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FROM EXPERIMENTAL WIND TUNNEL TO WIND-STRUCTURE INTERACTION SIMULATIONS OF A SHELL STRUCTURE

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ABSTRACT

This paper studies the transition from downscaled wind tunnel testing to prototype scale numerical simulations. The study is performed using OpenFOAM as fluid solver, EMPIRE as coupling tool, and Carat++ as the structure solver. The current work aims at finding sufficient settings for wind-structure interaction simulations. Also, the efficiency of the software chain to simulate natural wind flow is approved. For this purpose, different flow conditions such as uniform, atmospheric boundary layer (ABL), and flow behind a cube (structure is positioned in the wake region behind a cube) are simulated. These complicated, unsteady, and recirculating flows are simulated to study the aeroelastic effects on light weight shell structures. Wind-structure interaction simulations are performed where the dynamics of the structure play a crucial role in the wind effects. An Aluminum shell structure was tested in the wind tunnel to have an experimental benchmark for aeroelasticity. Throughout spectral analysis of structure vibrations and statistical evaluation of forces, the modeling approach shows a very good agreement with the experimental results. Finally, scaling issues represent a great challenge to wind tunnel testing especially when it comes to light-weight structures. While significantly, numerical simulations are shown to be an efficient tool for the prediction of wind loading on structure under different wind conditions.

Keywords: Wind tunnel test; Wind-structure interaction; Atmospheric boundary layer; Aeroelastic effects

1. INTRODUCTION

Light-weight materials are widely used in the construction industry as covering systems for large span structures. Safety and serviceability requirements are the two main objectives of a structural engineer while designing using light-weight materials. Wind load has a great influence on light structures. Consequently, wind effects are to be assessed by the means of experimental and numerical simulations. Nowadays, wind tunnel testing is the most reliable mean of assessing wind loads on structures. However, the downscaling of such thin and light structures imposes a huge challenge to the wind tunnel experts. Therefore, numerical simulations play a crucial role in understanding the structural behavior of such structures under wind load. The aim of this study is to compute and validate the experimentally tested shell structure in both model scale (wind tunnel scale) and prototype structure. At this level of simulation, the interaction between wind and structure movement known as Wind-Structure Interaction (WSI) is taken into consideration which leads to a multiphysics problem. The aeroelastic testing of an Aluminum shell structure is numerically simulated. The comparison between experimental and numerical simulations is based on the force coefficients and power spectral density of the displacement data. As a result, the numerical tools (OpenFOAM as fluid solver, EMPIRE as coupling tool, and Carat++ as the structure solver) are tested and validated to properly simulate similar structures. Therefore, more credibility can be put on numerical WSI simulations which can be a powerful assisting tool for experimental wind tunnel.

2. EXPERIMENTAL SETUP

This section summarizes the experimental study of the Aluminum shell structure under investigation. First of all, two terms that will be repeatedly used have to be defined:

1. Wind tunnel scale: “down-scaled”, “model scale” or “small scale”. Any setup associated with this scale refers to the scales of the wind tunnel experiment.
2. Real scale: “up-scaled”, “prototype scale” or “full scale”. All the parameters defined for these simulations are resulting from applying the scaling parameters to wind tunnel scale in order to simulate reality.

Due to the complexity of the original structure geometry, wind loading cannot be predicted by design codes and standards. Therefore, a thorough investigation for the wind effects on the four tubes module shown in figure 1 was performed to predict the aerodynamic characteristics of the structure. CRIACIV, Atmospheric Boundary Layer Wind Tunnel, Italy, was commissioned to perform experimental investigation for the inflatable structure. Eight angles of wind attack (0, 45, 90, 135, 180, 225, 270, and 315 degrees) at four different wind speeds were considered for the test cases. It is very important to point out that the geometrical description of the wind tunnel model was independent from the intended actual structure (a membrane inflatable structure). Moreover, the complexity of producing a down-scaled inflatable tubes led to the Aluminum shell simplification.
The test was conducted for the measurements of mean values (quasi-steady approach). It requires one time trace per wind condition with a sufficient duration to ensure that a longer time trace will not give another mean value. This method is suited for the analysis of forces and moments to determine the wind loading on the main structure.

2.1 Model description

An Aluminum sheet was used to model the Aeroelastic phenomena effects on a shell like structure. Table 1 shows the material properties for the down-scaled model and the structure thickness.

