

# DEVELOPMENT OF AN AUTOMATICALLY TUNED DRIVE TRAIN DAMPER FOR VARIABLE SPEED WIND TURBINES

Athanasios Mathiopoulos<sup>1</sup>, Simon Watson<sup>2</sup>,

<sup>1</sup>Centre for Renewable Energy Systems Technology (CREST), Department of Electronic and Electrical Engineering, Loughborough University, Loughborough, LE11 3TU, UK, Tel: +44 1509 222421, Fax: +44 1509 610031, email: thanos.mathiopoulos@gmail.com

<sup>2</sup>Centre for Renewable Energy Systems Technology (CREST), Department of Electronic and Electrical Engineering, Loughborough University, Loughborough, LE11 3TU, UK, Tel: +44 1509 222421, Fax: +44 1509 610031, email: s.j.watson@lboro.ac.uk

**Abstract:** The drive-train of a modern wind turbine is probably one of the most unreliable mechanical systems of a modern utility scale wind turbine. Damping the drive train by controlling the torque of the generator is almost universally used for reducing the fatigue loading to the drive train components in variable speed wind turbines. A particular implementation of such a drive train damper has been developed. The novelty of this damper is that it can automatically and autonomously self tune by a standard controller of a wind turbine. The results have shown that this methodology does produce dampers that achieve better results when compared to the results achieved by using manually tuned dampers.

## 1 Introduction

The drive-train of a modern wind turbine is probably one of the most unreliable mechanical systems on a modern utility scale wind turbine. For variable speed wind turbines, where the drive train of the wind turbine is not sufficiently damped by the generator, a means of adding damping is necessary in order to reduce the fatigue loading on the drive train components. Usually this is done by means of controlling the torque of the generator in a way that increases the damping of the drive train.

The way in which a controller is changing the torque of the generator to damp the driver is usually defined by an engineer who, using a model of the wind turbine, can tune the drive train damper (DTD). The most commonly used DTD type is a filter applied to the generator torque demand that, in effect, adds a small ripple in the torque demand at the drive train frequency and at such a phase that counteracts the effects of resonance [1].

Thus the amount of damping depends, amongst others, on the quality of the model of the wind turbine used and the expertise of the control system engineer. This paper presents a methodology of automatically tuning a drive train damper. The parameters of this damper are not tuned based on a mathematically derived model representation of the wind turbine and the subsequent manual tuning of the damper by an engineer.

The automatically tuned drive train damper methodology developed uses a system identification technique to identify a system representing the real wind turbine drive-train and then, using this system, automatically tunes the parameters of a band-pass filter that is used for damping the drive-train loads.

## 2 The methodology

The automatically tuned drive train damper methodology can be divided in 4 stages. These stages are shown visually in Figure 1.

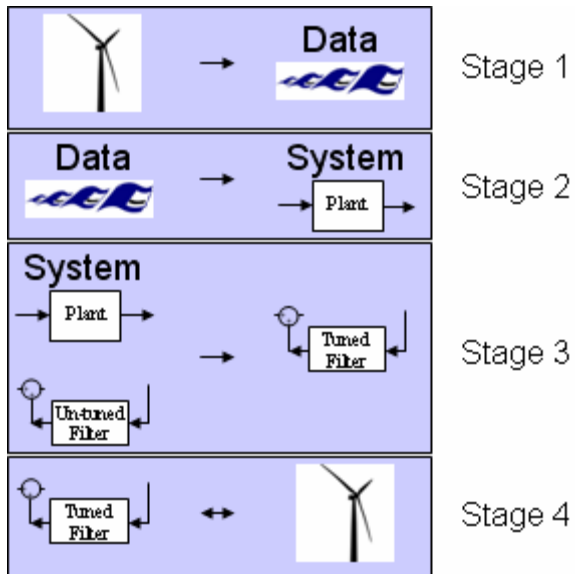


Figure 1: The stages of the automatically tuned drive train damper methodology.

## 2.1 Stage 1

The controller of the turbine first runs a number of experiments in order to collect the necessary data used in the next stage. The experiments should be run at wind speeds above cut in and below rated wind speeds. In this wind region the turbine can run without the use of a drive train damper with no adverse effects on loading, since the changing torque-speed relationship naturally used in controlling a VSWT (Variable Speed Wind Turbine) at this operating region acts as a damper. The optimal wind speed was found to be close to 6 m/s 10-minute mean at the hub height.

