FLOATECH

An advanced open source wind turbine controller for power generation and load mitigation using real-time feedforward wave information

FLOATECH
THE FUTURE OF FLOATING WIND TURBINES

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1   EXECUTIVE SUMMARY

The development of Floating Offshore Wind Turbines (FOWTs) has accelerated in the last years as offshore sites with high quality wind resources are often located in waters too deep for conventional fixed bottom offshore wind turbines. FOWTs are affected by external environmental disturbances that disrupt their operation. The two most abundant disturbances for FOWT can be allocated to the influence of the intrisic turblence in the wind and the excitation caused by waves. As wind turbines still mostly are placed onshore and operate without the influence of waves, wind disturbances have been well investigated in the past [10, 7]. A common technology is wind disturbance rejection using LiDAR measurements to mitigate the influence caused by the wind. Wave disturbances, on the other hand, are far less researched and understood. With the exposure of FOWTs to wave excitation, an increased understanding and subsequently mitigation of wave disturbances is necessary in order to advance the technology.

The idea of avoiding the wave disturbances basically depends on the possibility to predict the loads caused by the incoming waves through the determination of their elevation. Having predicted the incoming waves, the gathered information can be provided to a controller that makes use of this input in order to be able to take a proper control action before the waves hit the FOWT. Consequently, the wave disturbance effects are avoided.

Accordingly, this deliverable describes the development of a new wave feedforward controller for FOWTs with the objective of avoiding wave disturbances on the FOWTs. Furthermore, this deliverable serves as a handbook to compile the controller as a Dynamic Link Library (DLL) on Windows, or a Shared Object (SO) on Linux, that are compatible with state-of-the-art aero-hydro-servo-elastic simulation suites as OpenFAST, HAWC2, or QBlade.

2   INTRODUCTION

The objective of this task is to define the specifications for the implementation of a feedforward (FF) wave-based control system. These specifications reflect both on existing subsystems of the floating wind turbine and on the proper integration of the tailored wave prediction chain fitted to the task of feed forward wave-based control. Each component of the feedforward (FF) wave-based control system will be evaluated to meet the requirements of a robust and operational control system. Both numerical and experimental set up of the FF wave-based controlled FWT will be defined through this task. The numerical and experimental systems include notably the following components:

- the wave remote sensing technique;

- the wave reconstruction, assimilation and propagation algorithm;

- a model capturing the response of the FWT to the induced hydrodynamic loads;

- an advanced wind turbine control algorithm for power generation and load mitigation .

The chain of numerical subsystems will be integrated into QBlade-Ocean for refinements, testing and exploitation. The chain of experimental subsystems will be tailored to the needs of the experimental validation.

The controller can be accessed via the Data-Driven Control Github repository under this link

https://github.com/TUDelft-DataDrivenControl/WaveFFControl

It is important to mention that the controller is under continuous development.

3   THE CONTROLLER

This report describes the development of a new wave feedforward controller for floating offshore wind turbines (FOWTs) with the objective of mitigating wave disturbance effects on the FOWTs. It builds up on Delft Research Controller (DRC) [6], where the wave feedforward control functionality has been added. It has been adapted to the NREL 5 MW Reference Wind Turbine (RWT) [4] atop the OC3 Spar floating platform [3]. However, it is built in such a way that it can accommodate different turbines and platforms.

In the first section, the model-based controller will be introduced, then, the compiling process of the controller will be discussed so that it can be integrated with any FOWT simulation tool as Open-FAST [8], HAWC2 [2], or QBlade [9].

