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Millville Wind Turbine Generator

Failure Analysis and Corrective Design Modification

July 1979

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prepared by
DOE Rocky Flats
Wind Systems Program

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ABSTRACT

Fatigue cracks in the blade skins of the Millville Wind Turbine Generator were fractographically analyzed. It is believed they were caused by large flapwise deflections during a wind storm on December 4, 1978. The deflections caused the skin to buckle, which initiated rapidly growing fatigue cracks. Propagation continued to the leading edge, moving radially inward and outward along the leading edge radius. Communication between Rockwell and Millville resulted in a modified blade design which incorporates several corrective techniques.

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INTRODUCTION

The Millville Model 10-3 IND is a commercially available small wind energy conversion system (SWECS). It was purchased by Rockwell to develop data on its performance and operational characteristics through testing. The testing will be complete when the system has experienced at least one wind storm with velocities of 85 miles per hour (mph) or greater and sufficient data has been collected in the operational range to develop a reliable power curve and obtain other information.

The Millville Wind Turbine Generator was installed December 3, 1978, atop a 40-foot (ft) Rohn SSV tower with a 12-ft tubular tower extension. The following day the machine experienced a severe wind storm with a peak velocity of 94 mph (42 meters per second (m/s)). The tail was in the furled position so that the rotor was oriented edgewise to the wind. A poststorm inspection revealed skin cracks in all three blades. No instrumentation had been connected, and thus no record of blade skin strain could be obtained. The subsequent analysis and interface with the manufacturer resulted in blade modifications using several corrective techniques.

This report covers the wind storm, the damage to the blade skins, fractographic analysis, details of a fatigue review conducted by Dr. David Hoepfner and the details of the resulting blade modifications incorporated by Millville.

MACHINE OVERVIEW

The Millville Wind Turbine Generator Model 10-3 IND is shown in Figure 1. It is an upwind, three-bladed, horizontal axis machine with a manufacturer's rated output of 10 kW at a wind speed of 11 m/s (25 mph). Power is generated by a 220 V ac, 3 phase, induction generator which is driven by the rotor through a 1:24 three-stage transmission. The blades are constructed of aluminum with a tubular main spar, cast ribs, and 0.030 inch (in.) thick 5052 H 34 skin. The ribs are clamped to the

Figure 1 - View of Millville WTG at Rocky Flats

main spar. The skin is riveted to the ribs and is folded and crimped to form the trailing edge.

The rotor revolutions per minute (rpm) are controlled initially by centrifugal loads produced by the blades. These loads operate the blade feathering mechanism as the rotor nears synchronous speed.

The blade feathering mechanism operates in the following manner. The main spars of each blade enter the hub through tubes whose ends are cut on a 45° slope. A collar, cut with a mating 45° slope, is attached to the end of the spar. A pitch arm extends from each collar and presses against a plate. This plate is preloaded by a spring located in a tube extending from the forward face of the hub. The point at which the blade centrifugal loads overcome the spring load and allow feathering can be adjusted by a screw. When the wind velocity drops, rotor rpm is reduced, and blade centrifugal loads drop below the preset point, the spring gradually returns the blades to the full run position. Figures 2 and 3 show the blade pitch control mechanism in the hub and the spring reaction adjustment screw.

Further rpm control is accomplished in the following manner. The rotor is offset, and in wind speeds above 20 m/s (45 mph), wind pressure on the blades begins to turn the rotor until it is angled out of the wind stream. At speeds above 27 m/s (60 mph), the tail is mechanically furled by a cable attached to the tail boom. This turns the rotor completely edgewise to the wind.

LOADING CONDITIONS

During the wind storm of December 4, 1978, the tail was mechanically furled, thus turning the rotor edgewise to the wind. In this configuration, the blades tend to orientate with one upwind and two downwind. Some occasional rotation takes place but usually not more than about 5 rpm.

