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Go Forth Draft

Wind Turbine Blade Dynamics

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Abstract

In this paper we characterize the acceleration of an extruded aluminum wind turbine blade's tip as a second-order system with ω_n= 19 ± 1.7 Hz, and ζ = 39e-4 ± 1.2e-4. Besides the frequency uncertainty from an uncertain sample rate, the second-order model is the obvious choice, given, the tip's single vibrational mode and the linearity of its logarithmic decremennt. Having a simple model of blade dynamics is a step towards the ultimate goal of my Go Forth project: analyzing the forces on a blade both with and without control mechanisms for reducing forces on the blade.

Introduction

A wind turbine's goal is to make electricity as cheaply as possible, and for modern turbines this objective has led to larger and larger turbines each generation. Recently, a great deal of attention is being paid to offshore wind power, a realm with even more incentives for making bigger turbines. However, as turbines increase in size, current blade designs will be insufficient to handle large and irregular winds. Since mechanically stronger blades would increase the cost of energy production a great deal, there has been a good deal of research exploring alternatives, including actively 'pitching' blades (rotating them into/out of the wind) quickly enough that they can react to the wind. So far this research has focused on theoretical modeling of the blade[1]; this paper is part of a research project for a controller that uses machine learning methods to discover (without theoretical approximations) how best to reduce the blade's bending. In the initial stages of this project I have characterized the blades and derived some theoretical results; in tests still to come I will analyze the blade's loading at different wind speeds with and without the controller.

Beam Vibration, Fourier Transforms, and Second-Order Systems

Because the blades we are using are extruded aluminum, with a constant cross-section and no twist, their vibrational modes are quite simple and will be dominated by the first mode (when the whole blade bends in one direction). [2]

To find the frequency of the blade's vibration we apply a Fourier transform (or more specifically, an FFT on a subset of our data modified by a windowing function). A Fourier transform moves our data from the time domain (e.g. the order of notes played by a musical instrument) to the frequency domain (what notes were played). Any peaks in the Fourier transform correspond to a particularly common frequency (in our musical example, a note played more often). Each peak in the frequency domain of our signal will correspond to one of the blade's modes, allowing us to see how many of them are important to the blade's dynamics.

If there is only one peak in the frequency domain, we can model the system as a simple second order system, and describe it by Equation 1, where ω_n is the system's "natural frequency" (how it would vibrate in the absence of interference) and ζ (called the 'damping ratio') represents just how much interference there is.

$$H(s) = s^2 + 2\omega_n \zeta s + \omega_n^2 \tag{1}$$

ω_d, the frequency that the damped system vibrates at (as shown by peaks in the Fourier transform) depends on both ω_n and ζ, as in Equation 2.

$$\omega_d = \omega_n \sqrt{1 - \zeta^2} \tag{2}$$

To fully parameterize the system, then, we need to find the damping ratio and confirm that it's accurately modeled by a constant. Because the damping ratio is a measure of how fast a system slows down, it can be determined by comparing the peak value of one oscillation (A_0) to that of the next, (A_1) as in Equation 3.[3] This is often called the logarithmic decrement.

$$\ln \frac{A_0}{A_1} = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}} \tag{3}$$

In summary, the recorded data will contain the two parameters that define a second-order system, as well as signs of whether or not a second-order system is a good way to model the blade.

Measuring Tip Acceleration

For this experiment, the root of the blade was rigidly clamped down in a way that let the tip move freely. A Bosch BMA180 digital accelerometer in the blade's tip transmitted acceleration data to a microcontroller, which then interpreted the data and sent it to a computer for storage. For this initial test data was sent as ASCII characters, a choice which required additional data processing and confused the sample rate. Future tests will send data in little-endian bytes with a checksum.

Once the blade was clamped, and the accelerometer set to the correct sensitivity via the microcontroller, the logging application was started and the blade set vibrating with a flick. A timed series of impulses was performed, determining the average sample rate to be 200 ± 18 Hz; then the data of a decaying vibration was collected. After some processing to remove corrupted data, 512 samples were selected for analysis.

Results and Discussion

Our data show that the blade tip can be excellently modeled by a second order system, with an observed ω_n= 19 ± 1.7 Hz, and ζ = 39e-4 ± 1.2e-4.