Table 1: Aluminum shell model material properties

Material	Aluminum
Modulus of Elasticity	69.6 Gpa
Density	2711.5 Kg/m^3
Poison’s Ratio	0.33
Thickness	0.0005 m

*Wind tunnel engineers chose the thickness

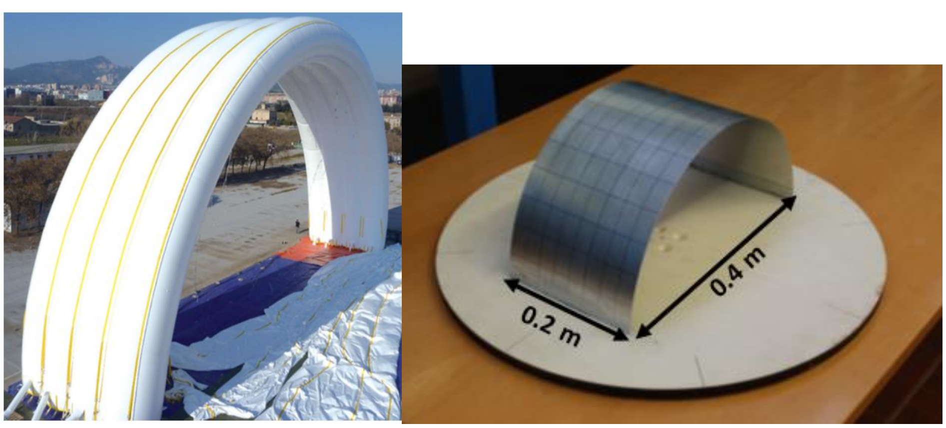


Figure 1: Four tubes module vs. Geometry and Dimension of the simplified Aluminum sheet in the wind tunnel

2.2 Flow conditions

Three flow conditions were tested in the wind tunnel and the test specifications are summarized in table 2.

Table 2: Wind tunnel tests specifications

Wind Tunnel Facility	CRIACIV
Flow	Uniform flow (smooth flow) Atmospheric Boundary Layer (ABL) Uniform flow with a cube
Sampling Frequency (HFFB)	2000 Hz
Sampling Period	60 Sec
Terrain Type (ABL Only)	Rough sea level terrain
Turbulence Intensity (ABL at Reference Height)	15.0%
Mean Wind Speed at Reference Height	[4.65],[11],[16.5],[22] m/s
Model Scale	1:150

2.3 Available Experimental Data

Four different mean wind speed were tested to prove the independence of the test results from Reynolds number. For each wind flow, a High Frequency Force Balance (HFFB) was used to acquire the total forces acting on the structure. Moreover, four accelerometers were used to measure the structural vibrations as shown in figure 2.

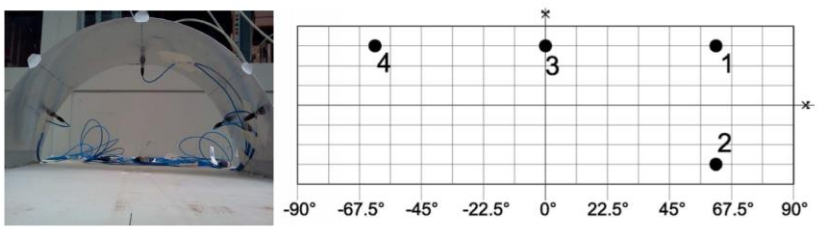


Figure 2: Accelerometer arrangement

3. COMPUTATIONAL SETUP

The simulations were performed in two scales. First, wind tunnel scale simulations were performed to mimic all the experimental conditions and to assure that our simulation assumptions are working properly for this problem. Then, the up-scaled simulation were calculated to indicate the correctness of the scaling parameters defined in table 3 and show the ability of the software to simulate real structures features and scales under different wind conditions.

Table 3: Model to prototype scaling factors

Scaling parameter	Factor
Geometric (λ_g)	150
Velocity (λ_v)	5.59
Density (λ_ρ)	1
Time (λ_t)	150 : 5.59
Frequency (λ_f)	5.59 : 150

It is important to point out that coupled CFD simulation or more precisely WSI simulations are highly application and targeted values dependent. Furthermore, it is of a great importance to consult the available Best Practice Guidelines as a source to predict how the computational setup should look like and make use of others' work in similar fields. “Besides a well-suited simulation software, the quality of results largely depends on modeling issues.” (Kupzok. 2009). Most of the modeling decisions in the current work are highly influenced by (AlSofi. 2013) (DeVilliers. 2006) (Franke et al. 2004) (Franke et al. 2007) (Kupzok. 2009) (Stathopoulos et al. 2007).

