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Inclusion of rotor moments in scaled wave tank test of a floating wind turbine using SiL hybrid method

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Abstract. The hybrid testing method developed by CENER for floating wind turbine scaled tests combining wind and waves (SIL) has been upgraded in order to introduce not only the wind turbine rotor thrust, but also the out-of-plane rotor moments (aerodynamic and gyroscopic). The former ducted-fan has been substituted by a multi-propellers actuator system. The new system has been completely developed, calibrated and used on a test campaign carried out at MARIN's Concept Basin. It was installed on a 1/50 scaled model of the DeepCwind 5MW semisubmersible turbine built by MARIN within the EU MARINET2/Call No.3 under ACTFLOW project framework. The control strategy of the floating turbine was developed by POLIMI and TUDELFT and integrated into the SIL numerical model. The experiment has proved a good behaviour of the enhanced SiL method. It has revealed that the relative importance of gyroscopic moments is low in comparison with the aerodynamic rotor moments in the considered cases. The results also show how rotor moments are particularly important in the floating turbine dynamics in cases with large rotor load imbalances such as situations where one blade fails to pitch.

1. Introduction

The scaled testing at wave tank of a floating wind turbine is an important step in the design process to reduce risk and uncertainties and to verify the concept and tune the simulation tools. To accurately represent the floating turbine dynamics, the inertial, gravitational, hydrodynamic and aerodynamic forces must be correctly scaled in terms of magnitude and frequency. Floating wind turbines are subjected to wave and wind loads and a precise scaling of both forces is needed to obtain reliable conclusions of the system dynamics. Unfortunately, the Froude scaling rules that are typically applied in wave tank tests to obtain equivalent hydrodynamic forces between full scale and prototype [1], does not maintain a constant Reynolds number, resulting in out of scale aerodynamic forces.

One alternative to sort out this conflict is to redesign the scaled rotor for a low Reynolds condition, obtaining a thrust representative of the full scale aerodynamic force around the design point [2]. A different approach consists of using a tuned drag disk instead of the scaled rotor [3] that will provide the scaled thrust subjected to the wind flow, although the effects of turbulence or the rotor control strategy cannot be captured.

In the real time hybrid testing the aerodynamic rotor loading is applied to the scaled model based on simultaneous simulations, coupled to the experiments, whilst the effect of the waves over the floater is physically tested. We presented and validated a hybrid testing method for floating wind turbine scaled tests combining wind and waves in 2014 and we called it Software-in-the-Loop (SiL) [4]. The first version of SiL only introduced the total rotor thrust force using a ducted fan (Figure 1). In this paper, we describe how we have enhanced the system, using a 4 propellers actuator (Figure 2) to include the out-of-plane rotor moments (both aerodynamic and gyroscopic), achieving a more accurate testing method. The inclusion of these moments allow to include cases described at the guidelines that were not capture with enough accuracy with the previous version, such as blade failure cases, rotor imbalances or extreme shear cases.

Figure 1. Former ducted fan actuator for the inclusion of the trust as point force

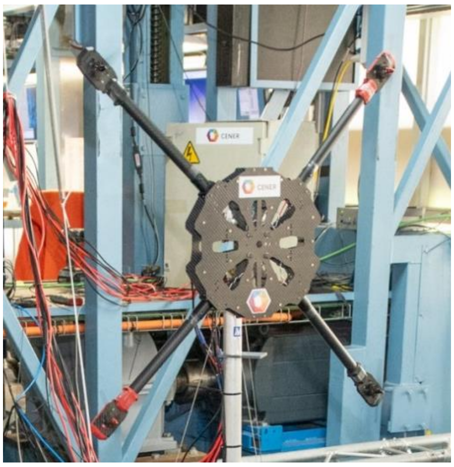

Figure 2. New 4 drone propellers for the inclusion of thrust and moments

The improved method was verified to a test campaign of the 1/50 scaled model of the OC6 5MW semisubmersible turbine at MARIN wave tank.