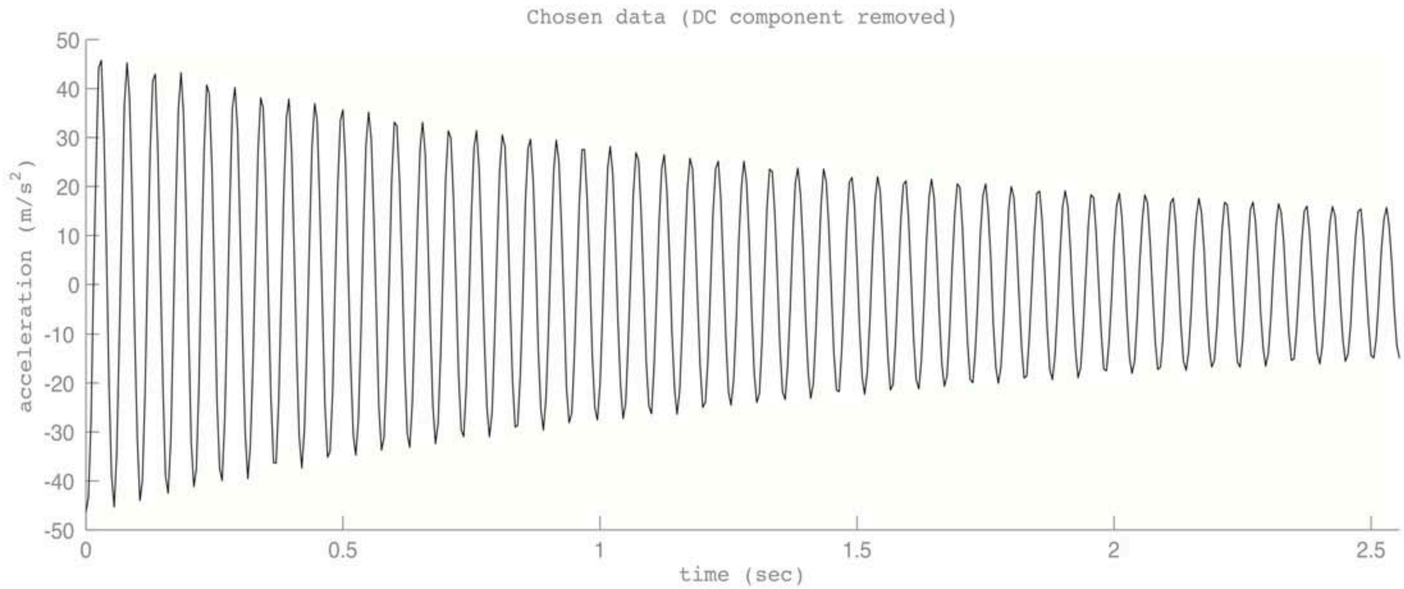

Figure 1 The samples selected for analysis. The simplicity of the sinusoid and its decay are clearly visible.

In the frequency domain, the data had a spike at 19 ± 1.7 Hz, as seen in Figure 2.