3.1 Computational domain

The size of the computational domain is the first decisive parameter on how expensive the simulation will be. It is controlled by both geometric area of the structure under investigation and boundary conditions. The computational domain should be big enough to encompass large, energetic relevant flow structures. The size of the domain is decided taking into account the following issues:

- The blockage ratio (BlR) should be kept ($\approx 3\%$) to prevent the generation of artificial accelerations and be consistent with the wind tunnel specifications.
- The distance between the inlet and the structure should be big enough to prevent artificial pressures due to inlet boundary conditions.
- The distance from the structure to the outlet should be big enough to allow the flow re-development behind the wake region and avoid pressure shocks due to the outlet boundary conditions.

Finally, a blockage ratio (BlR = 2.857%) is used and all the domain size parameters are shown in figure 3 and dimensions are summarized in table 4.

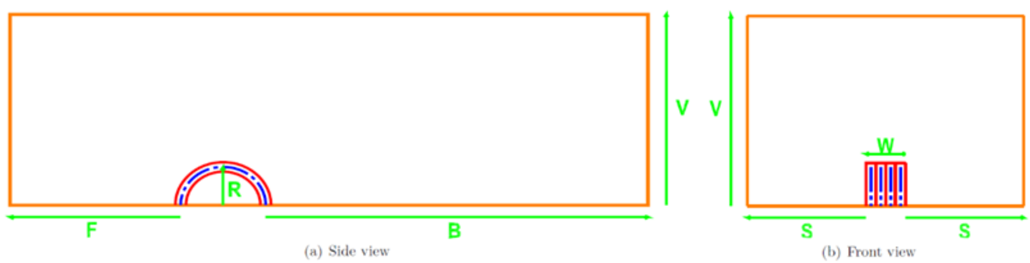


Figure 3: Computational domain parameters representation

Table 4: Computational domain dimensions for model and prototype scales

Parameter	Chosen domain factor (* R)	Dimensions model scale [m]	Dimensions prototype scale [m]
R	1	0.2	30
W	1	0.2	30
S	3	0.6	90
V	5	1.0	150
B	8	1.6	240
F	5	1.0	150

Moreover, a Large Eddy Simulation (LES) is performed with the use of a kinetic energy one equation eddy-viscosity turbulence model and cube-root of cell volume as the LES filter. Backward differencing scheme is used for time integration. This scheme takes the last two values into account which resembles a second-order accuracy and implicit discretization scheme. Moreover, the scheme reduces numerical diffusion and is computationally cheaper than other schemes falling into the same category (Gramlich. 2012). The simulations are based on the standard Gaussian finite volume integration which requires not only cell-center values but also values on the cell faces. Consequently, an interpolation scheme is required and a linear scheme is used. The term linear in the OpenFOAM context corresponds to the central differencing interpolation scheme. The scheme used represents a second-order gradient-term discretization and a second-order, unbounded divergence-term discretization (Gramlich. 2012).

3.2 Inlet flow condition

In the following sub-section, the process of simulating wind characteristics in CWE are briefly discussed. Two different inlet wind conditions were used in the wind tunnel testing campaign. For uniform flow, the target is to expose the structure to constant unfluctuating wind. For ABL flow, a transient fluctuating inlet is required since not only the mean values are of interest in measurements but also transient ones (e.g. maximum). As stated by AlSofi, “this huge shortage in the results, especially in standard deviation and peak results, supports the claim that logarithmic mean wind profile will fail to serve as an inlet boundary condition for this kind of engineering problems. A transient fluctuating (turbulent) inlet is required.” (AlSofi. 2013). The procedures on how to generate such a fluctuating inlet conditions are briefly explained. First, it is important to find out the roughness length for the wind flow. A wave superposition based method developed by Mann 1998 is used to simulate the fluctuating component in the velocity field. “This method builds on the model of the spectral tensor for atmospheric surface layer turbulence at high wind speeds developed by Mann 1994. The wind field can be represented as a generalized Fourier-Stieltjes integral of its spectral components. Moreover, the applicability of the adapted numerical wind generator in simulating natural flow conditions is supported by AlSofi (AlSofi. 2013).