3.1   Implementation

The feedforward controller block, shown in Figure 1, is model-based, which means that it requires a mathematical model that can be linearized to obtain the mappings from the inputs to the outputs of the FOWT, especially the wave disturbances. It is already known that waves are not the sole source of disturbance on a FOWT, but also there is wind turbulence, which has its own well-established feedforward control algorithm known as LiDAR feedforward [10, 7]. However, this work focuses on wave disturbance mitigation via feedforward control.
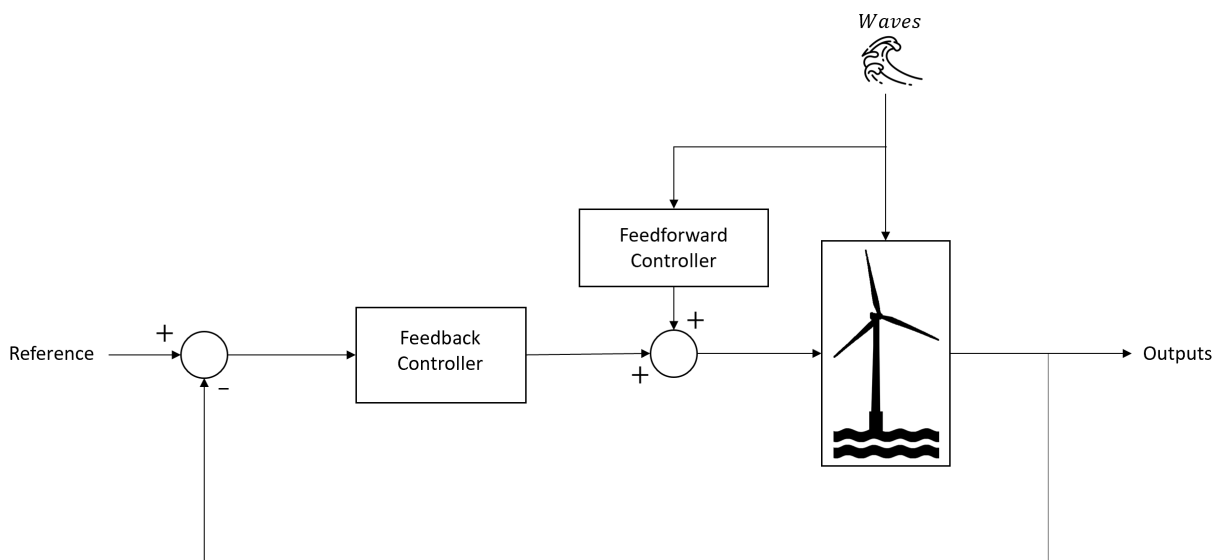

Figure 1. Block diagram of the general controller logic in the provided FOWT controller.

To obtain the different transfer functions of the system, a non-linear reduced order model (ROM) was derived based on first principles applying the Newton-Euler formulation. The model set-up for this work has four degrees of freedom (DOFs) with the generalized coordinates comprising platform surge x_p, platform pitch, θ_p, the tower top displacement, x_t, in platform coordinates, and the rotor speed, φ_r, collected in q as

$$q = \begin{bmatrix} x_p \\ \theta_p \\ x_t \\ \varphi_r \end{bmatrix} \tag{3.1}$$

Afterwards, Newton's second law for translational motion is written for each body as well as Euler's law for rotational motion, and transformed with the corresponding rotation matrices to the inertial reference frame to arrive at the non-linear equations of motion. The ROM was, consequently, validated against OpenFAST [8].

Subsequently, a linear model was developed from the ROM non-linear equations of motion, and linearized at different operating points across the wind speed spectrum of the power curve of the NREL 5 MW RWT in a state-space format, for the design of the controller, can be derived as

$$\dot{x}(t) = \frac{\mathrm{d}x}{\mathrm{d}t} = \begin{bmatrix} \dot{q} \\ \ddot{q} \end{bmatrix} = Ax(t) + Bu(t) \tag{3.2}$$
$$y(t) = Cx(t) + Du(t)$$

At this point, the feedforward controller in Figure 1, can be designed according to the following equation

$$K_{ff} = -\gamma G_d G_p^{-1} \tag{3.3}$$

where γ is a scalar gain to modify the intensity of the control signal counteracting the wave disturbances. Should $\gamma = 1$, then the feedforward controller, K_{ff}, is optimal. G_d is the mapping from the wave disturbance to the output of interest, and G_p is the mapping from the control input to the output of interest.