2. Software in the loop method

In the SiL method the aerodynamic rotor forces are computed by a numerical model fed in real time by the measured motions of the platform in the wave tank. In the first version, a ducted fan is used to include the rotor thrust as a punctual force at the hub position. The real-time simulation of the rotor aerodynamics provides this thrust force, considering turbulent wind, control actions, etc. As the simulation-actuator system is coupled in real time with the model motions at the wave tank, the thrust introduced considers the aerodynamic rotor damping. This effect is very important to accurately capture the whole system dynamics. It can act as an important source of positive damping below rated wind speed. Over rated wind speed, due to the pitch control strategy, this effect can add negative damping, and therefore, the SiL method is very useful to evaluate the control strategy.

Along these years the SiL method has been applied to many test campaigns of semisubmersible [5], TLP [6] and spar platforms [7] in many different European wave tanks.

3. System upgrade to include rotor moments

The main limitation of the first version of the system, that uses a ducted fan to include the aerodynamic thrust, is that the rotor moments caused by aerodynamic effects such as imbalances, wind shear, pitch failures, misalignments, or gyroscopic effects are not captured. In this work, a new version of the SiL method has been developed to overcome these limitations. The improved method required designing and building a new actuator, using 4 drone propellers and the development of the simulation and control software.

3.1. *Design of new SiL actuator to include moments*

The introduction of moments needs the application of forces at different positions. Therefore, the former single ducted fan was replaced by drone propellers equally distributed around the ideal position of the rotor hub of the scaled turbine, as it is represented in Figure 3. The figure also shows the reference system that is going to be used in this paper to represent the rotor loads. The system has the origin fixed to the hub height and tower centerline. The x axis is pointing in the nominal downwind direction and the z axis is vertical. The components introduced by the enhaced SiL system are the x force and the moments around the x and z axes.

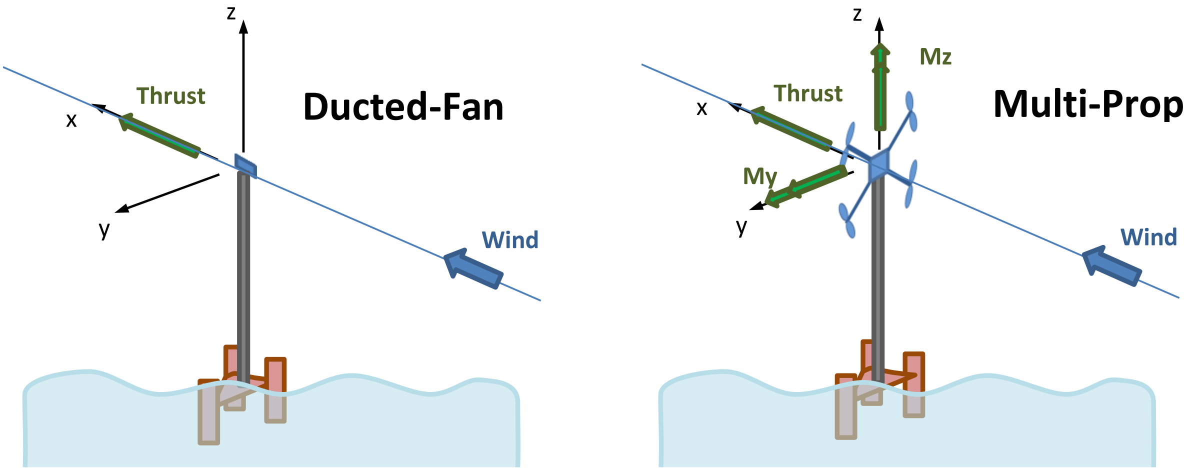

Figure 3. Scheme of SIL system upgrade

The forces introduced by the different propellers must add up the thrust. At the same time, the individual forces must variate between propellers to generate the demanded moments. The amplitude of these variations is an important design driver for the motor-propeller selection. If the amplitude required is too large in comparison with the total demanded thrust force, the design will result on a large motor-propeller system, with a potential loss of precision in the range of interest.

