15th EAWE PhD Seminar on Wind Energy
29–31 October 2019
Centrale Nantes, France

Independent Nacelle Control for Floating Wind Turbines

I Struthers[a]

[a]University of Edinburgh, Scotland

E-mail: i.a.struthers@sms.ed.ac.uk

Abstract

Most offshore wind farms use rigid substructures to support the wind turbines between the surface and seabed. However, sites in deeper water are not suitable for rigid substructures and will require floating substructures, with compliant sections between the floating platform (substructure) and the interface with the seabed (foundation). Floating wind turbines present a number of novel engineering challenges, including for supervisory control. Current control solutions are platform specific and require turbine performance compromises to avoid low stability margins or unstable generator speeds. These issues can be avoided by using a novel approach which transforms the dynamics of the wind turbine nacelle from an inertial to a non-inertial frame of reference. This transformation is represented by fictitious forces which are developed algebraically from analysis of the dynamics in different frames of reference. The effect of these fictitious forces on the hub and generator speed can be found and implemented into a controller as a feedback loop based on measured nacelle accelerations. This report assesses the suitability of this method by modifying the Supergen 5MW exemplar turbine tower stiffness and frequency to mimic the motion a floating platform, and applying the fictitious forces to hub and generator speed control loops. The performance of the controller is assessed for a reduced tower frequency.

Keywords: Floating wind, generator speed control, fictitious forces

1 Introduction

Floating wind turbines are by far the least developed substructure type for commercial wind power generation with a cumulative installed capacity of 61 MW in 2018 compared to offshore bottom-mounted 23 GW and onshore wind at 568 GW [1]. Floating wind turbine technology is accordingly far less well developed and uses some of the approaches deployed in onshore and fixed offshore plant. However, floating wind turbines possess completely different structural properties to their rigidly secured cousins, which necessitates careful design and implementation.

Floating wind turbines are far less stiff than onshore and bottom-mounted (fixed) offshore designs, and so have structural frequencies which are very low by comparison. Applying conventional onshore control strategies to floating wind turbines has been shown to impose negative damped oscillations in fore–aft due to the low natural frequency of the floating structure [2]. This fundamental difference necessitates a different approach to supervisory control as will be described below.

This paper describes an analysis of the fictitious force method by considering an onshore turbine with heavily modified tower properties, simulating floating conditions as a first approximation.

1.1 Problem Description

The main focus of this paper is the motion of the wind turbine *nacelle*. The nacelle is located at the top of the wind turbine tower and as a result will experience the same motions as the top of the tower. As this paper is concerned with nacelle dynamics, the motion of the "tower head" is of key interest.

The motion of the tower is governed by the tower structural modes. These are conventionally separated into fore-aft and side-to-side modes. Only the first mode is considered in this analysis due to time constraints and is primarily concerned with the fore-aft mode. The first fore-aft tower mode is very lightly damped and can oscillate significantly from even a small amount of the excitation which is naturally present in the wind [3]. The tower damping comprises two components: aerodynamic and structural.

- The structural damping is set by the structural properties of the tower (and the platform, if present).
- The aerodynamic damping, in this case, refers to the aerodynamic damping of the rotor. This is much larger than the aerodynamic damping of the tower itself [3] and the rotor aerodynamics are ultimately coupled to the tower dynamics. The aerodynamic damping is highly non-linear and can be positive (*dissipating* tower motion) or negative (*driving* tower motion).

Consider a variable speed, pitch regulated wind turbine, situated in an air flow, with its generator speed and pitch controllers. In wind speeds above the rated speed of the turbine, to avoid overspeed, the generator speed controller will actuate the turbine blades, pitching them about their longitudinal axis to reduce their aerodynamic lift and drag. The rotor speed and torque (hence power output) are thus held at the required value. With lower aerodynamic forces acting on the blades, the steady state rotor thrust (which acts on the nacelle in a direction parallel to the drive-train axis of rotation) is reduced [4, 5]. This reduction in thrust can increase the forward acceleration of the nacelle. This increases relative wind speed at the blades, increasing lift and rotor speed, and hence generator speed. To compensate, the controller attempts to reduce thrust by pitching the blades again, and so entering an unstable cycle of controller commands. Nevertheless, this scenario will only occur if the tower modes are *within* the pitch controller bandwidth [5]. This is typically around 1 rad/s for wind turbine controllers. For onshore turbines towers, the natural frequency of the first fore-aft tower bending mode is relatively high; 1.7293 rad/s for the Supergen 5MW turbine. Thus onshore, or even offshore bottom-mounted, support structures, do not experience this instability as the blade pitch controller is *slow-acting* relative to the tower motion: the controller bandwidth is *below* the first bending mode of the tower[5].

