

Structural and motion system dynamic analysis of a two-axes solar tracker under wind action

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Abstract: Solar trackers are being increasingly used within the industry in order to improve the amount of power produced by photovoltaic systems. The design of these devices must pay special attention to wind action as the most relevant load seen by the generally flexible structure supporting the panels. However, standard building codes may not be particularly suitable for this sort of very flexible, extremely wind-exposed and not very critical-from-a-safety-point-of-view structures.

In this context, a sensible approach in order to estimate the aerodynamic loading acting on the system, has been carried out by a coupling of CFD and structural analyses performed with FLUENT and Abaqus/Standard, respectively. Some relevant aspects such as most critical scenario selection, influence of incoming turbulence in the dynamic response of the structure, and sizing of the motion system (two axes of rotation) in order to overcome the aerodynamic loading during positioning of the tracker, were addressed.

Keywords: Wind loading, turbulence, aerodynamics, structural dynamics, random response analysis, solar tracker.

1. Introduction

1.1 Overall description of the solar tracker

The IN0627 solar tracker is a dual axis device intended to be continuously actuated so that the sunbeam angle remains always normal to the photovoltaic panels orientation. By tracking the sun, the efficiency of the solar panels can be increased by 30-40% with respect to fixed support designs.

The motion of the structure supporting the panels is provided by two rotations, the first one around a vertical axis, usually called azimuth, and the second one around a horizontal axis, usually called elevation. These two rotations are shown in Figure 1.

The azimuth motion is provided by means of a geared motor which transfers the rotation to the upper part of the device through a gearing system, depicted schematically in Figure 2. The elevation motion is provided by a set of two hydraulic actuators, as shown in Figure 3.

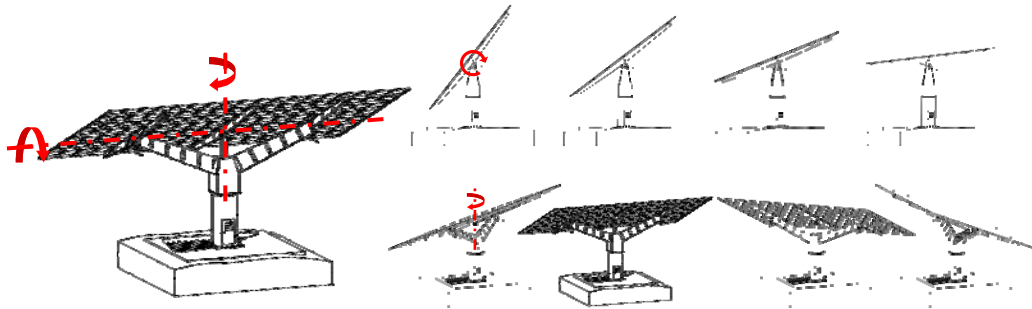


Figure 1. Elevation and Azimuth rotations - Scheme.

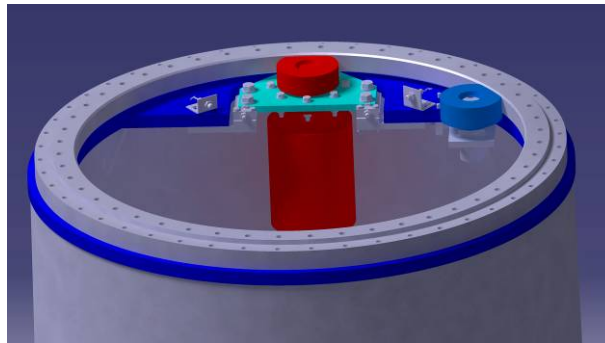


Figure 2. Mechanical system providing the Azimuth rotation.

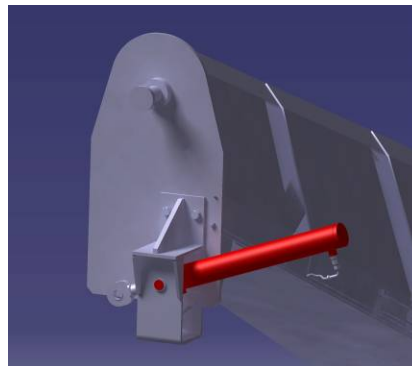


Figure 3. Mechanical system providing the Elevation rotation.

The structural design can be split in three basic parts: the column, running from the foundation to the first stage of rotation (azimuth), the central body, including a central support and the two structural arms whose ends serve as the support of the hydraulic actuators, and the supporting grillage for the photovoltaic panels. An exploited view of these parts is shown in Figure 4.