For the duration of every experiment the controller of the WT demands a predefined generator torque that was specifically created in order to excite the coupled drive train frequencies, and thus collect the information needed for the next stage. This predefined torque changes temporally either following a chirp signal or a PRBS (Pseudo Random Binary Signal). The data collected using the PRBS have been generally found to provide more consistent results (and has been used successfully in the past by other researchers for identifying the dynamics of the drive train of WTs [2 3]), but in some cases the chirp signal based experimental procedure has shown better results. So, it is suggested that both experimental procedures should be run.

Both procedures have been optimised in a way that both allow for the collection of useful data, but also do not add to the fatigue loading of the WT.

An example of the gearbox torque loads during a ten minute chirp signal based experimental procedure, and a ten minute run at a normal power production state for the same turbine is shown in figure 2.

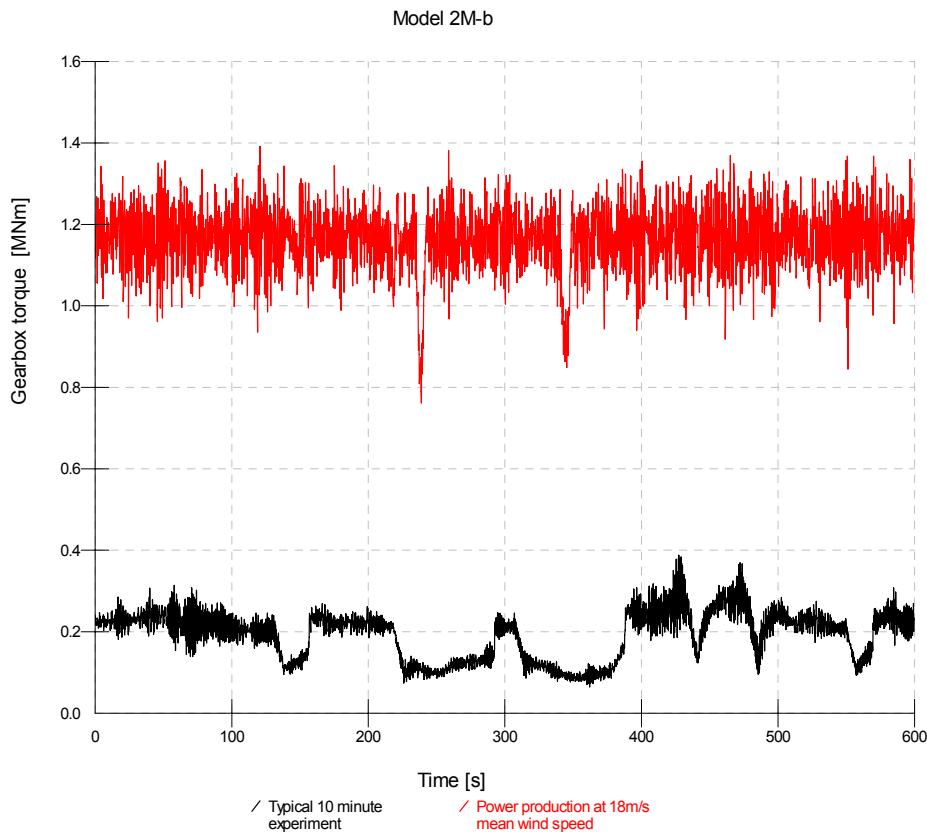


Figure 2: Gearbox torque comparison.

The gearbox and other loads on the wind turbine during the PRBS signal based experiment are even lower than the ones produced under the chirp signal based experimental.

## 2.2 Stage 2

Stage 2 is the "linearization procedure". In this stage a fully automatic system identification procedure is run to identify a linear system representing the real turbine (one linear system is created per experiment run). A state-space linearized model describing the "Generator torque" - "Generator speed" relationship is created using the experimental data collected from stage 1. In order to create this model Matlab's system identification toolkit is used.

The inputs for the system linearization are the generator speed and a signal based on the rotor azimuth. The output signal for the system linearization is the generator torque. The state-space model used for the linearization was selected after testing a number of model structures (including the ARX, ARMAX, output-error, Box-Jenkins models and a spectral analysis model) using various estimation methods (more on such modes and estimation methods can be found in [4]). The estimation method that was finally used was a particular numerical algorithm of Matlab's Subspace State Space System Identification algorithms. This type of system identification is fully automatic and has shown good consistency among all tested WT models (10 WT models were used, ranging from a relatively stiff 750kW VSWT to a relatively flexible 3MW VSWT). The result is a state space system representing the "Generator torque" - "Generator speed" relationship.