Several designs of the actuator, with different number of propellers, were considered. We performed numerical studies and concluded that the performance using 4 fans provided a good balance between the number of propellers required and the amplitude of the variations for the moment generation. The use of 6 propellers did not translated into a reduction of the force amplitude demanded to the individual propellers and was discarded.

We decided to use drone propellers because it is a technology with a great development during the last years and currently offer reliable and cost effective components. Also, they provide an accurate thrust and a fast response variation as needed by the stability and high maneuverability of drone flight. In addition, they are also light components, which is very convenient to obtain a low weight actuator to be installed at the scaled floating wind turbine tower top.

For the dimensioning of the frame for the propellers and for the selection of the motor-propeller system, we assumed the base case of the DeepCwind semisubmersible platform that supports the NREL 5MW baseline design. This is the model that we tested in scale 1/50 at MARIN for the validation of the method, as will be showed in Section 5.

We decided to assume a distance in diagonal between two propellers of 0.95 m. Preliminary tests showed that with this distance the interaction between fans was negligible and the actuator was stiff enough to avoid any spurious vibrations. Considering this distance, we studied three cases to evaluate the requested force to each of the propellers: one case considering power production a 11.4 m/s turbulent wind, another case where the rotor is yawed 30º under 16 m/s turbulent wind and a third one of power production with 16 m/s turbulent wind where one of the blades fails to pitch and blocks at 10º. Figure 4, Figure 5 and Figure 6 shows the instant where the maximum force is requested to any of the four propellers. Figure 7 shows the numbering of propellers position.

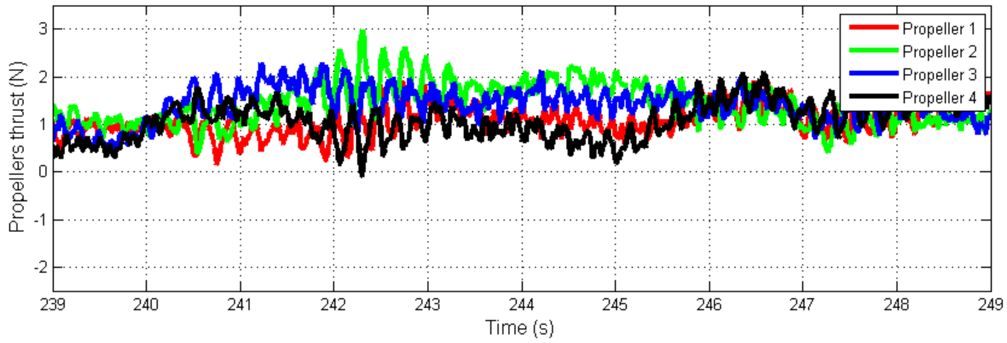

Figure 4. Thrust requested to the propellers for a production case with 11.4 m/s turbulent wind

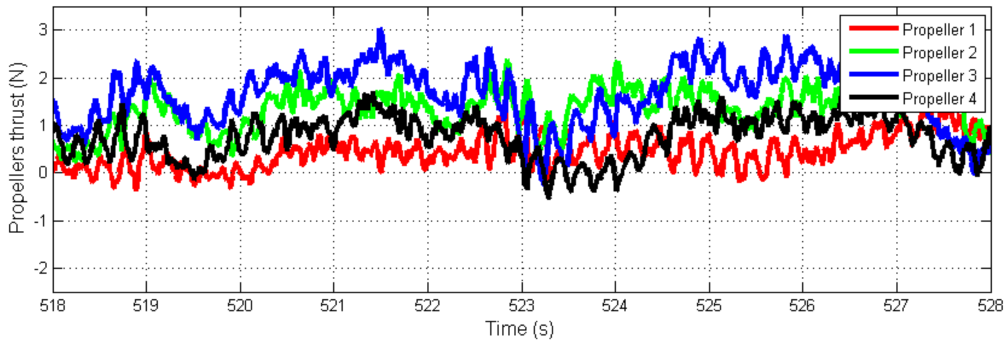

Figure 5. Thrust requested to the propellers for a production case with 16 m/s an the rotor yawed 30º