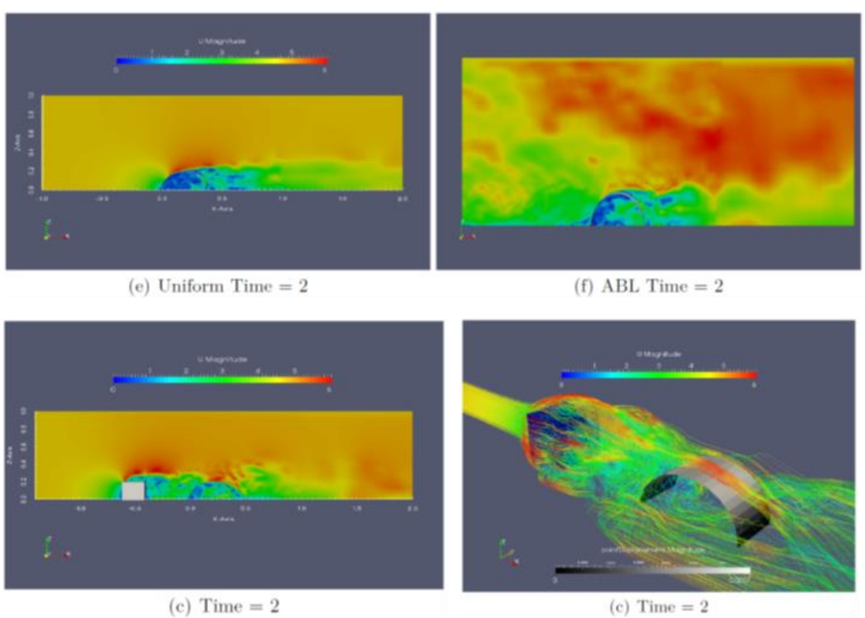
3.3 Carat++ settings

Carat++ is the structure solver. An 8-noded quadrilateral shell element is used for the modeling of the shell structure. This shell element is a “degenerated” shell element with 6 (external) degrees of freedom per node. Reissner-Mindlin kinematical description is used for the shell description. Moreover, using 8-noded element introduced a problem to the coupling software. This problem is introduced by the existence of only 4-noded element mapper in EMPIRE. Skinning approach is used to overcome this problem. A 4-noded membrane, zero-thick, is introduced as a ghost layer. Both shell structure and membrane have the same 128 elements mesh. Finally, NEWMARK non-linear (NEWMARK_ NLN) algorithm is used as the dynamic structure solver.

4. ANALYSIS OF COMPUTATIONAL RESULTS

The simulations are performed in two stages:

- Wind tunnel scale: all the flow conditions are tested in model scale. The ABL numerical wind generator fitting algorithm is tested. The model scale is tested first to make sure that the software tool chain is working properly.
- Up-scaled model: the simulations are performed to assure the applicability and results of the dynamic scaling of the structure. These simulations are performed based on having good results in wind tunnel scale.



(e) Uniform Time = 2 (f) ABL Time = 2

(c) Time = 2 (c) Time = 2

Figure 5: Features of the flow over the structure

4.1 Results discussion for wind tunnel scale simulations

A qualitative assessment for the flow around the shell is performed. To start with, aeroelastic effects play a crucial role in the flow properties and in the level of forces affecting the structure. Not only pressure and viscous forces are introduced, but also dynamic response of the structure. Figure 6 shows the statistical evaluation for the force coefficient in the flow direction CF_x from the three flow conditions under investigation.

For ABL flow, it is clear that the structure response is well captured. The mean is perfectly matching the simulation but the standard deviation is slightly different as shown in figure 6. This marginal difference in the standard deviation is the result of losing some wind energy due to the structure vibrations which affects the fluid domain. Another reason is not resolving small scales of motion which does not highly contribute to the forces affecting the structure. Finally, both mean and standard deviation for the force coefficient are in a very good agreement with the experimental results.

For uniform flow, it can be observed that the mean and standard deviation for the flow are perfectly matching the experimental results shown in figure 6. This indicates the accuracy of the simulation to capture scales of motions that are highly contributing to the forces exerted on the structure.

For uniform flow with cube in front of the structure, the flow condition is highly complicated. The properties of the flow over the structure are defined by the recirculating flow in the wake region behind the cube. It can be seen that the mean force coefficient is perfectly matching the experimental result. In the other hand, the standard deviation is slightly smaller than the experimental value. This difference can be seen in losing some scales of motion in the wake region behind the cube which leads to lower energy content in the flow hitting the structure. To examine the loose of fluctuations in the force component in this case, we can start by clarifying that an LES model is used which resolves eddies up to two times bigger than the cell size. Consequently, mesh coarseness should be controlled. Flow behind a cube exhibits separation and large-scale unsteadiness with an expected minimum wavelength $\lambda_{\min} = 0.01207m$. It requires maximum cell size of $0.00603m$ to resolve the biggest scale of motion. A $0.008m$ cell size was used in the simulations. It can resolve wide range of scales of motion. These large length scales are highly contributing to the energy content of the flow which can be clearly seen in figure 6.