1.2 Application to Floating Wind Turbines

For floating wind turbines, the controller bandwidth is *above* the lowest frequency structural mode. In general, the dynamics of floating wind turbines are completely different [6], where the lowest natural frequencies are significantly lower and described by rigid body motion modes, as opposed to beam bending. As an example, the first mode of an onshore turbine is lateral bending at 23 rad/s, but the first mode of the same turbine mounted on the spar buoy HYWIND concept is (rigid body) horizontal translation at 0.57 rad/s.

The low frequency of these rigid body modes means that the tower modes are *within* the pitch controller bandwidth, and the iteration of nacelle motion and generator speed has an instability that must be controlled [7]. As a result, conventional blade pitch controllers for rigid support structures therefore cannot be used on floating wind turbines without modification. In addition, the likelihood of excitation is higher as the wind field frequency distribution has more components around the natural frequency of the floating structure's pitch response than around the first bending mode of a fixed foundation [5]. Typically, the most problematic modes are those which cause the rotor to move out of plane, surging or pitching.

1.3 Generator Speed Control Methods: Current Solutions

Nevertheless, stable operation of floating wind turbines *can* be achieved in a number of ways, including: pole placement tuning [6]; wind speed estimation, determination of platform eigenmotion and feedback [7], and; wave disturbance control loops [2]. However, these methods can be platform specific (necessitating a unique controller design for a given wind turbine and platform design), and typically result in higher maximum rotational speeds and electrical power outputs than onshore controllers.

1.4 Novel Approach: Fictitious Forces

An alternative novel approach has been proposed which considers the fictitious forces acting at the nacelle due to the motion of the rotor and platform [8]. By augmenting the measured generator speed with the effect of these fictitious forces the stability of the speed control can be assured, and in addition, the motion of the platform is reduced [8].

1.5 Concept of Fictitious Forces: Inertial vs Non-Inertial Reference Frames

The principle of the method used in this paper is based on the concept of inertial and non-inertial reference frames:

- Consider a wind turbine nacelle mounted on an infinitely rigid support structure. This would be equivalent to an *inertial* or *rigid* reference frame; one that is not accelerating.
- Now consider a wind turbine nacelle on a non-rigid support structure. This can be considered a *non-inertial* reference frame; it is accelerating relative to a stationary observer.
- The difference in acceleration experienced by the nacelle in these two conditions can be described by *fictitious forces*. Tower fictitious forces are the apparent forces acting on the nacelle, caused by the motion of the tower.

Note in this treatment, "the nacelle" is a hypothetical point with the same rotation properties as the rotor hub, and the tower head. In reality, these two points are not co-located, but this contraction is made to simplify the analysis.

1.6 Aim of this Paper

The aim of this paper to verify that the nacelle dynamics can be decoupled from the support structure dynamics by augmenting the measured generator speed signal with the effect of the fictitious forces caused by the motion of the tower. This is advantageous because the speed controller does not need to be altered, since the correction on measured generator speed transforms the non-inertial reference frame to the inertial reference frame, and suppresses the low frequency right half-plane zeroes introduced the floating platform [8]. The analysis will consider a fixed turbine, but with modified tower frequencies, to simulate the response of a floating wind turbine as a first approximation.

2 Method

2.1 Project Scope

The duration of this study was approximately six weeks, which meant a succinct approach was required. To complete the study in this time, the analyses were based solely in MATLAB® and Simulink® environments, and a methodical approach was taken to assess performance.

2.2 Resources

The wind turbine and controller model used in this study was provided by researchers in the Wind Energy & Control Group at the University of Strathclyde. The model was a modified version of the SUPERGEN Wind Energy Technologies Consortium 5 MW exemplar turbine with controller. In addition, the equations of motion, derivations and subsequent equations for the generator speed augmentation were provided by Dr Luis Recalde (luis.recalde-camacho@strath.ac.uk) and Prof. Bill Leithead.