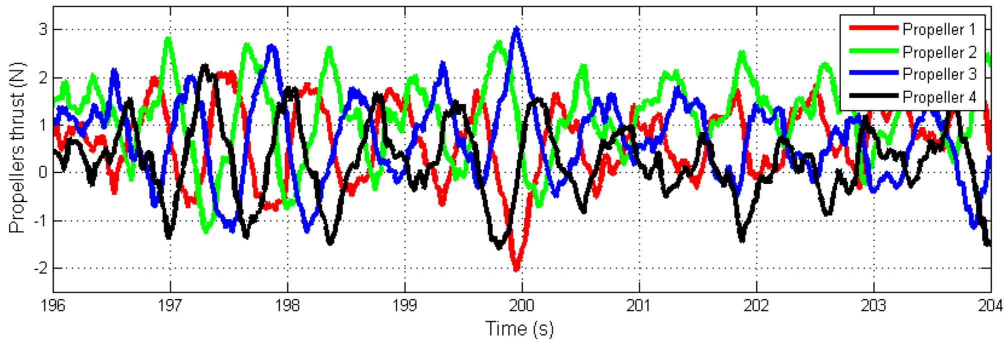

Figure 6. Thrust requested to the propellers for a production case with 16 m/s with one blade that fails to pitch and is fixed at 10º

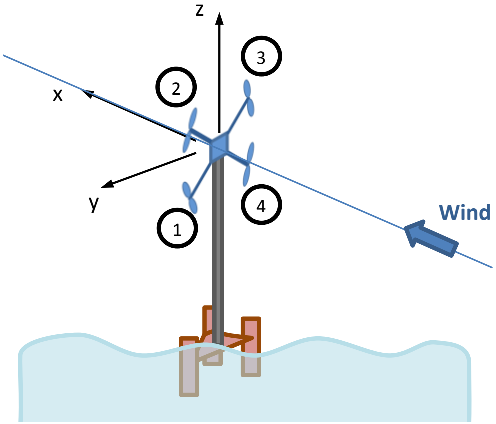

Figure 7. Numbering of the propellers positions

From these pre-calculations, we assumed that the maximum thrust requested to a fan will be 3 N. We decided to look for a motor-propeller system with a maximum thrust approximately doubling 3 N, as working in the lower part of the motor-propeller system provides higher accuracy in the response.

The main components of the actuator system have been selected from drone commercial hardware. Brushless electrical motors have been selected from racing drones as they offer a very high thrust-to-weight rate and very fast response. In order to introduce positive and negative thrust forces, bi-directional propellers have been selected. These propellers have a symmetrical configuration and can rotate in both directions.

A commercial drone frame has been used to build the actuation system. It complies with the required arm's length, has a very light weight and is dismountable at the same time that offers a good support for the hardware.

To create the PWM signals for the motors ESC controllers, an Arduino board has been used as for the previous versions of SIL. In this case, four channels for each of the ESCs are used. Four 15V CC power supplies are powering individually each of the four motors.

3.2. SiL software update

The rotor simulation model was expanded to obtain, together with the total rotor thrust, the total My and Mz moments at the rotor. These three loads are sent to the Labview scripts that control the multi-propeller actuator system. An algorithm is in charge of transforming these three loads into the individual propellers demanded force. This algorithm is based on the idea that forces introduced by the different propellers must add up the thrust and at the same time, variations between the individual forces must be introduced to generate the demanded moments.

In addition, an update of the software scripts related to the control of the actuator by LabView was performed. The communication with the rotor simulation model was updated to obtain several variables instead of one. The algorithm that transforms thrust and moments into propellers demand forces was also integrated.

4. Calibration

Once the complete actuator system was setup, a thorough calibration was performed in order to validate it and to assure that the actuation will be set during tests.

Initially the drone propellers were individually calibrated to characterize their thrust reaction to the control PWM (duty cycle) signal. A calibration tool (Figure 8) was built to place one propeller in a load cell that measured the thrust.

