Average Blade Path and Variation Determination under Operating Conditions

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- Abstract -

A basic assumption of wind turbine design is that materials, manufacturing, and installation will realize symmetrical rotor blades that rotate on a single plane perpendicular to the rotors axis. Each blade should then bend to an equal degree more or less under the operational wind loads. Fabricator's manufacturing tolerances of flange perpendicularity and to the blade axis, aka. tracking, range from ± 0.15° to ± 0.2°with ± 0.14° deduced from 0.5% of the mean blade mass moment as maximum rotor imbalance. However, tolerances for variation under operational conditions are not as well defined and for reasons of technique, time, and cost not measured to the degree fabrication holds units to when matching sets together before shipment.

Repeated service and operation visual observations of wind turbine rotor eccentricities indicate in some cases one or two blades were rotating at some distance outside of the rotor plane during operation. The consistency with which a single blade or blades were closer to the turbine seemed to point up this proximity to the tower was not the random effect of wind turbulence, as if a single blade is circling on a plane parallel to the optimal rotor plane, displaced along the rotor axis. Application of averaging and deviation sampling techniques to video footage of operating turbines allows for this aerodynamic and balance impacting variation to be documented and quantified with a patent pending methodology.

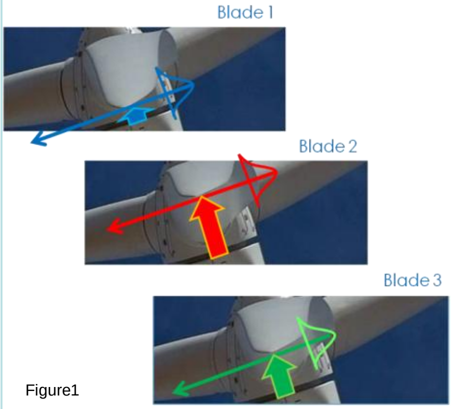

Figure1

- Objectives -

Stationary photo assay methodology currently offers the most often used comparative means to test for axial displacement of blade tip path. Three blade tip photos are shot from a single camera position pointing up from the base of the turbine and at the hub's axis using the rotor lock for positioning the target blade in the vertical down position. A disadvantage of this old method is manually rotating the drive train in near wind still conditions and subsequently activating the rotor lock in exactly the 0°, 120°, and 240° positions. At the same time, manpower needed to perform a single photo assay is typically 3-4 service personnel for weather dependent 4-8 hours. Most importantly, since measurements and comparisons are done with the rotor in a static state, alignment and behavior under load is not demonstrated or determined.

To address the deficiencies of stationary photography, using a video filming technique, a sequential capture of at least 72 high resolution still frames of the moving rotor is made. To understand the action of the blade tip and its relative position, we employ statistical analysis to the set of data generated by measuring the distance of the blade tip from the tower each time it passes the tower for a minimum of 24 revolutions. A running turbine is filmed at fixed position from the foot of the turbine requiring a single person at the unit for about five to ten minutes without interfering with the normal operation of the turbine.

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- Methods -

Turbine # 1.2.29			
	Blade		
Sequence	1	2	3
1	-25	-26	-5
2	-14	-14	-1
3	-17	-20	15
4	-8	-11	6
5	-17	-7	16
6	-12	-14	-3
7	-18	-15	8.5
8	-15	-9	8.5
9	-9	-9	9
10	-16	-14	2.5
11	-20	-22	-5
12	-24	-18	1.5
13	-18	-20	-5
14	-23	-20	0
15	-17	-17	11
16	-12	-7	15
17	-9	-7	8
18	-8	-1	23
19	0	2	19
20	-5	-3	17
21	-2	-1	15
22	-8	-6	18
23	3	11	28
24	-3	-2	14
25	-13	-1	18
Average	-12	-10	9.3
Std. Dev.	0.3	0.3	0.4

Table 1

A sequence of rotations is used to ascertain the average path (mean) and the normally distributed variation for each blade of the rotor. The results of the average path within the set and the variation of individual blade distances allow for an estimation of any moderate axial displacement of the individual blade's plane of rotation from the blade set's optimal plane of rotation. Sample size of this study was 34 turbines from three different locations. The turbines represent 1.5–2.0 MW class type and three different blade designs. Average wind speed as indicated from the turbines control system ranged from 6.6-12.6 m/s. A minimum of 24 rotations were filmed in a segment of just under two minutes. Although proprietary optical recognition software currently allows automatic sequencing, location, and coordinate identification in such a way that axial displacement calculation is plug and play, the methodology as used in the first trials is described here for the purposes of this presentation.

Deriving the average path is the first step. As the blade passes its lowest vertical point, its tip is measured relative to the distance from a fixed point along the rotor axis, here the leading edge of the nacelle cover (Figure 1 and Table 1). A value is determined for each blade every time the vertical position is passed. The average and standard deviation values for each of the blades are then calculated from these results.