It is fair to mention that according to Equation (3.1), the feedforward controller only mitigates wave disturbance effects in the fore-aft direction of the FOWT. As that mode was the one considered as-

suming that waves and wind are uni-directional to consider the worst case scenario. However, other platform DOFs can indeed be considered following the same approach in Equation (3.3).

3.2   Compiling the controller

The controller was built in Matlab/Simulink [5] as shown in Figure 2, which provides the opportunity to compile the controller as a Dynamic Link Library (DLL) on Windows Operating System (OC), or as a Shared Object (SO) on Linux OS.
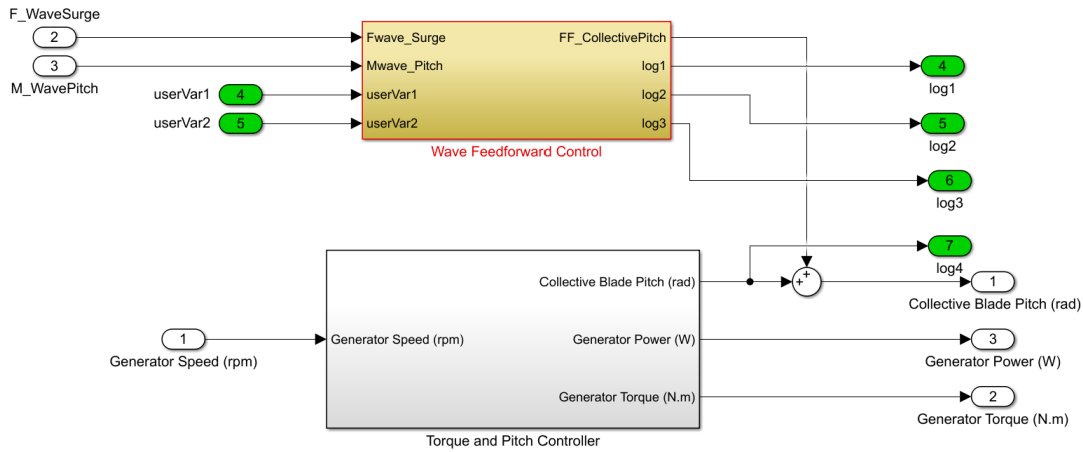

Figure 2. Controller blocks in Simulink

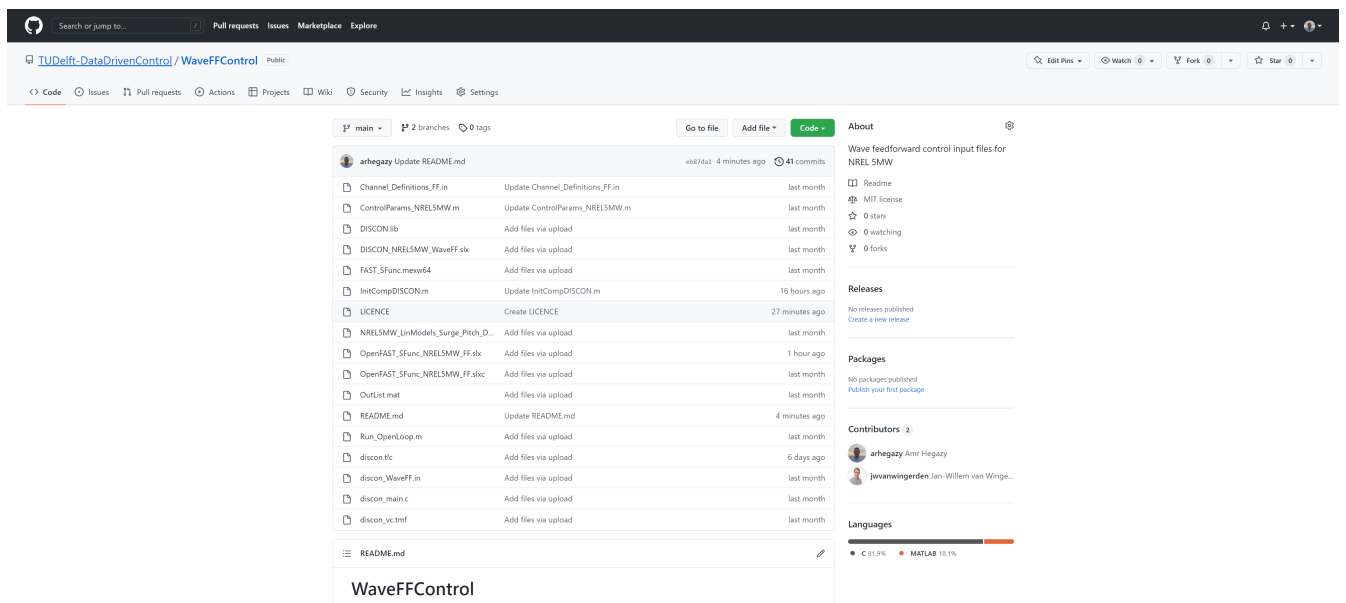The files needed for compiling can be accessed through the TU Delft Data-Driven Control Github repository [1].