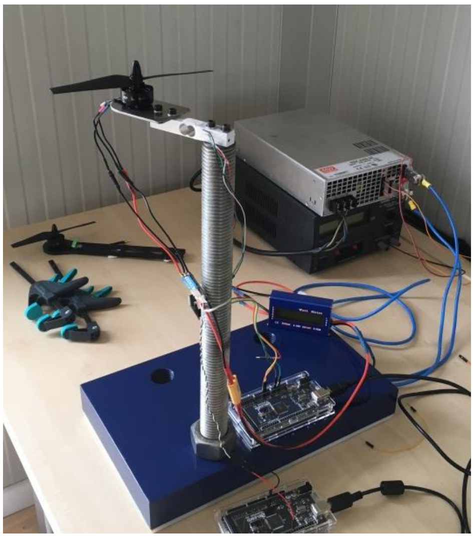

Figure 8. Individual calibration tool

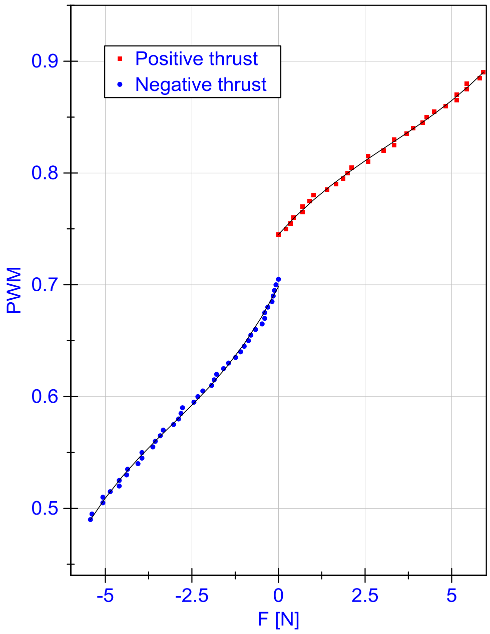

Figure 9. Single propeller response curve

Figure 9 shows the response curve of one propeller in its complete range of positive and negative thrust. The curve can be matched to a cubic spline as shown in the figure.

Once the individual motors were characterized, the complete actuator system was placed in a calibration stand (Figure 10). A 6-component multi-axial load cell was used to measure force and moments.

Figure 10. Actuator system calibration stand

The load cell allows calibrating the complete thrust force and the moments introduced by the actuation system. The calibration takes into account the interference effect of the motor supports on the propellers wake. It also captures the possible wake interactions between the four propellers, although this effect showed to be negligible.

The calibration was performed with the final configuration of the system, including the long power cables (10 m.) to be used in the wave basin test. This assures a better accuracy of the final calibration results as takes into account for instance the actual voltage applied by power supplies to the motors, which has an important effect on their response.

5. Performance of the system on a wave basin test

The enhanced hybrid SIL system was installed on a 1/50 scaled model of the DeepCwind 5MW semisubmersible turbine built by MARIN. A test campaign was carried out at MARIN's Concept Basin, within the EU MARINET2/Call No.3 under ACTFLOW project framework. The control strategy of the floating turbine was developed by POLIMI and TUDELFT and integrated into the SIL numerical model. The test campaign included cases under different environmental and operational conditions, and also cases with a blade in a pitch failure situation, which induces important rotor moments.

The test setup included a 6-components load cell installed in top of the model tower and holding the SIL actuator system. This allowed measuring in real-time the applied forces and moments and they could be compared to the desired set points calculated by the system that were also sent to the data acquisition system. This comparison showed good results as can be seen in Figure 11 and Figure 12.