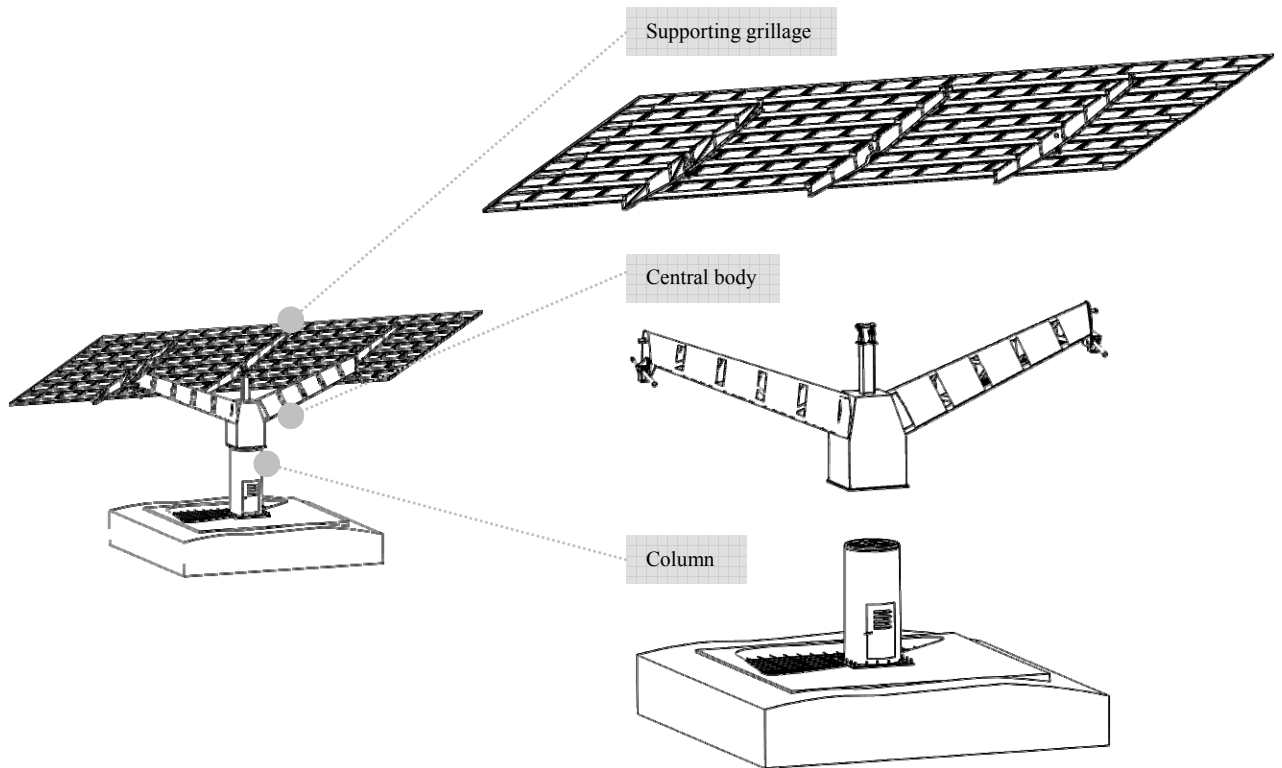


Figure 4. Structural design.

1.2 Problem statement

The solar tracker is aimed to optimize the energy production efficiency by following the sun trajectory, and, therefore, the panels must remain always normal to the sunbeam direction. Obviously, there is no correlation between this solar motion and the direction on which the wind may act at a particular site and moment, which results in a wide variety of possible wind load scenarios in terms of the device orientation with respect to the wind direction.

Most designs are instrumented with anemometers, so that when the wind speed records exceed a predefined threshold, the control system takes the device to a so-called safety position, where the aerodynamic lift and drag forces are reduced as much as possible. However, these events should be kept to a minimum in order to optimize the energy production efficiency of the plant. On the other hand, if the overall system is designed to withstand extremely high wind loads for any possible orientation, the design will not be attractive from an economical point of view, and will have to be discarded.

Therefore, a reasonable assessment of the design performance under wind action is crucial in order to tune the final design parameters in accordance to the desired wind speed limit beyond which the system is to be taken to the safety position.

But wind speed is not the only parameter defining the wind load levels to be encountered by the solar tracker. Wake effects and complex terrain geometries, along with the relatively low height of a solar tracker, make incoming turbulence a potential risk. Since the conceptual design is likely to be quite flexible, the overall dynamic response may result in much higher loads than those expected from a standard static approach. Therefore, in order to evaluate the response of the solar tracker under turbulent wind loading, a dynamic approach must be considered, in which the frequency content of the excitation is characterized and the dynamic behavior of the structure is accounted for. Both phenomena are not particularly easy to address beforehand, and some simplifications will have to be adopted.

2. Wind loading

2.1 Benchmarking exercise

According to previous correlations between numerical results and experimental data, it is well known that CFD calculations often find difficulties in accurately reproducing the wake flow field. This effect usually results in an underestimation of suction forces for this sort of external flows in which a massive separation of the boundary layer takes place. The differences in the wake region are inherent to the calculation method and it is an intrinsic limitation of turbulence k- ϵ models. These models normally overestimate the turbulent kinetic energy generation, yielding a reduction of the wake region which, in turn, underestimates the overall suction downstream. This limitation is widely documented in bibliography (Richards, 1993).

In order to gain some confidence on the reliability of the aerodynamic forces for the solar tracker obtained by numerical simulations, a preliminary analysis covering a similar problem for which experimental data was available in the literature was performed. The benchmark exercise was carried out for a flat plate with an aspect ratio of 5 for different yaw angles (Flachsbart, 1934), a problem similar in geometry and configuration to the solar tracker problem.

The main purpose of the benchmark was twofold:

- First, the results obtained by applying the CFD methodology were to be compared to those available in bibliography, in order to estimate the level of accuracy to be expected in the aerodynamic loading analyses.

- Secondly, by identifying key parameters of the CFD which yielded better results when compared to the experimental results, an analysis strategy would be derived and applied to the solar tracker case. These key parameters were mainly: meshing strategy, turbulence model, convergence criteria and interpolation scheme.

