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Partnership for Advanced Computing in Europe

SHAPE Project Vortex Bladeless: Parallel multi-code coupling for Fluid-Structure Interaction in Wind Energy Generation

J.C. Cajas[a*], G. Houzeaux[a], D.J. Yáñez[b], M. Mier-Torrecilla[a]

[a]*Barcelona Supercomputing Center - Centro Nacional de Supercomputación, Spain*
[b]*Vortex Bladeless S.L., Spain*

Abstract

Vortex-Bladeless is a Spanish SME whose objective is to develop a new concept of wind turbine without blades called Vortex or vorticity wind turbine. This design represents a new paradigm in wind energy and aims to eliminate or reduce many of the existing problems in conventional generators. Due to the significant difference in the project concept, its scope is different from conventional wind turbines. It is particularly suitable for offshore configuration and it could be exploited in wind farms and in environments usually closed to existing ones due to the presence of high intensity winds.

The device is composed of a single structural component, and given its morphological simplicity, its manufacturing, transport, storage and installation has clear advantages. The new wind turbine design has no bearings, gears, etcetera, so the maintenance requirements could be drastically reduced and their lifespan is expected to be higher than traditional wind turbines.

It is clear that the proposed device is of prime interest, and that scientific investigation of the response of this wind energy generator under different operation scenarios is highly desirable. Thus, the objective of this SHAPE project is to develop the needed tools to simulate Fluid-Structure Interaction (FSI) problems and to reproduce the experimental results for scaled models of the Vortex-Bladeless device. In order to do so the Alya code, developed at the Barcelona Supercomputing Center, is adapted to perform the Fluid-Structure Interaction (FSI) problem simulation. The obtained numerical results match satisfactorily with the experimental results reported.

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1. Introduction

Fluid-structure interaction problems are multi-physics problems where a fluid interacts with a deformable solid body exerting forces on it. These forces deform the solid body, which modifies the fluid flow as it moves. This kind of interaction is highly complex and different interesting physical phenomena arise. One of them the vortex induced vibrations (VIV), that are vibrations in the solid body resulting from the synchronisation of the vortex shedding frequency and the natural frequencies of vibration of the structure through the so called lock-in effect. This interesting phenomenon has been investigated along years and has been recently used to design new wind energy generators, like the proposed by Vortex-Bladeless.

Vortex-Bladeless [1] is a Spanish SME whose objective is to develop a new concept of wind turbine without blades called Vortex or vorticity wind turbine, that uses the VIV. The vortex design aims to eliminate or reduce many of the existing problems in conventional generators and represents a new paradigm of wind energy. It is morphologically simple and it is composed of a single structural component, so its manufacturing, transport, storage and installation have clear advantages. The new wind turbine design has no bearings, gears, etcetera, so the maintenance requirements could be drastically reduced and their lifespan is expected to be higher than traditional wind turbines. In the development of this new device, it is of prime importance to be able to test different geometrical configurations, operation conditions and to have energy production predictions. However, it is very hard and expensive to get all this information only through experimental test and devices. It is therefore desirable to have a numerical tool that can help and provide guidance in the design, and give useful information about the operation of the device.

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[*] Corresponding author email address: juan.cajas@bsc.es

Moreover, the numerical simulation of such problems is challenging and has received a lot of attention in the past few years. Different approaches and techniques exist to solve the FSI problems numerically and can be useful to simulate the VIV phenomena coming from the Vortex-Bladeless device. One of these approaches is the staggered multi-code one, where a code is in charge of the fluid flow simulation and another code is in charge of the solid dynamics simulation while the interaction among them comes through the exchange of information of boundary conditions and surface forces. In the present project the Alya code, developed at the Barcelona Supercomputing Center, is adapted and used to perform the Fluid-Structure Interaction (FSI) problem simulation for a scaled experimental vortex-bladeless device, and a comparison between the numerical and experimental results is done.

2. FSI simulation for Vortex Bladeless

2.1 The Alya system

The Alya system is a multi-physics code developed in the Barcelona Supercomputing Center [2]. It is written in FORTRAN language and is based on a finite element formulation. It is parallelised using a hybrid MPI+OpenMP strategy. Alya is structured using a modular architecture organised in kernel, modules and services. The kernel contains the facilities required to solve sets of discretised partial differential equations, while the modules provide the physical description of a given problem. There are modules to handle several different physical problems, and in the present simulation, the modules for the fluid flow problem to be used are Nastin and Alefor. Nastin has the physical description of the Navier-Stokes equations for incompressible fluids and Alefor provides the facility to deform the mesh of Nastin. For the solid mechanics problem, the module Solidz will be used.