As an example of such an identified system's bode plot is shown in Figure below:

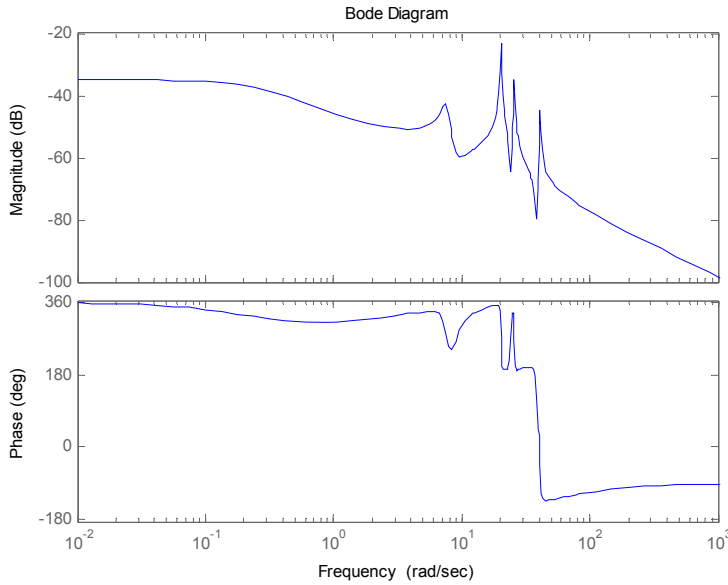


Figure 3. Example of an identified system.

### 2.3 Stage 3

In this stage the linear system, identified in stage 2, is used in order to find the appropriate constants for the DTD. As previously mentioned, the DTD is a band-pass filter. The form of this filter is presented in Equation 1:

$$G \frac{2\zeta\omega s}{s^2 + 2\zeta\omega s + \omega^2} \quad \text{Eq. 1}$$

Where:  $G$  = gain,  $\zeta$  = damping and  $\omega$  = frequency.

In order to find the appropriate constants for the DTD a MATLAB script creates a closed loop system, with the plant being the linearized model from stage 2 and the compensator being the DTD of the form presented in Equation 1. Many combinations of  $\zeta$ ,  $\omega$  and  $G$  (the boundaries of which are dynamically set using the identified system parameters) are tried out and using a cost function approach, the best combination is selected. The cost function used assigns a high cost to closed system poles with low damping and inversely low cost to well damped poles.

### 2.4 Stage 4

After stages one to three have run for several times, a number of DTDs have been tuned. Selecting the best one is done in stage 4. In this stage the DTDs are introduced for short periods of time on the controlling loop of the WT when the WT is operating at an above rated wind speed.

Initially the authors tried to find a way to assess the quality of each DTD using commonly available signals. Good comparison between the effectiveness of the various DTDs could be made using a combination of the standard deviation of a high pass filtered generator speed signal with the standard deviation of the generator torque signal.

Unfortunately, this methodology was not reliable (i.e. in some cases one would select an inferior DTD when using this comparison methodology). Since it is very important to use the best

available DTD in the final implementation of stage 4, a gearbox torque signal needs to be used for the comparison of the effectiveness of the DTDs. As such a signal does not have to be calibrated, the use of a simple un-calibrated strain gage on the gearbox should be sufficient for the purposes of selecting the best DTD.

Using each of the DTDs tuned in Stage 3, the wind turbine is allowed to normally operate in the above rated region for a short period of time. The standard deviation of the gearbox torque signal recorded in this period with each DTD is compared. As the DTDs that result to the lowest standard deviation of the gearbox torque signal are the DTDs that perform better, a selection of a small subset of well performing DTDs is done first using such short experiments. Then using this limited subset, longer experiments are run and the DEL of the gearbox at an appropriate SN slope is used to make the final selection of the best DTD.

### 3 Results

The main reason behind developing an automatically tuned DTD was to create a damper that would be suitable to a wind turbine regardless of (a) how well the model of the turbine in the design phase resembles the real turbine manufactured (for example the final drive train component selection by different suppliers sometimes leads to different inertias in the drive train and thus different dynamics of the drive train), and (b) the quality and accuracy of the software used to simulate the turbine.

An added advantage of the automatically tuned DTD was found during this research. Because during the experiments (stage 1 of the automatic tuning procedure) the drive train is naturally excited at 3P (in a larger or smaller extent), the DTD later developed is also trying to damp the 3P excitation to the drive train.