2.3 Approach

The intended approach taken to verify the fictitious force approach to nacelle control was to:

1. Run the Simulink model with an unmodified controller and review default system performance
2. Modify the model so that the tower is effectively rigid and compare the results
3. Reduce the natural frequency of the wind turbine tower by a factor of four, such that the fore-aft displacement of the tower is increased. This was intended to be representative of a floating platform motion
4. Obtain equations for the effects of the fictitious forces on the measured generator speed and implement these as an augmentation to the generator speed signal

5. Investigate the results of this implementation for the different tower frequencies

As will be shown, steps 2) and 5) were not fully completed in this study.

2.4 Implementing the Equations of Fictitious Forces

The derivation of the effect of fictitious forces on the measured generator speed is not trivial. Multiple treatments of the topic have been developed in the Wind Energy & Control Group, four of which were investigated in this study. These are presented in isolation here for brevity, as the derivations run to many pages. Four equations were considered, these were (arbitrarily) referred to as: Short Form; Medium Form; Long Form; Array Form. All derivations are based on the equations of motion of the rotor and hub as detailed in [8]. Each derivation makes difference assumptions on frequency and linearisation, leading to the different forms. Ultimately, to transform to the inertial reference frame, a measurement of hub speed must be augmented by the *addition* of the fictitious forces contribution. Each of the forms will be considered in turn in Section A.2. In general, each form requires the calculation of the accelerations of the tower head motion. The equations for the nacelle (in-plane) angular acceleration *about* the local z-axis, and (out-of-plane) linear acceleration *along* the local z-axis due to tower motion are given by [9]:

$$\dot{\Omega}_{zN} = \ddot{\theta}_T cos(\phi_T) \tag{1}$$

$$\ddot{z}_N = -\ddot{\phi}_T.h \tag{2}$$

Where:

- $\ddot{\theta}_T$ = Tower head side-to-side (in-plane) angular acceleration [rad/s^2]
- ϕ_T = Tower head fore-aft (out of plane) angle [rad]
- $\ddot{\phi}_T$ = Tower head fore-aft (out-of-plane) angular acceleration [rad/s^2]
- h = Hub height [m]

These equations for the generator speed augmentation were implemented into the Simulink model of the wind turbine and controller, to assess their impact on the turbine's performance.

2.5 Wind Case

It has been shown that in low wind speeds (above rated), the zeroes migrate from the left hand plane of a pole-zero map, to the right hand plane [10]. The instability of interest in this paper occurs due to the phase loss of these zeroes, and so, the wind case used for the analysis must be at a suitably low speed. Furthermore, it is of interest to model turbulence, but to avoid switching transients, where the controller switches to *below rated* operation. For the Supergen 5MW turbine, rated wind speed is 11.2 m/s. The wind case is generated for the Simulink model using an accompanying MATLAB script. A few combinations of mean wind speed and turbulence intensity were investigated to obtain sufficiently low wind speed, but keeping the wind speed above rated at all times. The selected combination was mean wind speed of 13 m/s and turbulence intensity of 5%.

2.6 Tower Frequencies

A range of cases were considered to determine the performance of this technique. The default tower frequency for the Supergen 5MW turbine was 1.7293 rad/s. The reduced tower frequency was selected as a quarter of this, 0.4323 rad/s.

2.7 Generator Speed Augmentation Equations

2.7.1 Short Form

$$\Delta\Omega_G = N.G(s)(J_R\dot{\Omega}_{zN}) \tag{3}$$

And:

$$G(s) = \frac{1}{I_1 s + (B - \frac{\partial M_{A\theta}}{\partial \Omega})} \tag{4}$$

Where:

- $\Delta\Omega_G$ = Augmentation to measured generator speed [rad/s]
- N = Gearbox ratio
- J_R = Rotor moment of inertia [kgm^2]
- I_1 = Hub moment of inertia [kgm^2]
- $\frac{\partial M_{A\theta}}{\partial \Omega}$ = Partial derivative of aerodynamic torque w.r.t. rotor speed [Nms/rad]
- s = Laplace complex variable (complex frequency)
- $\dot{\Omega}_{zN}$ = Nacelle in-plane angular acceleration [rad/s^2]
- B = Drive-train damping coefficient [Ns/m]