Figure 5 shows an overall view of the computational domain and mesh for the benchmark problem, whereas Figure 6 shows a comparison between the experimental and numerical results for different meshing strategies as a function of the angle of incidence to the plate. The results show that the worst situation in terms of accuracy yields errors in the order of 16% for the drag/lift values, which was considered acceptable according to the nature of the problem at hand. This over prediction of forces takes place when separation effects are more significant, being the highest levels of accuracy reached with second order interpolation schemes.

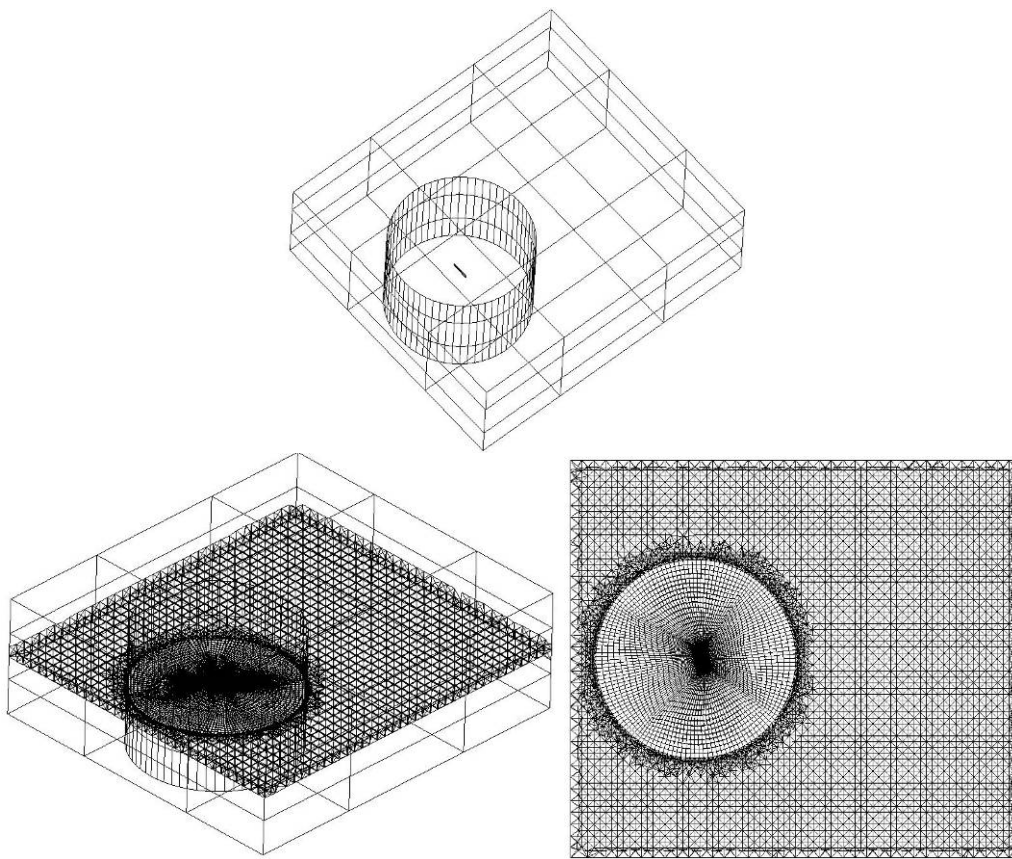


Figure 5. Benchmark case – Computational domain and mesh

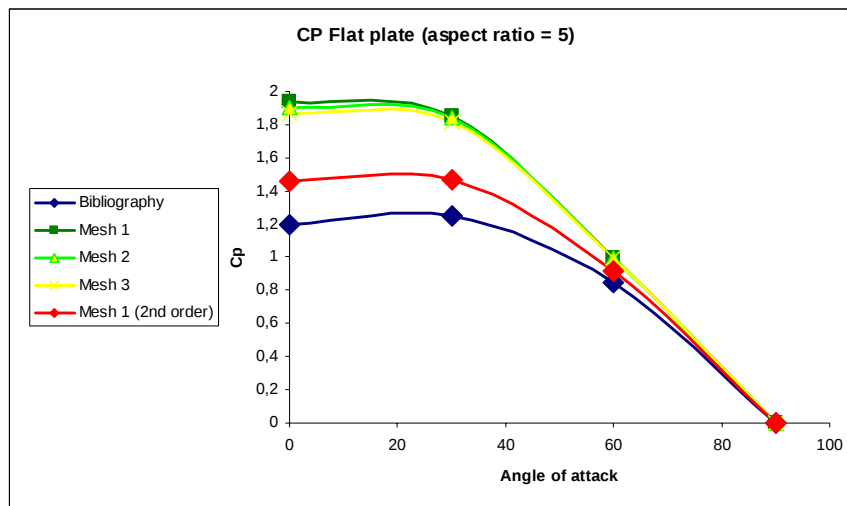


Figure 6. Benchmark case – Computational vs. Experimental results

Within the context of the project, these results showed that CFD predictions were accurate enough in order to predict the wind loading acting on a solar tracker at different positions, taking also into account wind directionality. The best CFD analysis strategies in terms of meshing, turbulence model, convergence criteria and interpolation scheme, were used for the solar tracker case.