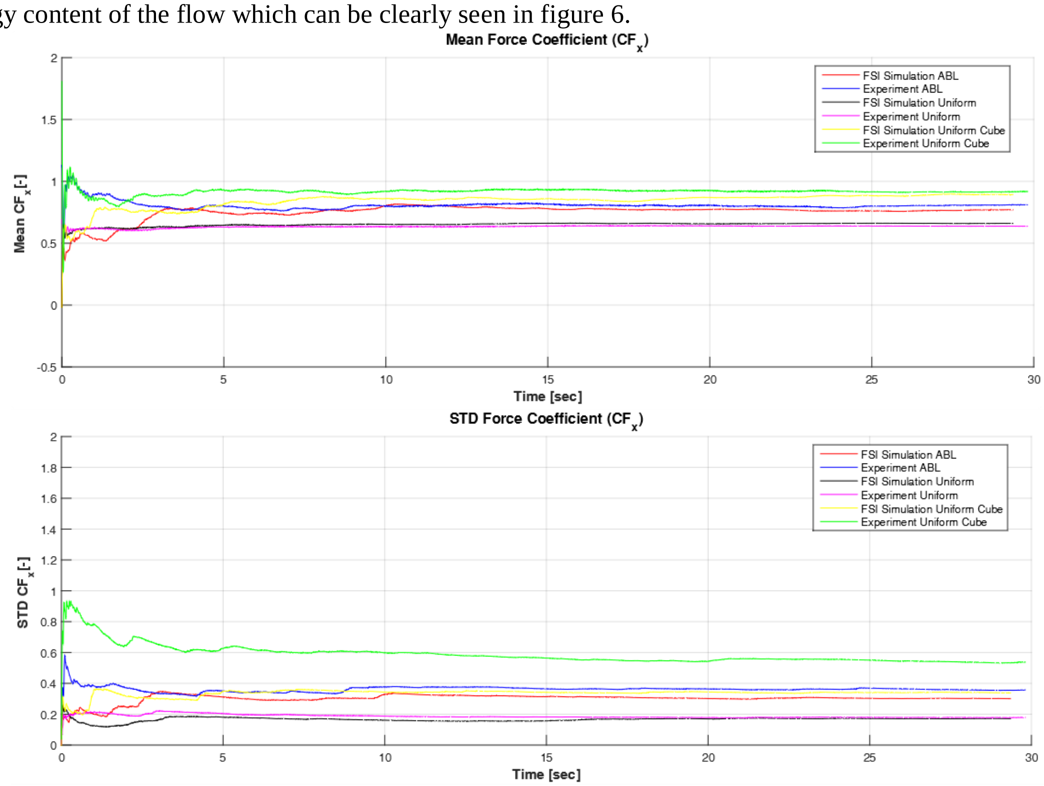


Figure 6: Mean and standard deviation for the force coefficient in flow direction (down-scaled)

The displacements are obtained from Carat++. Using a Power Spectral Density (PSD) analysis for the displacements, the first eigenfrequency from FSI simulation is found to be $10.221 Hz$ which is deviating by $\approx 10\%$ from the experimental values/// The PSD for the FSI simulations is calculated by taking the Euclidean norm for the displacements in three directions.