In the Alya system it is possible to perform multi-code multi-physics simulations through its coupling capability [3] and [4], this means that different instances of the code can communicate and send relevant information to each other. For the present contribution, one instance of the code will be in charge of the fluid mechanics problem, while in the other the solid mechanics problem will be treated. Then, the two codes will exchange relevant information to solve their respective problem. The fluid mechanics code, will calculate and send the forces over the wet interface to the solid mechanics code and will receive from this the position of the named surface.

2.2 Cases configuration

The computational domain for the solid mechanics problem represents the Vortex-Bladeless experimental device depicted in Fig. 1. The geometrical domain is divided in 239,655 elements and the simulations are carried out using 32 cores of the MareNostrum III supercomputer. An iso-linear solid material model is considered and a Newmark temporal scheme of constant average acceleration is used with a time step of $2x10^{-3}$ seconds. Finally a deflated conjugate gradient solver is used to invert the resulting algebraic problem.

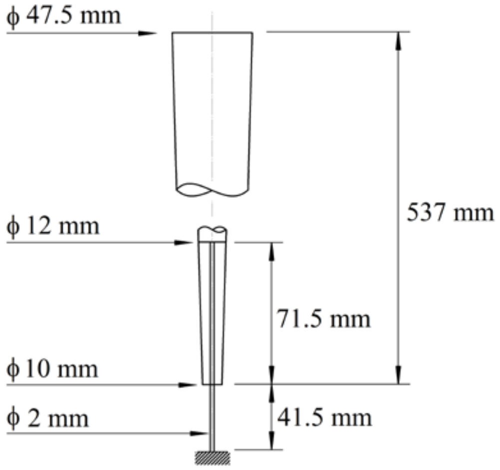

Figure 1: Schematic representation of the vortex-bladeless experimental device

In order to calibrate the solid mechanics model, a preliminary experiment was done. The scaled device was moved from its equilibrium position and then allowed to move freely with no current of wind to interact. The oscillatory response of the vortex was registered as it tended to its equilibrium position. With this information, the mechanical properties of the solid were varied and test runs were performed. The results are shown in Fig. 2 and the solid body is considered to be built of two different materials, the more flexible beam in the base with a

Young's modulus of E=0.97 x 10^{11} and density ρ=1365 kg/m^3, and the upper more rigid pole with Young's modulus of E=3.0 x 10^{11} and a mass of 0.091 kg. The mechanical dumping of the beam is simulated using the Rayleigh damping model with the usual non-dimensional parameters a_1= 0.7, a_2=0 [5].

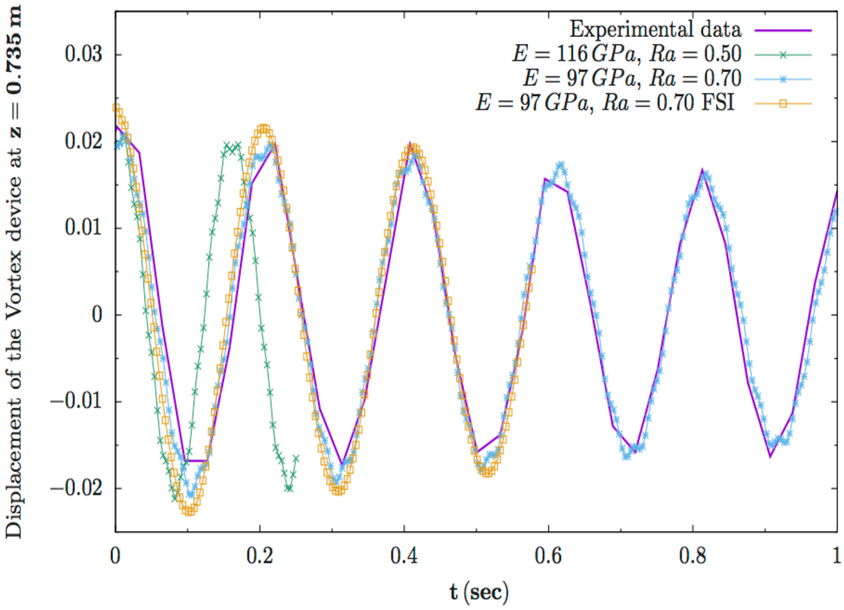

Figure 2: Calibration of the solid model against the response of the experimental device. The best values found were E=97GPa and RA=0.70