2.2 CFD analysis of the solar tracker at different positions for different wind directions

After the overall simulation strategy was settled in accordance to the results obtained for the benchmark case, a CFD model of the solar tracker was created. For the purpose of the study, the solar tracker was represented as a flat plate located at a certain vertical distance from the ground. A series of simulations were carried out in order to select the worst case scenarios for the structure and the motion systems (see Figures 2 and 3).

A matrix of 18 stationary cases was covered, with a combination of three different pitch angles (63°, 43° and 34°) and six different yaw angles (0°, 30°, 60°, 120°, 150° and 180°). The model was created, so that these different scenarios could be prepared almost automatically from the nominal mesh. Figure 7 shows the aerodynamic pressure contours and flow patterns under the six different yaw conditions considered, for a 63° pitch angle.

The resulting aerodynamic forces were computed at the center of every single solar panel (the supporting grillage contained a panel array of 7 rows and 18 columns): This set of forces was stored in order to be further introduced in the structural model as ***CLOADs**.

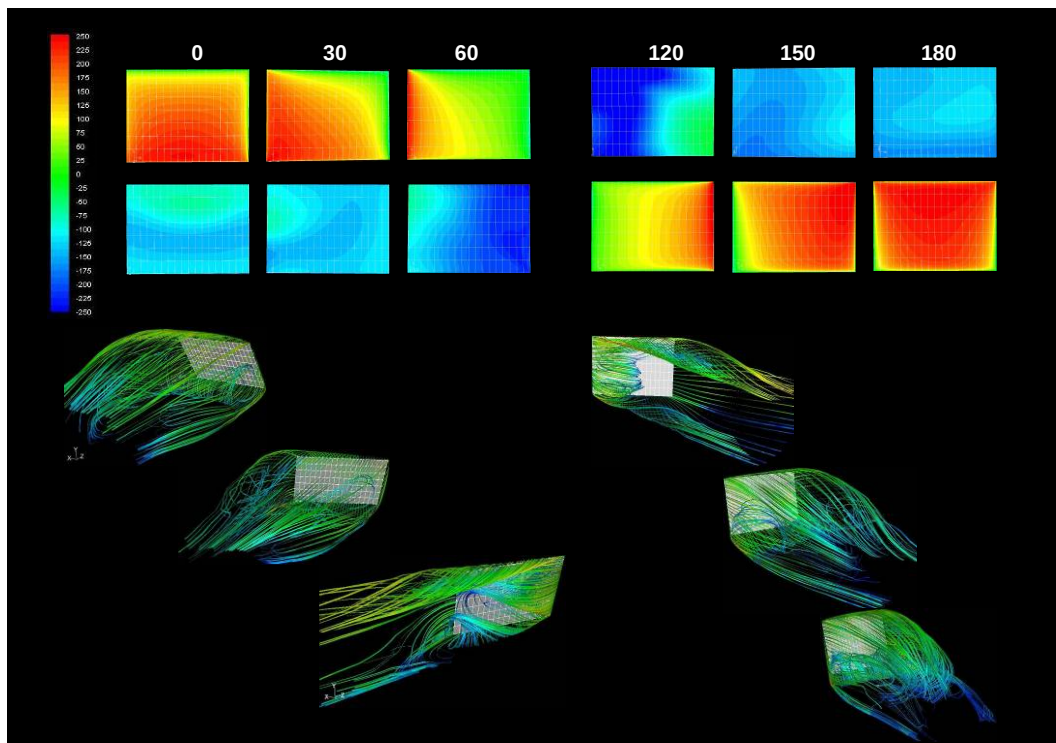


Figure 7. Aerodynamic pressure patterns for different yaw angles – pitch angle: 63°

2.3 Splitting of the mean and fluctuating components of the wind speed

In order to establish a wind loading criterion for the solar tracker, a different approach to that commonly used in structural engineering practice was adopted.

The main conceptual difference between a solar tracker and conventional structures lies in the fact that solar trackers do not have to be designed to withstand the highest wind loads likely to be encountered during their lifetime: they can minimize the wind loading by changing their orientation.

The solar tracker design basis define certain thresholds for the wind speed, above which, the solar panels must be taken to safe positions, where the aerodynamic forces and moments, are decreased to acceptable levels. Therefore, the decision about whether the device must be taken to a safe position or not depends on the wind speed monitoring program implemented on site, which most of the times provides wind speed records taken every few seconds. In this context, traditional concepts such as the so called basic wind velocity (Eurocode, 2004) may be of little use. On paper, the solar tracker design is not site-dependent. It must be able to withstand up to a certain

predefined limit and, beyond that, capacity of the motion system must ensure that it can be taken to a safe position. But adopting that predefined limit and treating it as a static value may result in non-conservative assumptions. The non-stationary wind speed components can excite a significant dynamic response in flexible structures. In these cases, the turbulent components can be characterized as a function of frequency by a power spectral density function

The new question could be put this other way: When a certain wind speed is measured on site, how do we split its mean and fluctuating components? This could be achieved by implementing some sort of control routine for post-processing of the recorded values, but from a mechanical and structural design point of view, a reasonable estimation has to be made much in advance. If too conservative, the design will be expensive. If too loose, there will be more failures than desired once the solar trackers have been installed on site.