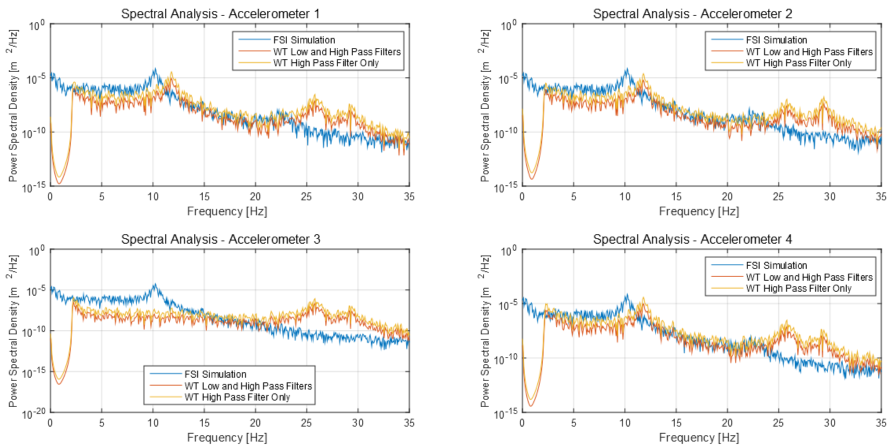


Figure 7: PSD for displacement for ABL Flow

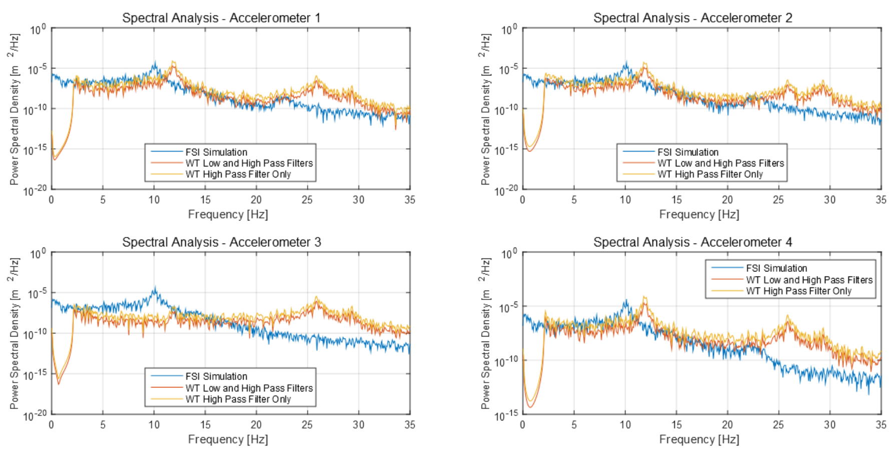


Figure 8: PSD for displacement for Uniform Flow

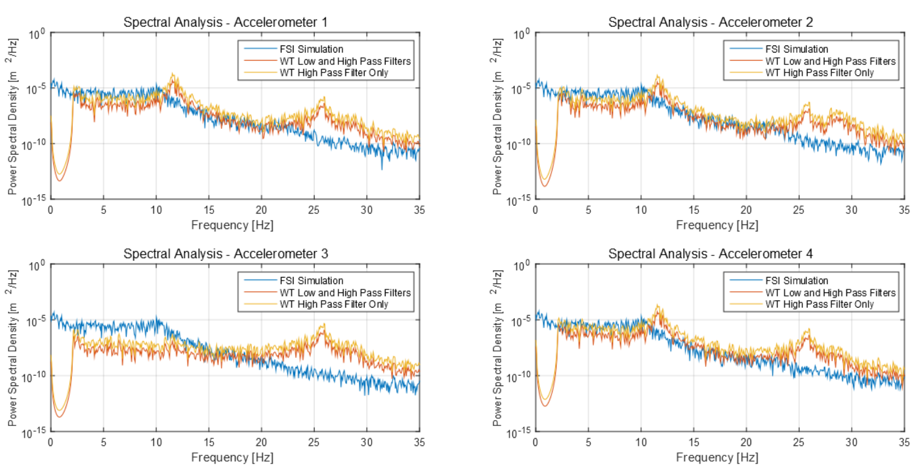


Figure 9: PSD for displacement for Uniform Cube Flow

The first three eigenmodes represent non-symmetric bending, symmetric bending, and non-symmetric torsion respectively. These modes are well identified for both ABL and uniform flow as shown in figures 7 and 8. For flow behind a cube figure 9, higher modes are not well captured. Higher modes in this case are caused by high frequencies in the vortex shedding region behind the cube which corresponds to very small wavelengths that needs very fine mesh to capture these effects. For the three flows, the energy content in the vibration of the structure is well conserved because most of the energy is contained in the large scale vortices. Overall, it can be seen from the graphs and the analysis that wind-structure interaction simulations are in a very good agreement with the experimental data in hand.

4.2 Results discussion for prototype scale simulations

In the following sub-section, the structure is up-scaled where the dynamic properties of the structure must be also modified to fit the up-scaled properties. Dynamically scaling the structure is a very complicated task. In the study under investigation, we do not have a real structure. Consequently, a virtual structure with the same geometry as in wind tunnel scale is simulated. The thickness is treated as a geometric parameter and the density is kept constant so that Scruton number similarity can be achieved. Therefore, modulus of elasticity is the parameter to be modified to fulfill the up-scaled natural frequency of the structure. The up-scaled structure properties are summarized in table 5.

