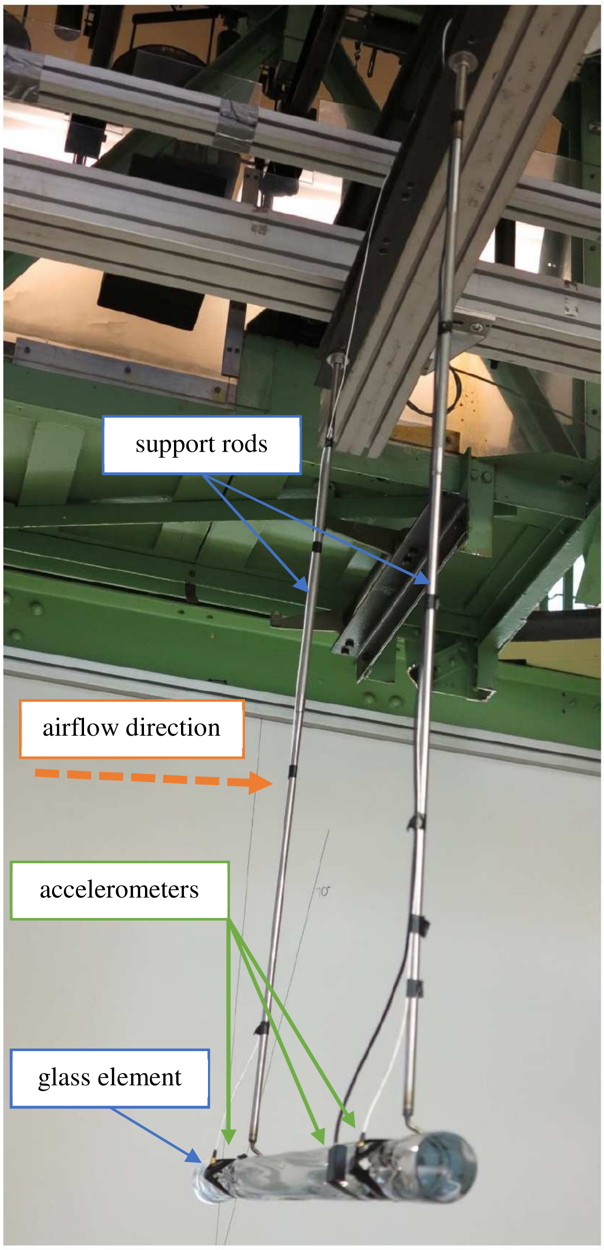

Fig. 14. Tested light sculpture element in the wind channel.

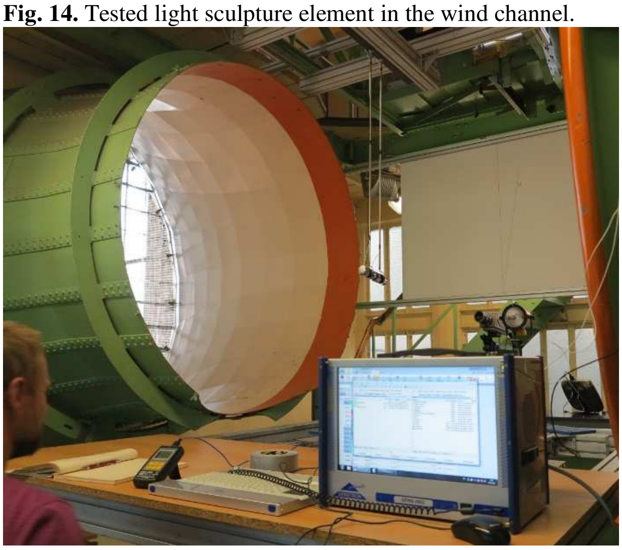

Fig. 15. Setup for measurement in the windchannel.

3.1 Results from the experiment and comparison with some relevant data from the numerical simulation

From the experiment were taken image sets of the glass element positions for various wind speeds. Fig. 16 shows the extreme case for a wind of 90 km/h.