In the context of this work, the splitting was made adapting the EC-1 formulation (Eurocode, 2004) and playing with the basic wind speed concept in a slightly different way, though a number of different formulations are available in the literature expressed in terms of key factors such as mean wind speed, height, turbulence intensity, surface roughness, etc (Simiu & Scanlan, 1996). According to the EC-1 formulation (Eurocode, 2004), the mean wind speed is expressed as a function of the basic wind speed, height and some surface-roughness dependent parameters. The corresponding power spectral density function (and therefore, the turbulence intensity and the standard deviation of the turbulence) is also a function of the same variables. It should be remembered that integrating the power spectral density function with respect to frequency yields the standard deviation of the wind speed, considered as a random variable. Therefore, in order to assign the splitting strategy for a certain total wind speed, v_{tot} , the decomposition was carried out as follows:

$$v_{tot} = v_{stationary} + v_{fluct} = v_{stationary}(v_b, z, roughness) + \sigma_v(v_b, z, roughness)$$

Once the total wind speed and the roughness parameters are selected, the equation is solved, so that the only remaining variable, the equivalent basic wind speed, v_b , is obtained. In order to compute the total responses, R_{tot} , the same approach is used, where $\sigma_R(v_b, z, roughness)$ is the root mean square of the response:

$$R_{tot} = R_{stationary} + R_{fluct} = R_{stationary}(v_b, z, roughness) + \sigma_R(v_b, z, roughness)$$

Figure 8 shows the power spectral density function of the wind speed velocity as a function of surface roughness at a height of 5 m for a basic wind speed of 70 m/s. Increasing the surface roughness results in higher levels of turbulence and, therefore, higher significance of the fluctuations with respect to the mean wind speed level. For this study, some preliminary analyses were carried out, finally adopting the terrain category IV (Eurocode, 2004), recommended for very

rough surfaces. Total spatial correlation has been considered, given the size of the surface exposed to the wind action.

In terms of the analyses with Abaqus/Standard, the process will then have two steps (apart from the required modal extraction):

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*STEP, PERTURBATION
** Aerodynamic forces taken from CFD and introduced by CLOADs at the
** center of panels for the stationary wind speed
*STATIC
1.0, 1.0
...
*CLOAD
** Aerodynamic forces adapted to the corresponding stationary wind speed
*END STEP
**
*STEP
** Random response analysis where the PSD corresponding to the fluctuating
** component of the wind speed is introduced
*RANDOM RESPONSE
0.1, 5.0, 10
*MODAL DAMPING, MODAL=DIRECT
1,50,0.02
*PSD-DEFINITION, NAME=WindSpectrum, type=force
...
*CLOAD, LOAD CASE=1
...
*CORRELATION, TYPE=CORRELATED, COMPLEX=NO, PSD=WindSpectrum
*END STEP

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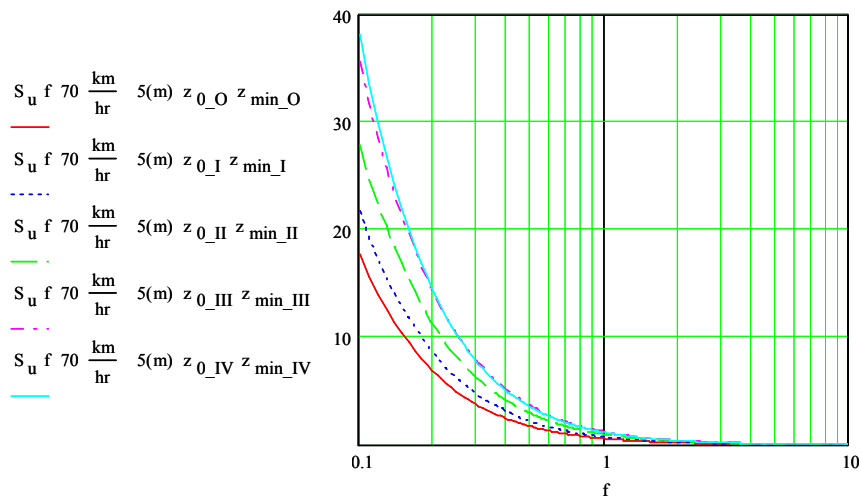


Figure 8. Power spectral density function as a function of surface roughness

3. Finite Element model of the solar tracker

The solar tracker structure has been mainly represented by a combination of beam and shell elements in Abaqus/Standard. Since some of the parts have been meshed independently, rigid (type BEAM) connector elements have been used to undertake the final model assembly. Internal forces at these connector elements have been carefully monitored in some critical locations in order to compare them with the structural capacity of the actual bolted connections. Figure 9 shows an overall description of the model, along with two more detailed views at relevant connections.

The mechanical systems providing the motion actuation for the azimuth and elevation rotations (see Figure 2 and 3, respectively) were modeled by means of connector elements, which allowed for a simple and easy way to post-process the resulting forces. In order to characterize the dynamic significance under the random response analyses, the root mean square values of force and moment components at these connector elements, were the most suitable output variables chosen for comparison purposes.