2.7.2 Medium Form

$$\Delta\Omega_G = -N.G(s)\left((J_R + I_1 + N^2 I_2)\dot{\Omega}_{zN}\right) \tag{5}$$

And:

$$G(s) = \frac{1}{(J_R + I_1 + N^2 I_2)s + (B - \frac{\partial M_{A\theta}}{\partial \Omega})} \tag{6}$$

Where the symbols have the meanings as above and:

- I_2 = Generator rotor moment of inertia [kgm^2]

2.7.3 Long Form

$$\Delta\Omega_G =$$

$$N.G(s)\left[\left\{(J_R + I_1 + N^2 I_2) + \left(\frac{\partial M_{A\theta}}{\partial \Omega}\bigg|_0 s\right)\right\}\dot{\Omega}_{zN} + \left\{\left(L\frac{\partial M_{A\theta}}{\partial V}\bigg|_0 s\right)\left(\frac{Ml}{J_R}\right)\right\}\ddot{z}_N\right] \tag{7}$$

$$G(s) = \frac{1}{(J_R + I_1 + N^2 I_2)\, s + (B - \frac{\partial M_{A\theta}}{\partial \Omega})} \tag{8}$$

The symbols have the following definitions:

- L = Effective blade length [m]
- $\frac{\partial M_{A\theta}}{\partial V}$ = Partial derivative of aerodynamic torque w.r.t. wind speed [Nms/m]
- M = Mass of three blades [kg]
- l = Distance between blade root and centre of mass [m]
- $\ddot{z}_N$ = Nacelle out-of-plane linear acceleration [m/s^2]

2.7.4 Array Form

The equations for the array form are given in the Appendix of this report. The derivation of the Array Form makes the fewest approximations of all the forms presented here. This accuracy is expected to yield the best improvement in performance.

3 Results

For the full figures of results see the Appendix of this report.

3.1 Un-augmented Controller

3.1.1 Default Tower Frequency

As expected for the default tower frequency, the un-augmented controller performs will with acceptable pitch actuation, nominal displacements and well controlled generator speed and electrical power output. This provided a useful benchmark for the rest of the analyses.

3.1.2 Reduced Tower Frequency

Reducing the tower frequency by a factor of four significantly increases the pitch activity and tower fore-aft displacement and velocity. The excursions on the generator speed are around 10%, and power oscillates around 10% over and 40% under the rated value.

3.2 Augmented Controller

3.2.1 Short Form

There is essentially no difference to the four parameters measured with the addition of the Short Form augmentation, which was not expected.

3.2.2 Medium Form

With the Medium Form, the Pitch angle is observed to have a serious error. Generator speed is arguably slightly improved from the un-augmented controller, however, this is not a conclusive success given the poor performance of the turbine overall.

3.2.3 Long Form

The Long Form also fails to implement discernible improvements, with similar performance to the Medium Form.

3.2.4 Array Form

The Array Form was observed to implement possible improvements to the generator speed relative to the un-augmented controller, but with negligible improvements observed in the other parameters.

3.2.5 Higher frequencies

The augmentation of the effect of fictitious forces performs poorly at higher frequencies (as would be expected) since the derivation of the fictitious forces is only valid for frequencies lower than the tower or blade frequencies [8].

3.3 Start-up transients

Some of the analyses experienced issues with start-up transients, which were remedied by using the final conditions from a previous analysis as the initial conditions for the next.

3.4 Stability

A sensitivity of the model to very low tower frequencies was undertaken in an attempt to replicate divergent fore-aft tower displacement (instability). Even at $0.1\omega_t$ divergent oscillations were not observed. This may be a limitation of the model (as stiffness is a function of frequency) or due to some other unknown feature.

4 Discussion

4.1 Limited Evidence of Improvement

None of the augmentations analysed yielded the expected improvements. This was unexpected, given the confidence in the method and the derivations. The reasons for this lack of improvement are considered below.

4.1.1 Partial Derivatives

All of the transfer functions and some of the augmentation equations feature partial derivatives. These were assumed to be constant, however, this is potentially incorrect for some, if not all, of the augmentation equations considered. The failure to implement the partial derivatives as varying parameters may be the reason that the expected performance improvements were not observed and should be investigated in further treatments of this approach.