The computational domain for the fluid flow problem represents a wind tunnel of 20 m length and a square cross section of 2 m x 2 m. The bottom wall and the Vortex-Bladeless device are considered as non-slip surfaces. While the side and the top walls are considered slip surfaces, and the outflow is considered a free surface. The computational domain was discretized using 3,285,932 elements, and the simulations were carried out using 357 cores of the MareNostrum III supercomputer. A pressure Schur complement approach is used to solve the Navier-Stokes equations together with an orthomin(2) algorithm. The continuity equation is solved using a deflated conjugate gradient solver, while the GMRES solver is used for the momentum equation. The time step used is 2x10^{-3} seconds. And the properties of air at 300 K were used.

The coupling algorithm is a loose coupled scheme. This means that in one time step, the fluid mechanics problem is solved, the forces in the wet surfaces calculated and sent to the solid mechanics code, who after deforming by the effect of these forces sends back the new position of the wet surface and the time step is advanced. This scheme is normally unstable when the densities of the solid body and the fluid are similar. But in the present case, the densities ratio is high and the scheme has proven to be stable. The simulation was started with a fully developed flow around the vortex-bladeless device, which was moved slightly from its equilibrium position in order to start with an asymmetrical configuration.

The fully coupled simulation was done with 389 processors divided as explained for the individual cases. One physical second took about four hours of simulation. The set-up of the individual cases for the initial condition, the geometry set up and the numerical treatment configuration needed around 10,000 cpu hours.

3. Results of FSI simulations

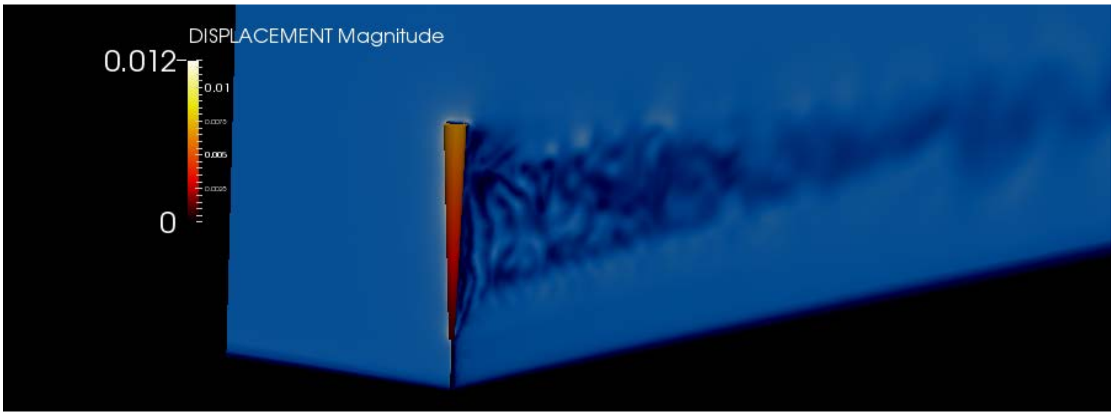

Figure 3: Typical response of deflection and velocity field of the Vortex-Bladeless FSI case.

The typical response of the Vortex-Bladeless in a given instant of time is depicted in Fig.3, and the oscillatory response of the system is shown in Fig.4, where the displacement of the Vortex-Bladeless device at a height of z=0.735m is depicted.