As a result the automatically tuned dampers show a reduction in loading of the drive train, even when the model of the wind turbine (used to manually tune the DTD) is exactly the same as the real wind turbine (for the purposes of this research, the real wind turbine is a simulated turbine in GH Bladed). The following table (Table 1) shows the lifetime weighted Damage Equivalent Load (DEL) of the gearbox torque, achieved by a manually tuned and an automatically tuned damper (both are based on single band pass filters). The ten columns represent ten models used for validation of the DTD performance (including two 750kW, four 2MW and four 3MW wind turbine models)

Lifetime weighted DEL in kNm [inverse SN slope: 3, IEC IA conditions]										
	750k-a	750k-b	2M-a	2M-b	2M-c	2M-d	3M-a	3M-b	3M-c	3M-d
Manually tuned	41	44	218	198	197	187	316	293	290	296
Automatically tuned	39	43	207	191	191	183	315	295	291	297
Load Reduction	3%	2%	5%	4%	3%	3%	0%	-1%	0%	0%

Table 2: Load reductions achieved by using the automatic tuning procedure.

Obviously, when the wind turbine characteristics deviate from those of the model used for the DTD tuning, the results will be even more favourable.

After running a large number of experiments a statistical analysis of the results was performed in order to quantify the number of experiments (stage 1) needed to produce a good quality DTD. A good quality DTD is defined as the DTD that increases damage at most 1% more than the best DTD that could be tuned by an infinite number of experiments. It was found that in order to be 99% certain that a good quality DTD a total of 60 experiments must be run.

## 4 Other Methodologies

Other ways to control the generator torque in a way that would damp the drive train and thus alleviate fatigue loads on the drive train were investigated as part of this research: An automatically tuned cascade of band pass filters, two Neural Network based controllers, and a PI control based controller. Unfortunately none of these could be made to work effectively.

One methodology that was investigated and did produce some positive results was one based on noise cancellation techniques. In this methodology one neural network is used to correlate the generator acceleration to the gearbox torque, and another neural network is used to predict the gearbox torque at the next time step. The first neural network is adjusted once and requires two time series: one of the generator speed (which is differentiated to get acceleration) and one of the gearbox torque. Since this neural network is only adjusted once and only the relative torque is needed, a carefully placed but otherwise simple and un-calibrated strain gauge can be installed on the gearbox and can be used to provide the generator torque signal. The second neural network, i.e. the one predicting the generator torque at the next time step, is initially trained and subsequently constantly reconfigured online in order to be able to make good predictions. Having a prediction of the gearbox torque for the next time step an additional torque is demanded from the generator in order to provide damping to the drive train.

For both the neural network that relates the generation speed to the gearbox torque (named 'Alpha2GBQ') and the neural network that predicts the generator torque at the next 50 ms time-step (named 'Predictor') a single layer ADALINE (Adaptive Linear Neuron) network is used. More specifically this ADALINE is constructed by a tapped delay line and a single linear neuron. Data for training the 'Alpha2GBQ' neural network and the initial training of 'Predictor' neural network is gathered under 3 minutes of normal operation of the WT above rated. For the 'Alpha2GBQ' neural network the tapped delay line shows optimum performance when 15 delays and 4 passes of the data are used (more delays and passes would only add to the computing time, with no apparent increase in the performance). For the 'Predictor' neural network the tapped delay line shows optimum performance when 13 delays and 3 passes of the data are used for the initial training. During the normal operation, at every time step the 'Predictor' neural network is both used to predict the generator torque at the next 50 ms time-step and is adapted (trained) using the current time-step data.

Using this predictive damping technique in synergy with the normal band pass filter showed an improved performance in comparison to the stand-alone normal band pass filter. However, this approach is based on the differentiation of a measured signal (the generator acceleration signal is a differentiation of the readily available generator speed signal), something that leads to the increase of noise in the data. As this research is based on simulations and not actual measured data, and the testing of this algorithm with a real turbine is out of the scope of this research, it was decided that this methodology would not be pursued any further, as the results of the analysis would be meaningless without the inclusion of the (most likely considerable) effects of noise on the effectiveness of this damping method.

## 5 Conclusions and Further Work

This research has shown that by using an un-calibrated strain gauge, and software programmed in the controller of any variable speed wind turbine (based on the presented methodology) one can run a fully automated procedure that can help optimise the DTD and thus reduce loads on the Gearbox and increase its lifetime.

More detailed research on the noise cancellation method briefly presented in the 4<sup>th</sup> section above can be performed, as a) this methodology seems to be reducing drive train loads in excess to a well tuned simple DTD, b) can be used in synergy with the manufacturers DTD, and c) does not rely on a special experimental procedure (which some WT owners would be reluctant to use).

Finally, both the main methodology and the noise cancellation techniques can be tested on a real turbine for validation purposes.

## **6 Acknowledgements**

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## **7 Reference**

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