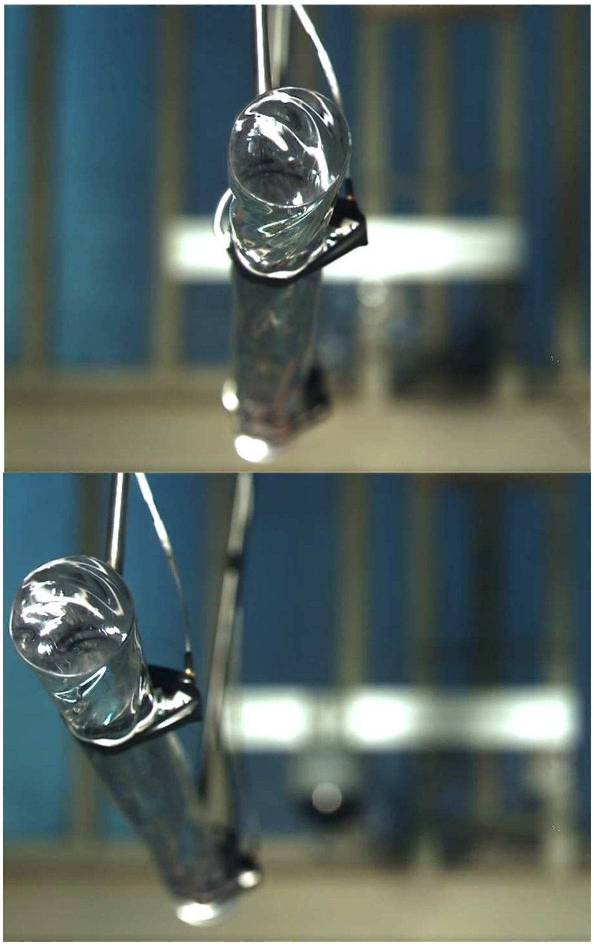

Fig. 16. Images for deflection evaluation a, calm state eq. any load b, maximum wind load.

The images from the cameras were evaluated and show a tendency commonly like in fig. 17. The central dashed line of the experiment shows a mid value of deflection while the dotted lines show the maximum and minimum values of the deflection for the given wind speed. It is evident that for slow wind speeds the deflections were too small to be captured. It was interesting that for the highest velocity the deflection would be higher about 35% than from the steady state computation.

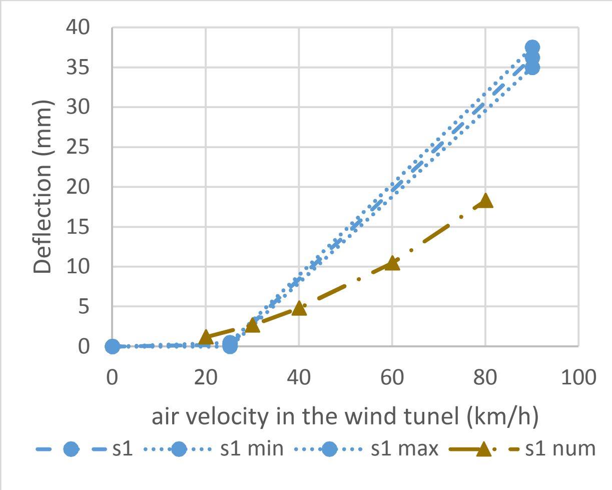

Fig. 17. Dependence between measured deflection (dot) and static numerical simulation one-way FSI simulation.

Fig. 18 shows the frequencies evaluated from the accelerometers and if they were compared with the results from the numerical modal analysis in fig. 9 a correspondence in the first two frequencies is visible and partially at the forth. That means that the sculpture element swings at the frequency 1st and 2nd natural frequency at the measured state.

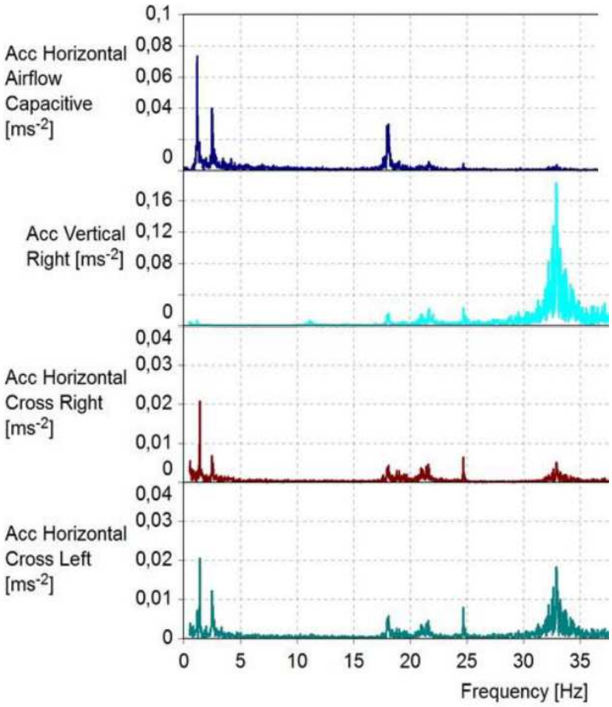

Fig. 18. Frequency spectra of acceleration measured on the glass element.

The frequencies change slightly with the measured wind speed, but mostly the swing on the 1st two natural frequencies is present everywhere.

4 Conclusions

The measurements at the wind channel had not identified any dangers regimes (flatter) for the light sculpture model during the tested air velocities. It also evaluate real deflections, which were taken in count to specify the space sizes between the light sculpture elements.

From the behaviour evaluation in the wind channel it was obvious that the factors of damping were quite high compared to the values used in the computations. An unsteady two-way FSI approach was not possible due to the lack of time/necessary computing power. The reason were geometrical ratios about more than 1:100 of the main sculpture element parts (tiny support part and long supports).

The work actually continues at VÚTS with the focus on the vibrations caused by mechanical waking. The main goal of the future research is to evaluate critical vibration modes waken by defined forces at specified frequencies numerically. That could later server for predictions of flatter for systems of diverse geometry for specified flow velocities.

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