4.1.2 Potential Solutions

It's possible that gain scheduling could be employed to implement partial derivatives which change with other system parameters. This would enable continued use of linear control techniques in the Simulink environment.

5 Conclusion

The main success of this piece of work is to present and discuss the technique of fictitious forces and record the main forms of the equations necessary to implement it. While none of the equations yielded notable improvements with respect to an unmodified controller, this was hypothesised to spring from an issue of implementation, rather than principle. This study presents a simple and methodical approach to investigating the potential improvements of the fictitious force method of independent nacelle control, and provides clear next steps for future investigators to follow - namely, implementation of partial derivatives which vary with system operation.

5.1 Further Work

It is recommended that future investigations focus on the Array Form of the equations as it is the form with the fewest approximations in its derivation, and should yield the best improvements in performance. In addition, implementing partial derivatives which vary with operation is recommended. It is possible that Gain Scheduling would resolve this issue while enabling continued use of linear controllers in Simulink. Lastly, the use of the Supergen 5MW model is useful for systematically investigating the effect of the augmentation, but ultimately the techniques presented here should be utilised in simulation environments with hydrodynamic modelling capability to test their performance more robustly, particularly for divergent fore-aft stability.

Acknowledgements

Grateful acknowledgement goes to Dr Luis Recalde and Professor Bill Leithead at the Wind Energy Control Centre at the University of Strathclyde for their help and guidance in this project.

References

[1] "Global Wind Report 2018," tech. rep., Global Wind Energy Council, 2019.

[2] S. Christiansen, T. Knudsen, and T. Bak, "Extended Onshore Control of a Floating Wind Turbine with Wave Disturbance Reduction," *Journal of Physics: Conference Series*, vol. 555, p. 012018, 12 2014.

[3] N. T. Burton, D. Jenkins, and E. B. Sharpe, *Wind Energy Handbook Wind Energy Handbook, Second Edition*. 2011.

[4] J. M. Jonkman, "Influence of Control on the Pitch Damping of a Floating Wind Turbine," tech. rep., 2008.

[5] B. Skaare, T. David Hanson, F. Gunnar Nielsen, R. Yttervik, A. Melchior Hansen, K. Thomsen, and T. Juul Larsen, "Integrated Dynamic Analysis of Floating Offshore Wind Turbines," tech. rep.

[6] T. J. Larsen and T. D. Hanson, "A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine," *Journal of Physics: Conference Series*, vol. 75, p. 012073, 7 2007.

[7] F. Savenije and J. Peeringa, "Control development for floating wind," *J. Phys.: Conf. Ser*, vol. 524, p. 12090, 2014.

[8] L. Recalde and W. Leithead, "Reduction of unwanted swings and motions in floating wind turbines,"

[9] V. Neilson, "Individual Blade Control for Fatigue Load Reduction of Large-scaled Wind Turbines: Theory and Modelling," no. March, pp. 40–54, 2010.

[10] L. Recalde, "Control principles for the design of wind turbine full envelope controllers Wind and Marine Energy Systems DTC," tech. rep.

A Appendix

A.1 Generator Speed Augmentation Equations - Array Form

The following figure is reproduced from notes provided by Prof. Bill Leithead and contains the equations for the Array Form augmentation for the measured generator speed.

Fictitious forces corrections for tower decoupling

The correction to measured rotor speed, $\Delta\Theta_H$, is found solving the following equations

$$\begin{bmatrix}\Delta\Omega_R\\ \Delta\Psi_R\end{bmatrix} \approx \int\left\{\Delta_M\begin{bmatrix}\Delta\Omega_R\\ \Delta\Psi_R\end{bmatrix} - A(\beta)]\begin{bmatrix}\Delta\theta_R\\ \Delta\phi_R\end{bmatrix} + A(\beta)\begin{bmatrix}1\\ 0\end{bmatrix}\Delta\theta_H + \begin{bmatrix}-\dot{\Omega}_{zN}\\ M\ell\ddot{z}_N / J_R\end{bmatrix}\right\}dt$$

$$\begin{bmatrix}\Delta\theta_R\\ \Delta\phi_R\end{bmatrix} = \int\begin{bmatrix}\Delta\Omega_R\\ \Delta\Psi_R\end{bmatrix}dt$$