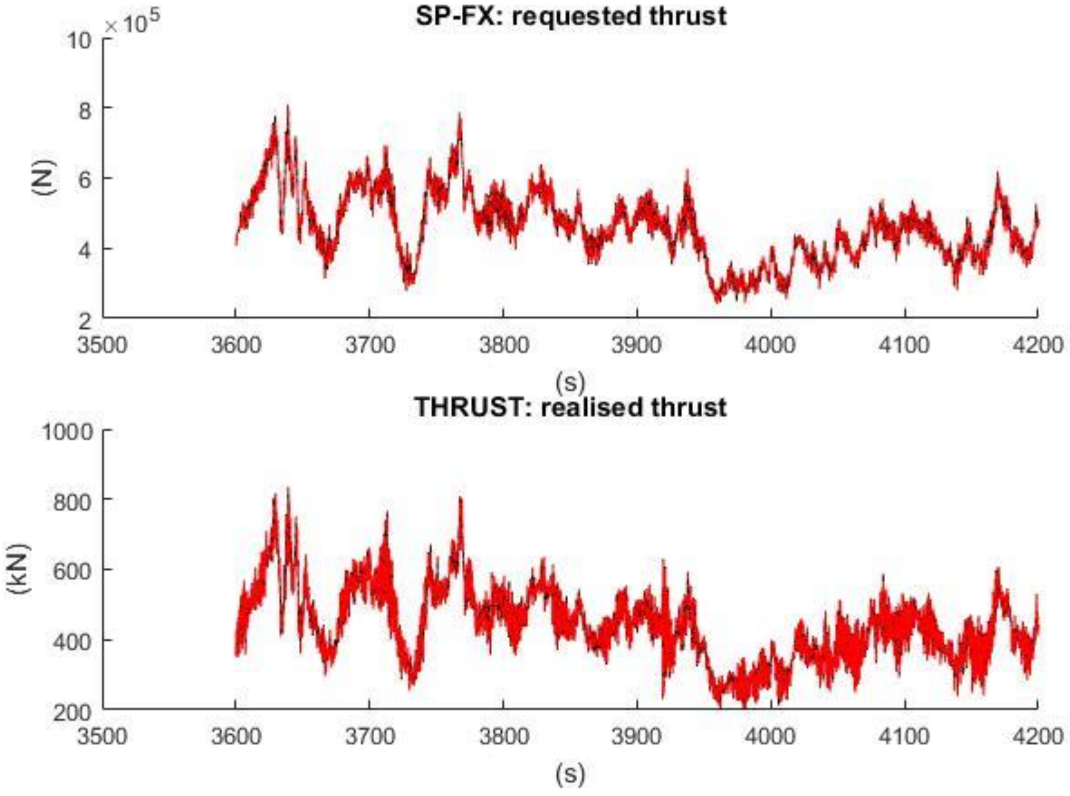

Figure 11. Comparison between actual thrust and set point

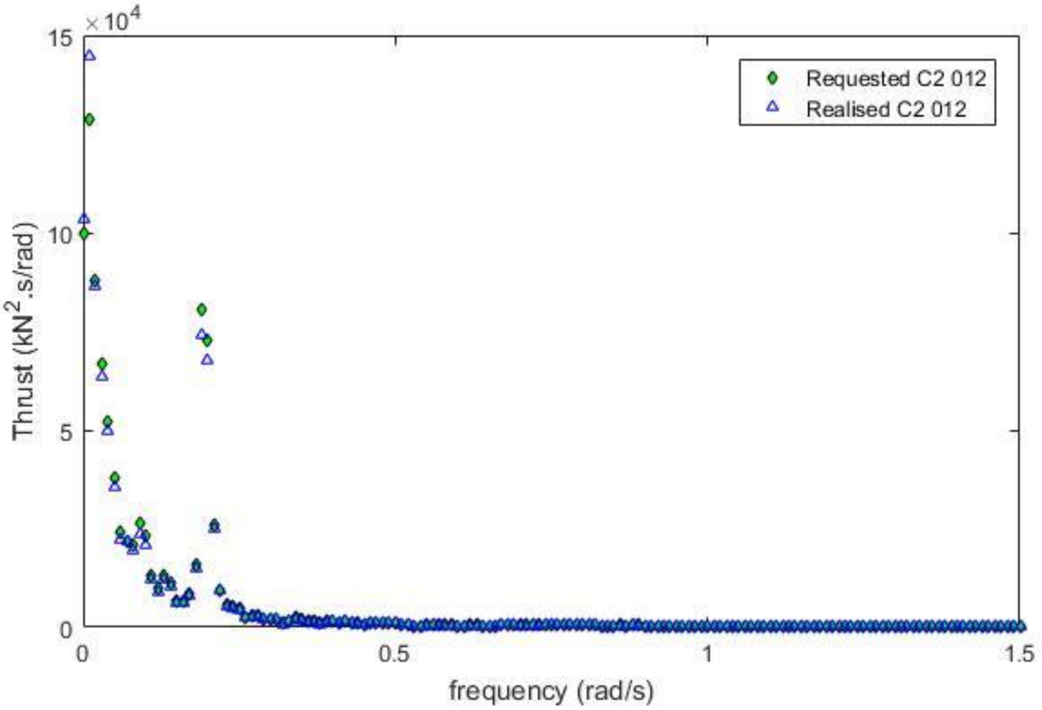

Figure 12. Comparison between actual thrust and set point in frequency domain

To evaluate the relative importance of the gyroscopic moments and the aerodynamic moments, Figure 13 compares the aerodynamic contribution with the gyroscopic contribution for the moments around the Z axis for a case with turbulent wind (11.4 m/s) and irregular waves (Hs = 7,1 m; Tp = 12.1 s). Although both contributions are included in the total moment requested to the actuator during the experiment, the aerodynamic moment dominates the response in comparison with the gyroscopic contribution of the moment. In addition, the aerodynamic moment presents higher frequencies than the gyroscopic.