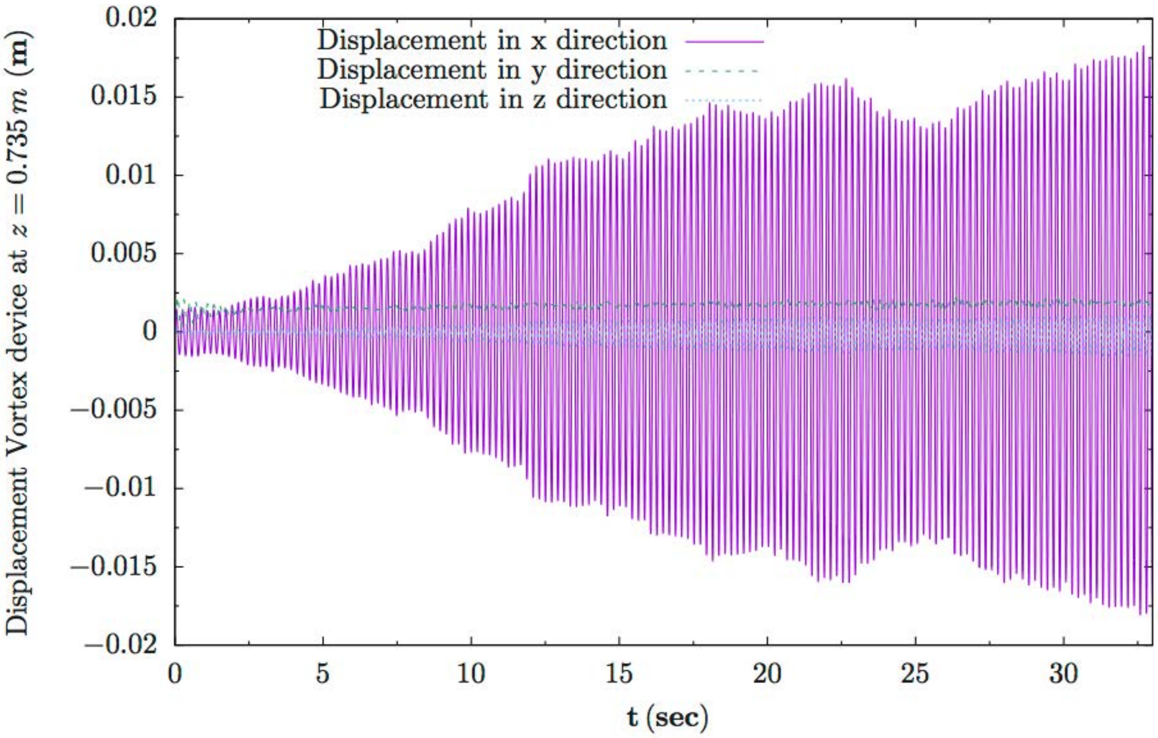

Figure 4: Displacement of the Vortex device, thirty-four seconds of simulation. The amplification of the maximum displacement of the oscillations is product of the lock-in effect. Different frequencies can be observed along the oscillatory process.

The amplification of the magnitude of the maximum displacement of the vortex-bladeless device shown in Fig. 4 shows that the lock-in effect is well captured by the FSI simulation and that the experimental device is taking energy from the fluid. Also, the small oscillations present in the flow direction show that the movement is not confined to a plane. It is remarkable that different low frequencies are present in the overall process as it can be clearly appreciated from the different peaks and valleys present in the picture.