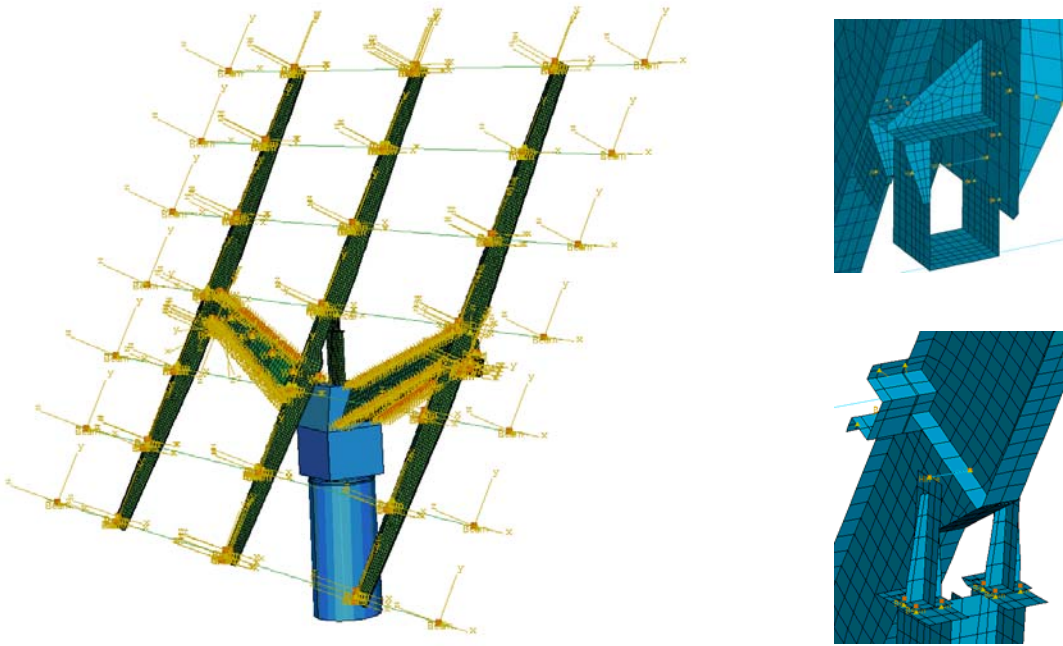


Figure 9. Overall view of the solar tracker finite element mesh

4. Results

The structural capacity of the three basic parts (column, central body and supporting grillage, see Figure 4) has been evaluated for different wind speed thresholds. In the main components, such as the central body arms supporting the grillage (see Figure 10), a direct comparison between the maximum computed von Mises stress and the material yield stress, has been established. For those parts in which the level of mesh refinement is not enough to provide reliable results in terms of peak stresses, the evaluation has been performed differently. Connector forces (CTF) acting at the connector elements representing each and everyone of the bolts, have been post-processed according to the splitting scheme described in 2.3, and compared to the ultimate combined shear and axial capacity.

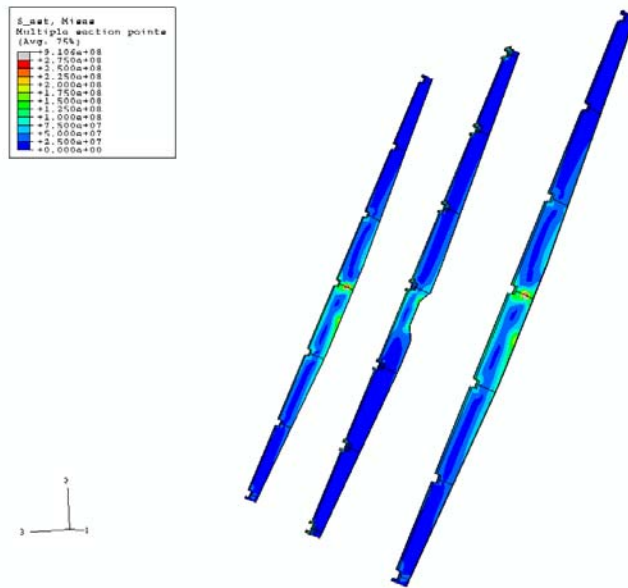


Figure 10. Stress contour at main arms of the solar tracker

Nevertheless, the analysis was more focused on establishing the load levels for the geared motor, the corresponding gearing system, and the hydraulic actuators. These systems were represented in the FE model by means of connector elements. Resulting connector forces were computed according to the splitting scheme described in 2.3.

Figure 11 and Figure 12 show the PSD function of the hydraulic actuator force and the azimuth moment at the interface between the column and the central body for a total wind speed of 90km/h. Figure 13 shows the mode shapes and frequencies of the most relevant modes which correspond to the PSD peaks.