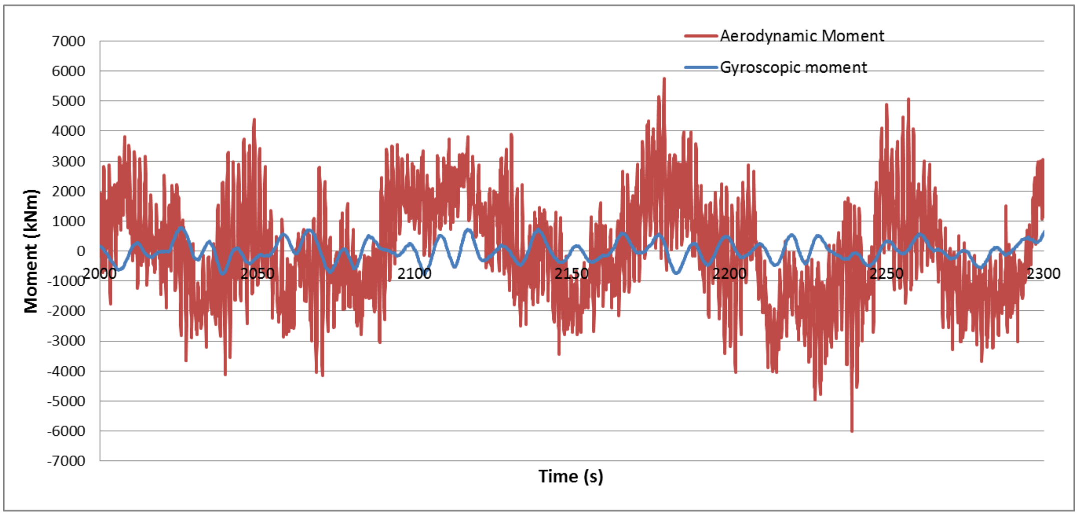

Figure 13. Computed aerodynamic vs. gyroscopic moments around the Z axis

6. Conclusions

The SiL hybrid testing method is improved to include rotor moments generated by aerodynamic and gyroscopic effects. This paper shows that the relative importance of gyroscopic moments is lower in comparison with the aerodynamic rotor moments in the considered cases. The rotor moments are particularly important in the floating turbine dynamics in cases with large rotor load imbalances such as situations where one blade fails to pitch. This paper illustrates how these cases can be now tested using this enhanced SiL hybrid testing method.

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