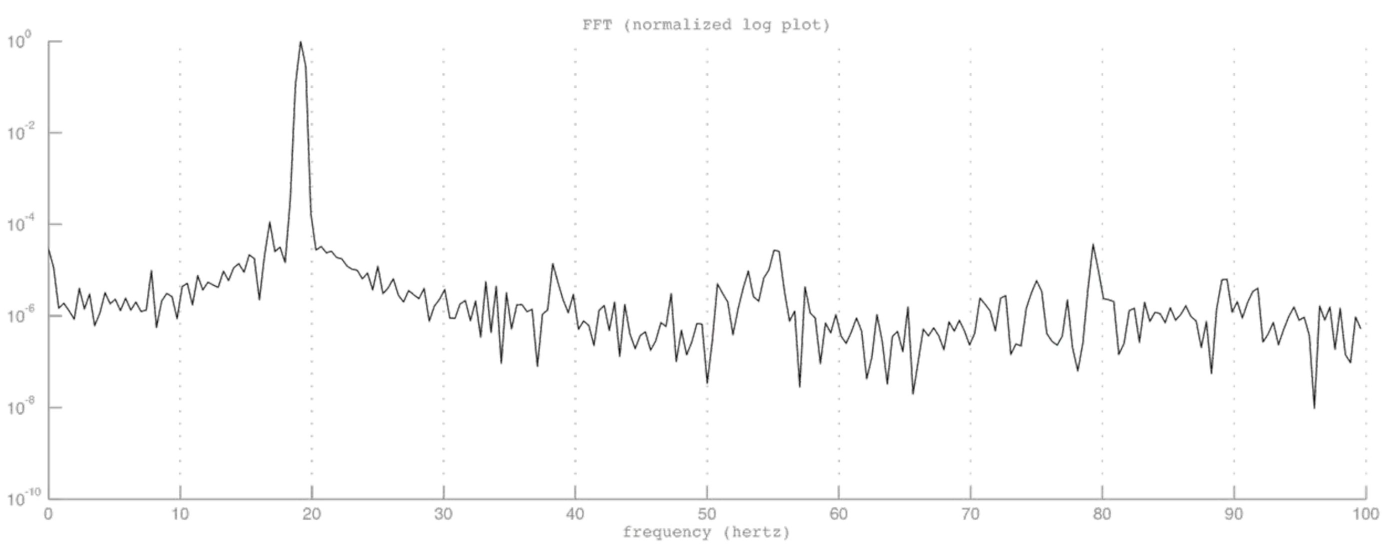

Figure 2 The frequency domain of the samples. The spike at 19 Hz is 4 orders of magnitude greater than any other frequency component; in general, the noise is six orders lower, implying that the amplitude of white noise in the time domain is three orders of magnitude lower than our signal.

Figure 2 also shows that the white noise of our measurement had a thousandth the magnitude of our signal. The uncertainty of the blade's natural frequency comes not from the Fourier transform (which leaves no room for uncertainty) but from the unknown sample frequency; when this is fixed results will be much more precise.

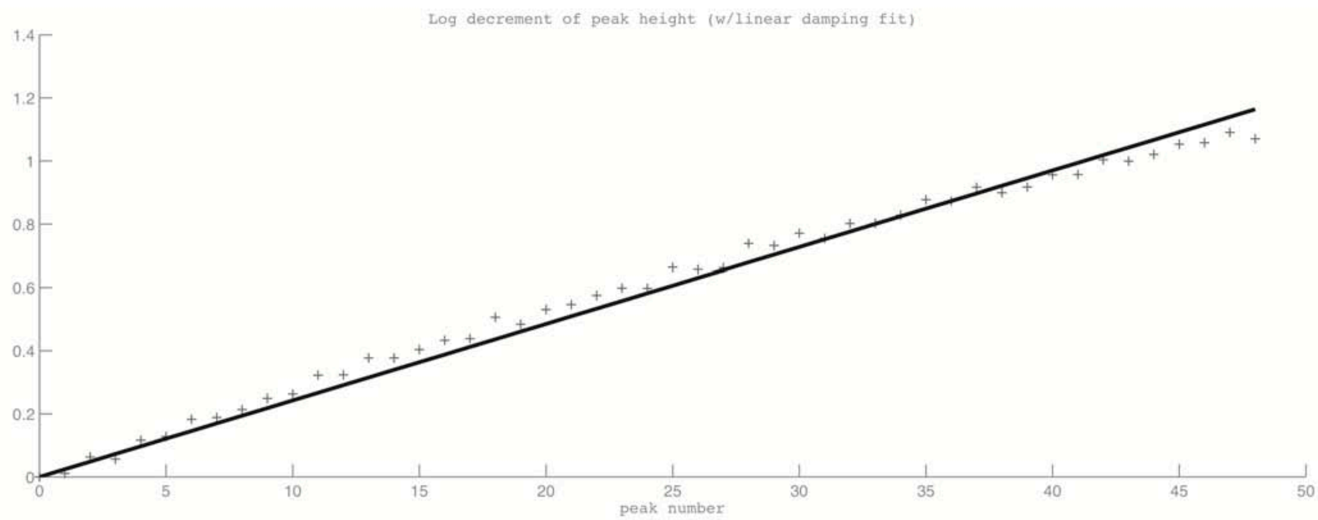

Figure 3 Fitting a line to the logarithmic decrement shows a clear fit, promoting a constant ζ.

The linearity of the signal's logarithmic decrement, indicates that a simple exponential decay (ie a constant damping ratio) will be a quite precise model; altogether, the data completely support the use of a second-order model for the wind turbine blade.

Conclusions

Overall, we have found that the blade's dynamics under low-magnitude impulses are well modeled by a second-order system with ω_n= 19 ± 1.7 Hz and ζ = 39e-4 ± 1.2e-4. The low uncertainty in ζ and the FFT confirm that a second-order model is an excellent fit, and the uncertainty in frequency comes from a programming mistake (transmitting data as ASCII without a checksum) which will soon be fixed.

The result of 19 Hz implies (by common approximations of turbine behavior) that gravity alone may resonate the blades at a wind speed of 5 m/s. In future experiment this will be a useful test to compare the relative effects of air turbulence and turbine rotation on the blade bending.

Acknowledgements

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References

1: Selvam et al. "Feedback–feedforward individual pitch control for wind turbine load reduction" (2008).

2: Whitney, Scott. "Vibrations of Cantilever Beams: Deflection, Frequency, and Research Uses." (1999).

3: Longoria, R. G. "DSC Lab: Logarithmic Decrement." (2008).