Figure 3. Github repository [1]

In the repository, shown in Figure 3, the user is supposed to run the script named **'InitCompDIS-CON.m'** only, which also contains explanation in the form of comments (the green text in Figure 4). The main part that user should work with is basically the first few lines shown in Figure 4.

As for the **TimeStep**, it should be set equal to the time step of the aero-servo-hydro-elastic code being used. Regarding the **Turbine** variable, this controller is for the NREL 5 MW RWT [4] atop the OC3 floating platform [3] for the time being. However, continuous development of the controller is going and other RWTs should be implemented soon. **TurbineType** variable has to do with the gains of the feedback controller whether they are the ones relevant to the onshore turbine, or the detuned ones corresponding to the offshore one. **GenerateDLL** is a flag that should be set according to the wishes of the user whether they need to compile a *.dll or an *.so file for the controller, or going to be used with the S-Function from OpenFAST, where a Simulink file of an OpenFAST simulation setup is also provided under the name **'OpenFAST_SFunc_NREL5MW_FF.slx'**. Lastly, **Kff_gain** corresponds to γ in Equation (3.3).

```
clear; close all; clc
% A script used to initialize the controller before compiling, then compile it to get
% a *.dll, or *.so file when run on a Windows or Linux machine, respectively.

% This script must be run before starting the compilation or the simulation.
% For compilation purposes, this script should be run separately.

%% User input parameters
% General inputs
TimeStep        =  0.05;        % Simulation time step (s)
Turbine         = 'NREL5MW';    % Turbines: NREL5MW, DTU10MW, IEA10MW, IEA15MW
TurbineType     = 'Offshore';   % Turbine foundation type ['Offshore' or 'Onshore'].
GenerateDLL     = true;         % A switch for DLL Generation

% FF controller
Kff_gain        = 0.3;          % A static gain to manipulate the intensity of the FF controller
```

Figure 4. Modifiable lines

Another important input file is **'discon_WaveFF.in'** which contains static gains in case the user wishes to modify the feedforward controller gains dynamically during the simulation. In that case, it would be easier to set **Kff_gain** to 1, and modify the gains directly from **'discon_WaveFF.in'** file.

4   CONTROLLER ACCESSIBILITY AND REFERENCING

The controller can be accessed through the TU Delft's Data-Driven Control Group Github repository [1].

In the event of publication of work resulting from the use of the controller, proper referencing to [1] and the present report should be included.

5   CONCLUSIONS

In this report the wave feedforward controller was introduced for the NREL 5 MW RWT [4] atop the OC3 floating platform [3]. Furthermore, it was described how it was implemented with respect to the the degrees of freedom included in the model used to design the controller.

Moreover, a guide to compile the controller, as a DLL or an SO, is given. The guide furthermore focuses on the files required to successfully run the controller and on the adaptation possibilities the user has to make modifications in accordance to their requirements. As the controller is disseminated via a GitHub repository, a link to the repository is provided in section 2.

Lastly, the repository contains a case using S Functions from OpenFAST ready for use.

It is important to mention that the controller is under continuous development.

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