$$\Delta\Theta_H \approx \int\left\{-J_H^{-1}B\Delta\Theta_H - \begin{bmatrix}-J_R J_H^{-1} & 0\end{bmatrix}A(\beta)\begin{bmatrix}-1\\ 0\end{bmatrix}\Delta\theta_H - \begin{bmatrix}-J_R J_H^{-1} & 0\end{bmatrix}A(\beta)\begin{bmatrix}\Delta\theta_R\\ \Delta\phi_R\end{bmatrix} - \dot{\Omega}_{zN}\right\}dt$$

$$\Delta\theta_H = \int\Delta\Theta_H dt$$

where

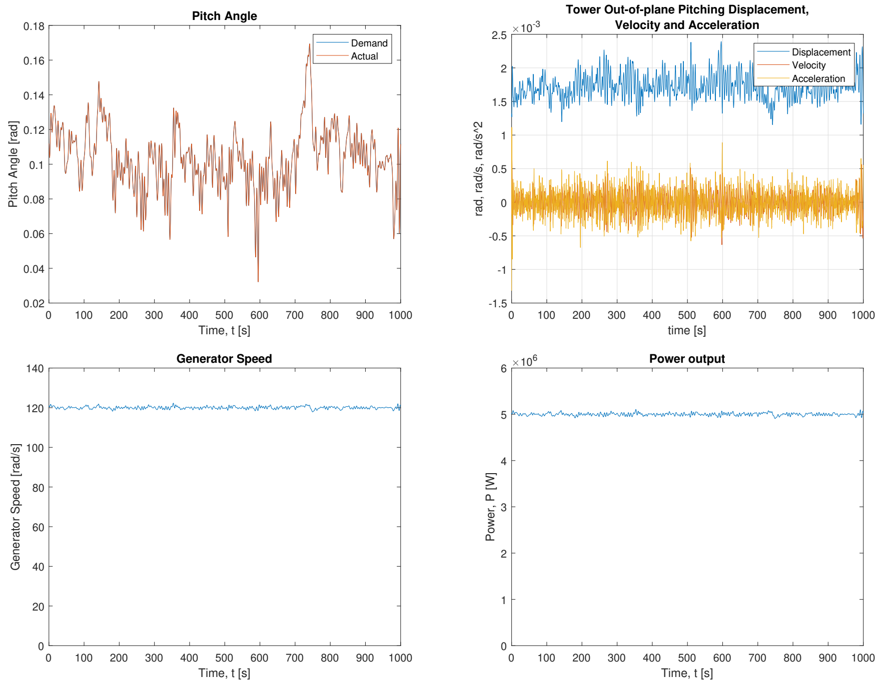
$$A(\beta) \approx \begin{bmatrix}(\omega_{es}^2\cos^2(\beta) + \omega_{fs}^2\sin^2(\beta)) & -(\omega_{es}^2 - \omega_{fs}^2)\sin(\beta)\cos(\beta)\\ -(\omega_{es}^2 - \omega_{fs}^2)\sin(\beta)\cos(\beta) & (\omega_{es}^2\sin^2(\beta) + \omega_{fs}^2\cos^2(\beta))\end{bmatrix}$$

$$\Delta_M = J_R^{-1}\begin{bmatrix}\frac{\partial M_{A\theta}}{\partial\Omega}\Big|_{\Omega=\Omega_R,\dot{\phi}_R=0} & -L\frac{\partial M_{A\theta}}{\partial V}\Big|_{\Omega=\Omega_R,\dot{\phi}_R=0}\\ \frac{\partial M_{A\phi}}{\partial\Omega}\Big|_{\Omega=\Omega_R,\dot{\phi}_R=0} & -L\frac{\partial M_{A\phi}}{\partial V}\Big|_{\Omega=\Omega_R,\dot{\phi}_R=0}\end{bmatrix}$$