Table 5: Aluminum shell up-scaled model properties

Material	Virtual material
Span	60 m
Height	30 m
Modulus of Elasticity	1600 GPa
Density	2711.5 Kg/m^3
Poison’s Ratio	0.33
Thickness	0.075 m

The up-scaled model must comply with the eigenfrequency calculated by the scaling laws. Modal analysis is performed for the up-scaled structure and the results are summarized in table 6.

Table 6: The first three Eigenfrequencies: up-scaled structure

Number	Eigenfrequency $[Hz]$
1	0.5069500
2	1.1145446
3	1.1369100

By setting up all the required modification for the structure, it is important to think about the scaling of the results. Forces are provided in a dimensionless representation which requires no scaling but accelerations must be scaled. Consequently, a scaling parameter is defined for the accelerations such that $\lambda_a = \frac{\lambda_v}{\lambda_t} = \frac{31.2148}{150}$. By using this scale parameter, the up-scaled accelerations are integrated to result in the up-scaled expected displacements. In figure 10, the force coefficients in flow direction are shown for both uniform and ABL flow.

For uniform flow, the mean and standard deviation for CF_x are perfectly matching the experimental data which confirms the accuracy of the structure solver, the dynamic scaling of the structure, and the ability of the fluid mesh to capture the important scales of motions. For the ABL flow, marginal deviation is observed in the mean and standard deviation. Finally, it can be concluded that the forces in the main flow direction is in a good agreement with the experimental data.

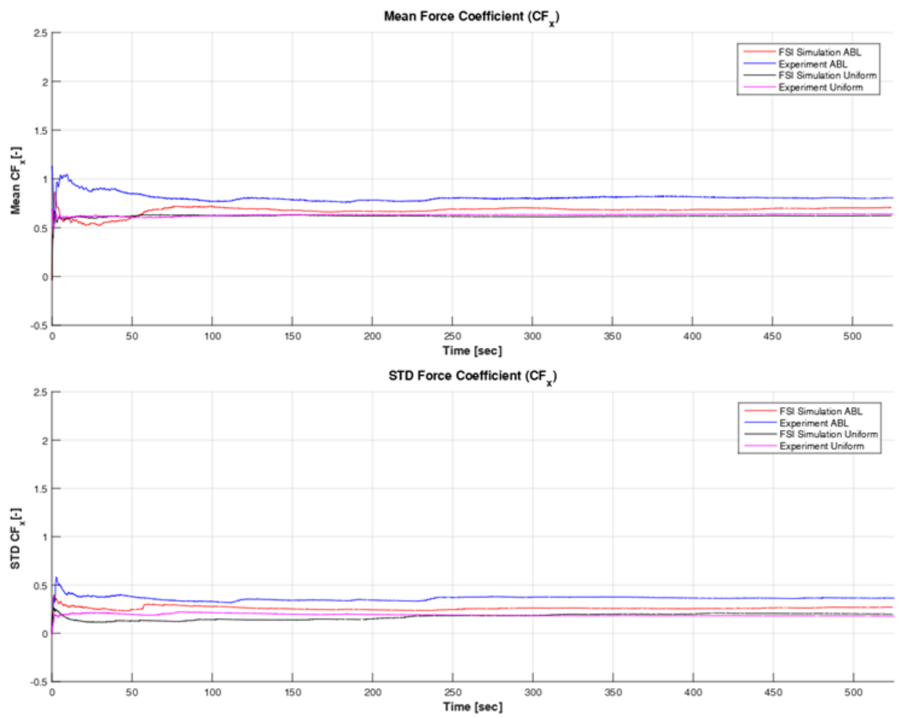


Figure 10: Mean and standard deviation for the force coefficient in flow direction (up-scaled)

From figures 11 and 12, we can find out that the peaks are the same for the numerical simulation and the experimental data with some deviations in the ABL flow. Moreover, there is a perfect matching in the structure's natural frequency from the PSD analysis where $f_{nsim} = 0.442Hz$ and $f_{nexperimental} = 0.4425Hz$ with slight deviation in the higher modes. Finally, $\approx 10\%$ reduction in the eigenfrequency has resulted from the FSI simulation which is the same reduction obtained in the experimental results which assures that the added-damping is well estimated by the FSI simulations. From figures 11 and 12, the main energy contributors are well captured. But by looking into figure 11, frequencies higher than 0.9Hz are not well-captured and this is due to the loss of frequencies from numerical wind generator through the mapping to the inlet of the computational domain. For uniform flow in figure 12, the high frequencies are clearly captured since the flow features are well resolved. In both flow conditions, the amplitudes of the signal are minimally differ from the experimental data. Moreover, the conservation of the scaling laws is preserved in the up-scaling of the structure and flow conditions which lead to a geometric scaling of the displacement.