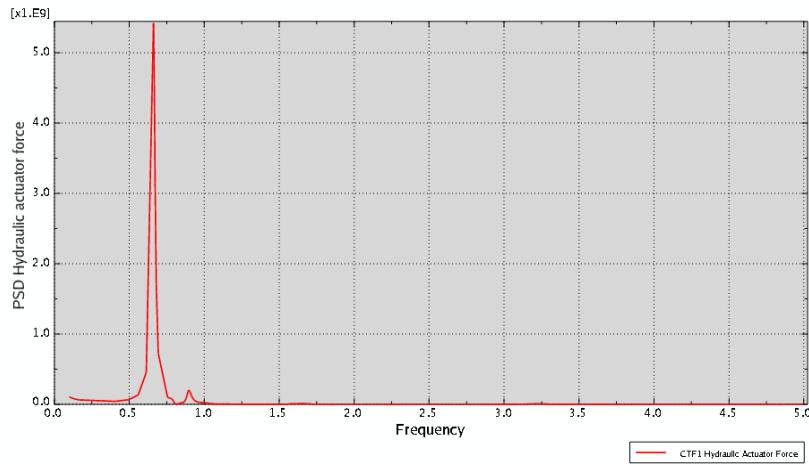


Figure 11. PSD function – Hydraulic actuator force

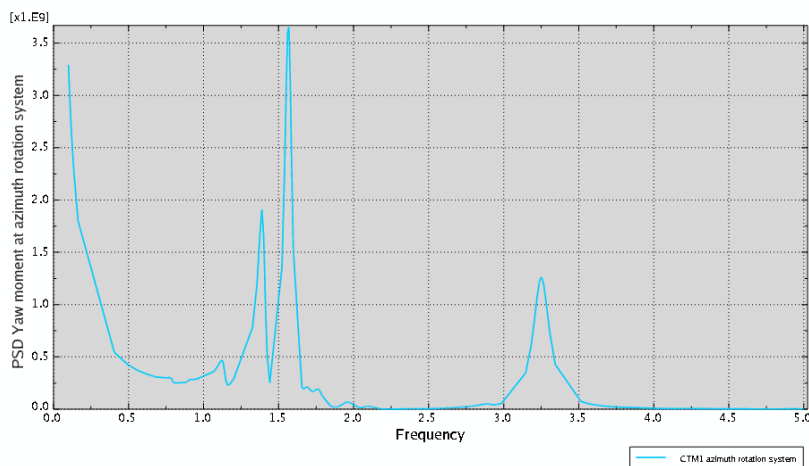


Figure 12. PSD function – Yaw moment at azimuth rotation system

In the case of the hydraulic actuators, the only relevant contribution to the dynamic response of the system is provided by the first mode (0.66 Hz), which is actually an elevation rotation mode. The corresponding frequency clearly depends on the stiffness assigned to the hydraulic actuator. In order to choose a reasonable value, a static test was performed on an existing prototype to find the relation between force and displacement.

In the case of the geared motor and the corresponding gearing system, more modes contribute to the response having an additional peak at 3.25 Hz which is due to the pure yaw rotation mode depicted in Figure 13.

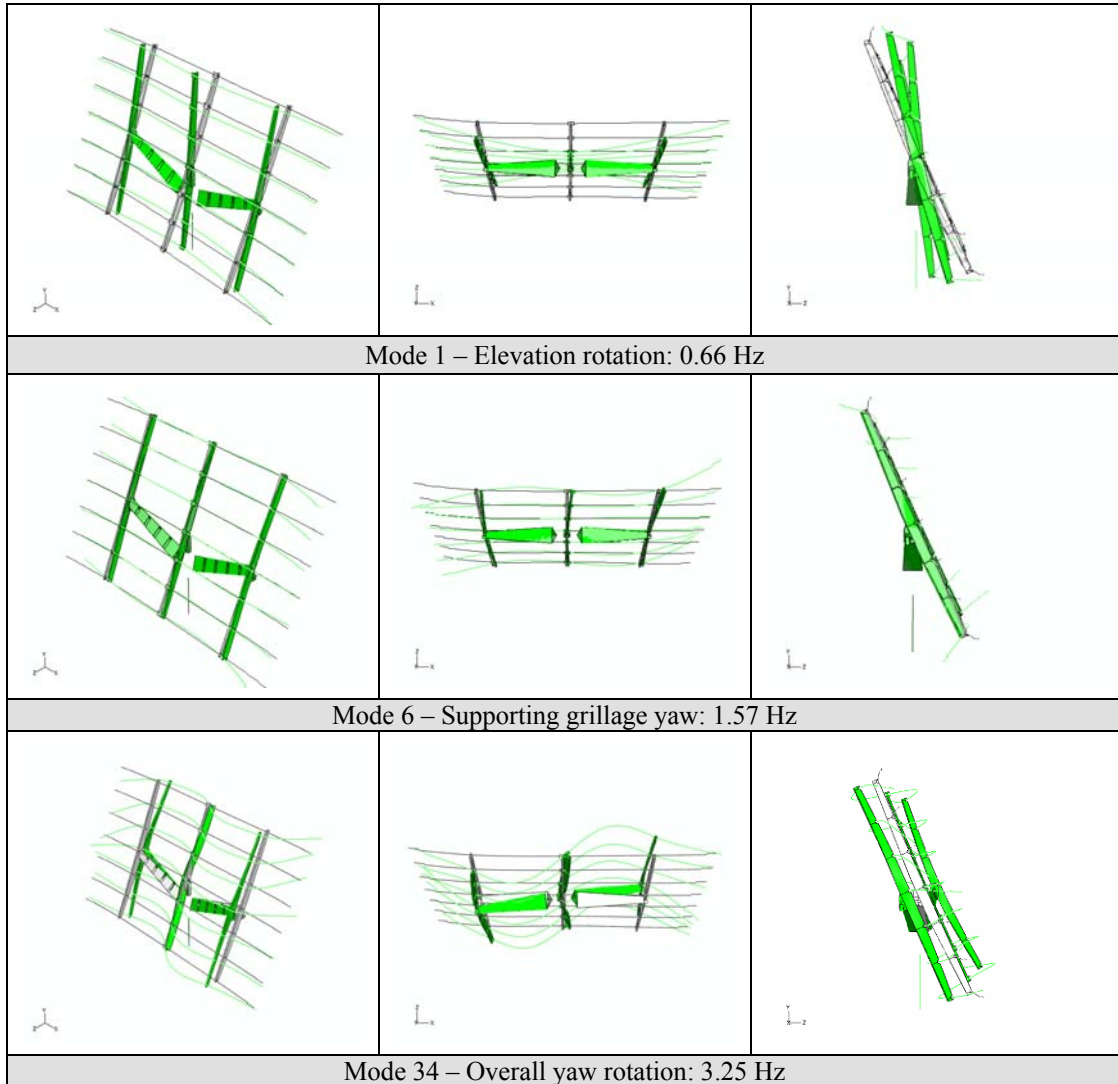


Figure 13. Most relevant mode shapes relevant in terms of motion system response

Finally, and after integration of the PSD functions, and addition of the stationary part according to the splitting scheme described in 2.3, the results in terms of the axial force acting at the hydraulic