The measurements taken from the still photos are in millimeters across the printed photos and need to be converted to the scale of the actual turbine. By using the blade length plus hub radius or rotor diameter displacement on the photos can be correlated. For the example photo measurement values, one millimeter is equal to 0.04 m and, given this particular 276.46 m circumference, a meter equals 0.77°. The difference in photo units from the two furthest average blade paths is calculated:

9.32 - (-12.32) = 21.64 photo units
21.64 * 0.04 m = 0.86 m
0.86 m * 0.77° = 1.14°

Here the average path of each of the blade tips is converted into the absolute difference in meters (Figure 2) and greatest distance is reported in degrees of axial displacement for the turbine. This displacement is not given as distance from the set's optimal plane, but as the difference between the two blades having rotational planes furthest apart.

The standard deviation indicates the tendency for the tip to be at or around the mean or average path (see bell shaped starting points in Fig. 1). An apt visualization for this is "flutter". Stationary photography does not pick this action at all and a fabrication unit's testing will only find a corresponding measure if they were to use some type of natural frequency or stiffness testing upon completion of each blade, assuming in part that the flutter effect is not due to a slight difference in blade pitch. The calculation of the flutter uses the standard deviation of each blade's path, dividing the largest by the smallest value and is reported as a percentile (Table 2). For want of an applicable guideline, ten percent is used here as an upper control limit and indicative of further investigation at design level.

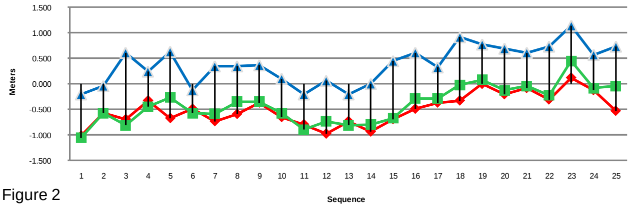

Figure 2

	Displacement		
Unit #	Degrees	Meters	Flutter
1.1.1	0.90	0.691	17.4%
1.1.2	0.27	0.207	6.2%
1.1.3	0.21	0.161	5.0%
1.1.4	0.45	0.346	12.9%
1.1.5	0.29	0.223	8.3%
1.1.6	0.48	0.369	10.0%
1.1.7	0.27	0.207	6.6%
1.1.9	0.33	0.253	17.4%
1.2.1	0.29	0.223	8.1%
1.2.6	0.20	0.154	5.0%
1.2.8	0.81	0.622	19.7%
1.2.9	0.06	0.046	18.8%
1.2.11	0.13	0.100	16.2%
1.2.12	0.51	0.392	17.9%
1.2.15	0.75	0.576	10.0%
1.2.16	0.33	0.253	10.0%
1.2.21	0.32	0.246	1.0%
1.2.22	0.17	0.131	15.0%
1.2.29	1.14	0.875	19.9%
1.2.30	0.38	0.292	7.5%
1.2.32	0.43	0.330	10.0%
1.2.33	0.40	0.307	3.1%
1.2.39	0.26	0.200	16.5%
1.2.42	0.78	0.601	15.0%
2.1.43	0.33	0.253	11.1%
2.1.42	0.61	0.468	19.0%
2.1.43	0.36	0.276	10.0%
2.1.47	0.03	0.023	9.0%
2.1.48	0.24	0.184	22.7%
2.1.49	0.22	0.169	5.8%
2.1.50	0.05	0.038	2.8%
2.1.51	0.05	0.038	2.8%
2.1.52	0.46	0.353	6.2%
Mean	0.38	0.29	0.11
StdDev	0.259	0.199	0.060

Table 2

- Results -

As indicated in Figure 1, the set of blades responds to changes in wind speed and turbulence as a whole. The methodology captures enough detail to determine average path and variation thereof. Almost 76% of the turbines have values in excess of 0.2° and it has been demonstrated that twenty percent of the turbines sampled indicated an axial displacement of greater than 0.5° or 38 cm (Table 2). Assuming normal distribution ten percent of the population shows a displacement of greater than 0.7° / 53 cm up to and including 1.4° or slightly more than one meter difference to the tower than its partner blades.

It is noted that flutter is greater than ten percent in over 40% of sampled turbines. This exceeds the assumed upper control limit. The distribution of values indicates a bi-modal condition with grouping occurring at 1-10% and another between 17-20% typically indicating two variables are at work.

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- Conclusions -

Through the use of this analysis a quantifiable axial displacement value under operational loads can be determined. Further turbine measurements and subsequent analysis will deepen our understanding of rotor eccentricities offering design and operations a valuable tool for optimization of the drive train, series fabrication, and individual units.

With average path displacement values, correlations to wind speed and axial vibration can be pursued for individual turbine tailored correction or cut-out speeds, as well as more exact determinations of cut-out speeds for series. This critical element of quantified aerodynamic imbalance can be done before costly dynamic weight balancing is attempted.

The appearance of and degree to which blades flutter must be subject to additional investigation. Both the large variation and the bi-model characteristic of its distribution point to potential repercussions to fatigue life and drive train wear in search of a root cause. Immediate possibilities of slight pitch variation, blade bearing, aerodynamic profile deviation, blade stiffness irregularities should be among the first investigated in light of these findings.

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