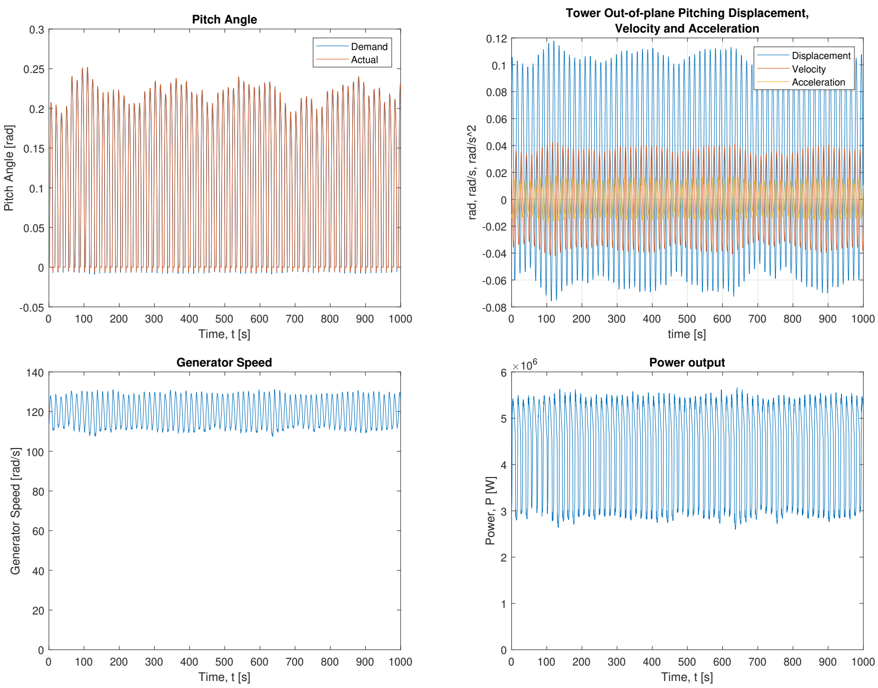
and Ω_R is rated rotor speed. Note, $\frac{\partial M_{A\theta}}{\partial\Omega}\Big|_{\Omega=\Omega_R,\dot{\phi}_R=0}$, $-L\frac{\partial M_{A\theta}}{\partial V}\Big|_{\Omega=\Omega_R,\dot{\phi}_R=0}$, $\frac{\partial M_{A\phi}}{\partial\Omega}\Big|_{\Omega=\Omega_R,\dot{\phi}_R=0}$ and $-L\frac{\partial M_{A\phi}}{\partial V}\Big|_{\Omega=\Omega_R,\dot{\phi}_R=0}$ are all functions of wind speed.

A.2 Results

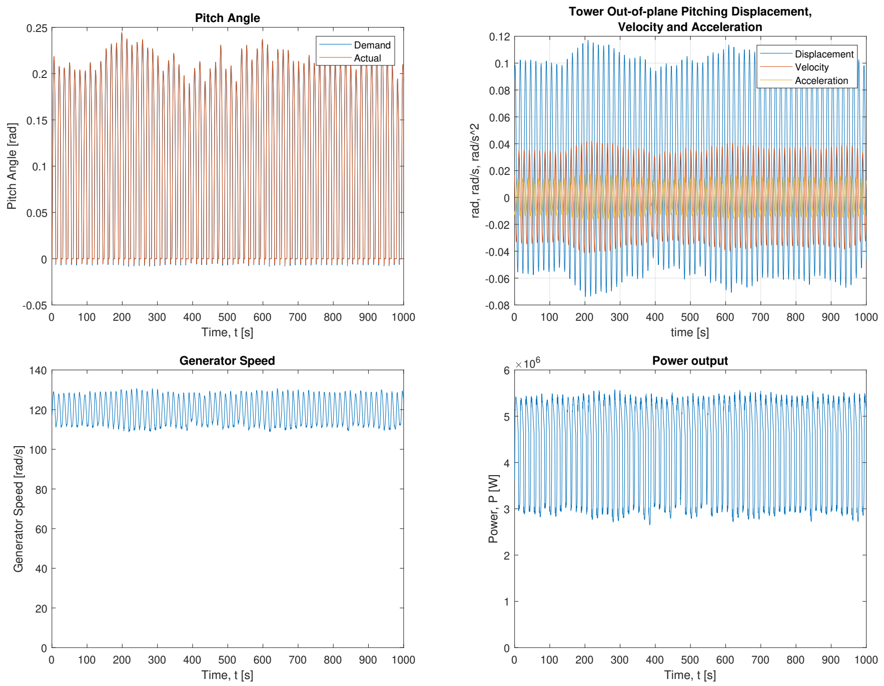
A.2.1 Default Tower Frequency, Un-augmented Controller