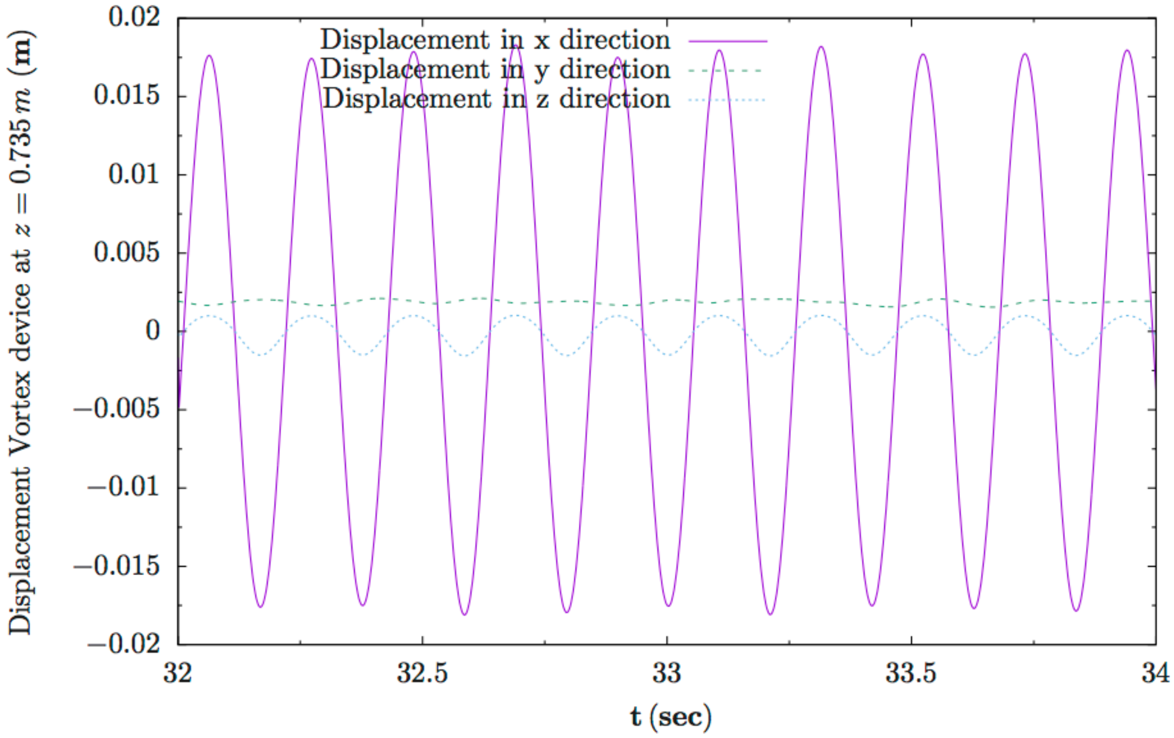

Figure 5: Displacement of the Vortex device, last two seconds of simulation. The maximum amplitude of the oscillations remains almost constant and the frequency remains stable. At this stage, one frequency dominates the dynamical behaviour.

A more detailed view of the oscillatory response in the last two seconds of the simulation is shown in Fig.5. We can observe that the maximum amplitude of the oscillation doesn't suffer significant changes and that one single frequency clearly dominates the dynamical behaviour of the vortex-bladeless device. The average maximum amplitude is **A = 0.036225757 m** and the frequency registered is **f=4.8Hz**. Experimental tests for this same device give an average amplitude of **A_{exp}=0.034 m** and a frequency of **f_{exp}=5.3Hz**, which is a very good comparison with maximum relative errors of **less than 10%**. The simulation can be improved with the use of more refined meshes and more complex solid models for large deformations.

4. PRACE cooperation and benefits for the SME

The Partnership for Advanced Computing in Europe (PRACE) provided the expert support to adapt the Alya code for this application and the machine time needed to perform the simulations, 100,000 cpu hours in the MareNostrum III supercomputer were assigned and part of the Computer Applications for Science and Engineering (CASE) of the Barcelona Supercomputing Center worked in the present simulations.

The results of this SHAPE project are providing guidance and support to the company in the development of its wind energy device. Once the full laboratory results are properly reproduced, it is expected to perform full-scale simulations, in order to do so, more computational resources and expert advice will be needed. For this reason the BSC and Vortex-Bladeless are looking forward to cooperate in the frame of European projects or other collaboration frameworks available.

The experience in this collaboration in the SHAPE projects framework has been satisfactory and encouraging. The main difficulties faced were the full understanding of the PRACE-SHAPE project procedures and the communication of advances and results of the work done by the BSC researchers. The best way we found to cope with this difficulty was to make teleconferences and write periodic reports in a non-deep technical (computer science) language so that the state and results of the work are clear to everyone.

The application procedure for SHAPE projects was initially confusing for the SME members. Given that we had to make two different applications for PRACE resources (the first one to get the approval of the project and the second one to get the real access for the calculation time), it was thought that the resources of the first application were not being used properly. This issue has already been discussed in the face to face meeting WP7 PRACE 4IP at Barcelona and it is foreseen that the next calls will include computational results starting from the first application.

5. Conclusions

The Alya code was adapted in order to simulate the physical response of a scaled device of the Vortex-Bladeless wind energy generator. The simulation was done using a multi-code coupling approach with a loose coupling algorithm. The comparison between the numerical results and the experimental data provided by the SME is very good, with maximum relative errors of less than 10%. However, the resources needed to perform the simulation are very high at the present, and the code can be improved in order to maintain the accuracy while accelerating the simulation.

The developed tool is providing guidance to the SME in the design and understanding of the physical response of the wind energy generator. It is expected to extend the tool in order to simulate the full-scale wind energy generator and give energy production prediction for this device. This SHAPE project has undoubtedly approached the SME to the HPC and provided an excellent framework to achieve the obtained results.

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