actuators and the yaw moment acting at the azimuth motion system are shown in Figure 14, where three lines (63°, 43° and 34° pitch angles) are displayed as a function of the wind directionality.

For the hydraulic actuators, additional dotted lines are shown which represent the equivalent static load had the dynamic effects been neglected. Computed dynamic amplifications reach values up to 35%, whereas the yaw moment at the column hardly shows any increment when dynamic effects are accounted for.

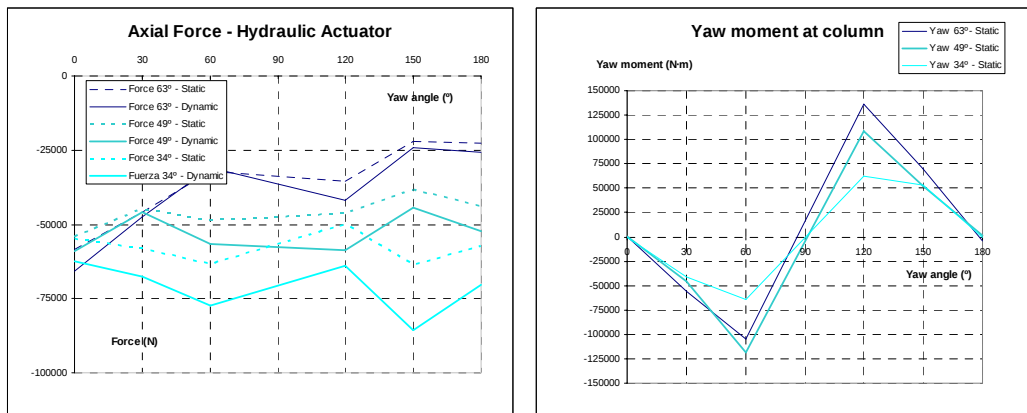


Figure 14. Loading on the solar tracker as a function of yaw and pitch angles

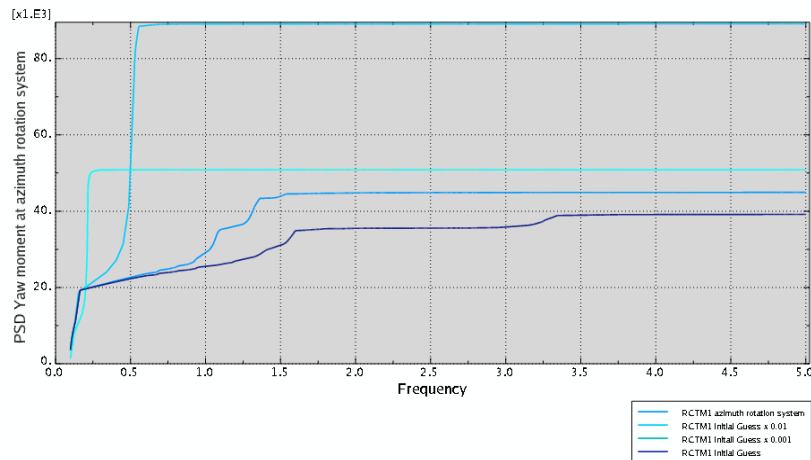


Figure 15. Integrated PSD function – Sensitivity analysis for the azimuth rotation system stiffness

Since the dynamic load at the azimuth motion system may quite dependent on the stiffness properties assigned at that degree of freedom, and since a very rigid estimation was made, a sensitivity analysis was carried out afterwards, by decreasing this initial value by three orders of magnitude. The results are shown in Figure 15, where the integrated PSD over frequency is displayed for fractions of 10%, 1% and 0.1% of the original stiffness considered. Within this range, the standard deviation is increased by a factor of two, but still final dynamic amplification values remain low enough to be neglected in design.

5. Conclusions

Wind action is one of the main driving factors for solar tracker design. In order to have a sensible estimation of wind loads and associated dynamic effects on these flexible structures has been undertaken by means of a combined CFD-FE approach. In this approach, the aerodynamic and mechanical/structural problems have been simplified, so that reasonably accurate answers could be obtained without very time consuming processes. The process involves a stationary-fluctuating splitting of the total wind speed, where the final response can also be obtained by addition of a stationary and a dynamic part.

The presented approach has been used in design in order to estimate, as a function of wind speed, the strength of the different structural components, as well as the requirements for the motion systems in terms of power and gearing characteristics. As a result, the final design has been optimized, so that no weak links were inserted in the chain, while reducing the capacity of the strongest links (mostly structural parts) in order to achieve significant cost reductions without reducing the overall design safety.

6. References

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