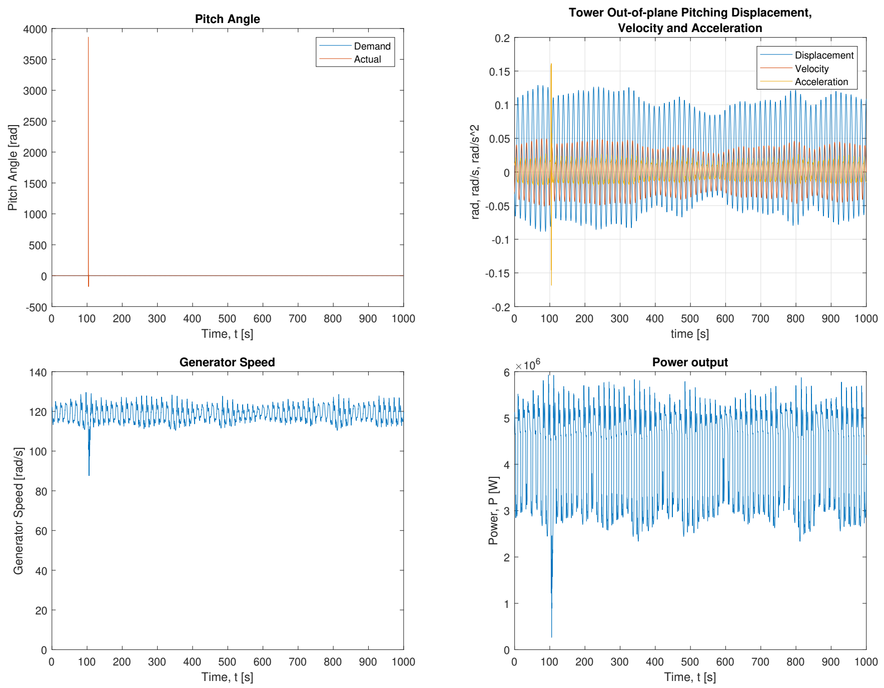
A.2.2 Reduced Tower Frequency, Un-augmented Controller



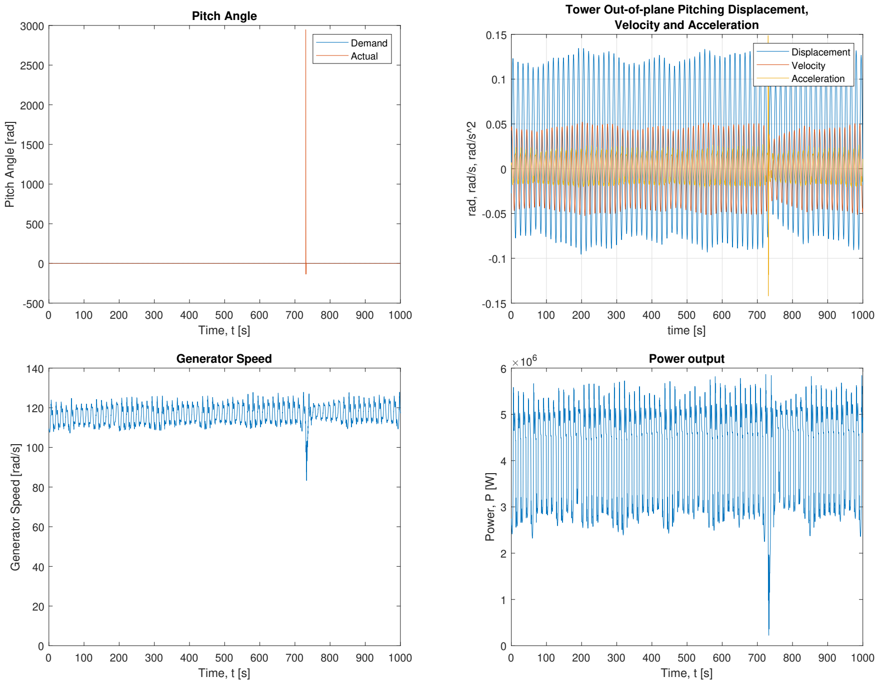
A.2.3 Augmented Controller - Short Form



A.2.4 Augmented Controller - Medium Form



A.2.5 Augmented Controller - Long Form



A.2.6 Augmented Controller - Array Form