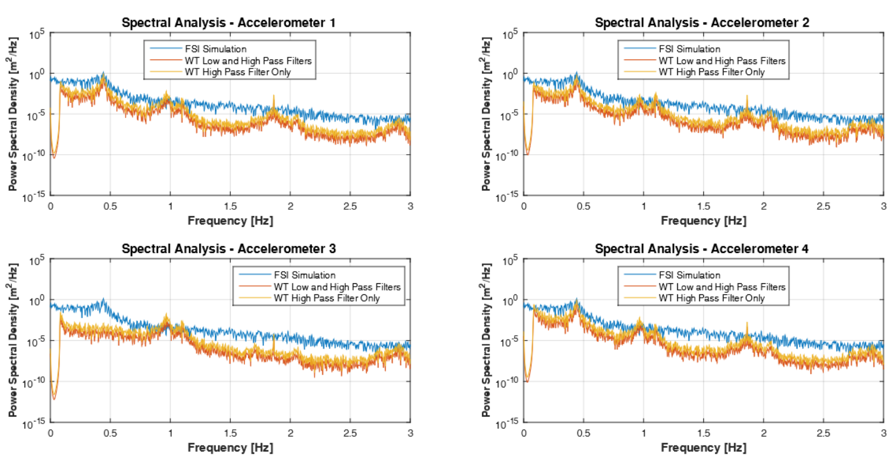


Figure 11: PSD for displacement for ABL flow full scale

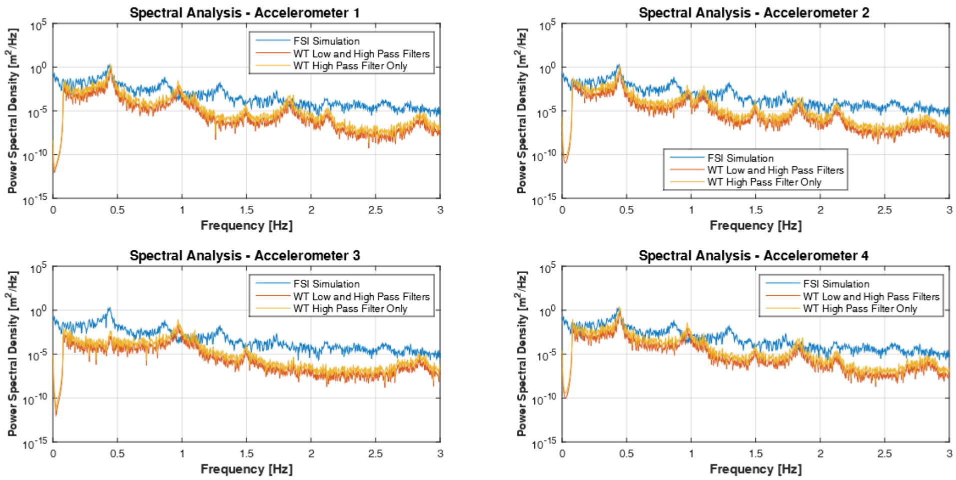


Figure 12: PSD for displacement for Uniform flow full scale

5. CONCLUSION

The target of this part of the project was to numerically reproduce the wind tunnel experiments with all the flow conditions investigated and define the appropriate scaling parameters to produce an up-scaled simulation. The simulations were performed and compared to wind tunnel data.

- The numerical simulation showed very good agreement with the experimental data.
- The setup for the Rayleigh damping coefficients should be carefully done to avoid deviation in the structure response.
- The errors associated with accelerometer measurements were investigated in the double integration of accelerations to get the displacements. Unphysical high frequencies and noise are misleading in the spectral analysis of such signals.
- The up-scaling of the structure is a complicated process that is limited by several parameters.
- The scaling is the biggest barrier in simulating wind-structure interaction for light-weight structures in wind tunnel.

The results for different test cases indicate the applicability of numerical wind-structure interaction. Several drawbacks of wind tunnel measurements showed that computational wind-structure interaction is a promising field in the investigation of wind loading for any type of structure especially light-weight structures. Wind tunnel experiments suffer from great problems in the scaling down of the real structure. Overall, the validations and other investigations showed many positive aspects associated with LES as a predictive tool for Fluid-Structure Interaction (FSI) in Computational Wind Engineering (CWE).

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