Figure 2 - View of Rotating Caps for
Pitch Control for Feathering

Figure 3 - View of Screw Adjustment
for Blade Feathering

The wind storm reached a peak velocity of 42 m/s (94 mph) at 15:24:29. This was measured by an R. M. Young Anemometer, 450 ft northeast of the Millville test site. A 4-minute plot of wind velocity, 2 minutes on each side of the peak, is presented in Figure 4. Since the blade strain gages were not connected, no record of strain loading could be made. Also, machine orientation to wind direction was not obtained. Consequently, static stresses could not be calculated from wind data.

Simple engineering calculations to determine blade loading indicated maximum design stresses were being encountered when wind side gust orientations neared 45°. No estimate of dynamic loadings were made; however, an indication of their magnitude will be presented from the fractographic analysis.

FAILURE ANALYSIS

The routine poststorm inspection revealed skin cracks in all three blades. Figure 5 shows fatigue cracks on both surfaces and along the leading edge of Blade No. 2. Also visible in the figure is the patch covering a strain gage bending bridge. It was noted during the bending bridge calibration that the flat, upwind skin, was "oilcanning" as the design limit load was approached. This is the area where the blade cracking occurred. The strain readings were affected enough to require blade regaging at a location further inboard. This location was found to be less sensitive to the local buckling strains due to a solid aluminum rod insert in the inboard 4 ft of the main spar. This insert ends near the first gage, causing a stress riser.

Figure 6 shows an initial fatigue crack in Blade No. 1, away from the leading edge, in a buckled, oilcanning area. Also shown at the left are two cracks that have propagated in each surface and are joined by a crack along the leading edge.

Figure 4 - Plot of Wind Speed vs Time During Peak Wind of December 4, 1978 Storm

Figure 5 - View of typical skin crack that has propagated to the leading edge. (Note: Black patch which covers strain gage on Blade No. 2.)

Figure 6 - View of upper and lower surface cracks propagating to the leading edge at left; also, initial crack starting in skin, but not reaching to the leading edge on Blade No. 1.

Figure 7 shows Blade No. 3 severely buckled, with fatigue cracks splitting and following the buckling lines.

A visual inspection revealed a total of 5 cracks in Blade No. 1, and 1 each in Blades 2 and 3. The Figures 5 through 7 are typical of the cracks found.

The inboard skin panel from Blade No. 1, containing the 5 cracks, was removed and sent to Rockwell Physical Metallurgy for examination.⁽¹⁾ The crack studied formed in a buckled area 35 in. from the inboard edge and about 3 in. from the leading edge. This section of the blade skin is shown in Figure 8. The cracked area was then pulled open in a tensile test machine.

Samples from Areas C and D in Figure 8 were examined in the scanning electron microscope. The samples were similar, and their principal features are those shown in Figures 9 and 10.

Figure 9 shows the area near the tip of the crack in Area C. The ductile areas were caused by the tensile tester tearing the crack open. The other area is the surface of the fatigue crack showing striations perpendicular to the sheet surface and having a spacing of about 3×10^3 mm per striation.

Figure 10 shows an area of Sample C away from the crack tip. Here the striations are parallel to the surface of the sheet, indicating that they formed when the sheet was loaded in a bending mode about an axis parallel to the surface of the sheet. This mode of loading is a direct consequence of the presence of buckling. The geometrical configuration of the sheet in the vicinity of a buckle is such that the tensile loading that normally occurs in the skin becomes (as the blade deflects) a bending load at the crest and valley of the buckle. The spacing of the striations in this area was about 2×10^{-3} mm per striation.

Figure 7 - View of severely buckled and cracked skin on Blade No. 3

Figure 8 - Photograph of the crack studied in this investigation.
The leading edge of the blade is to the left,
and the tip of the blade is at the top.

Figure 9 - (a) Area "C" near the crack tip. Ductile failure at the left.
(100 X)

(b) Same area showing orientation of striations. Note the fine
striations between the arrows. (450 X)

Figure 9 - Higher magnification of Area "C" near the end of the fracture.

Spacing of the striations is approximately 3×10^{-3} mm/striation.
(1800 X)

Figure 10 - Scanning electron micrographs of Area "C" approximately 3/8-in. away from the crack tip.

- (a) An overall view showing the orientation of fatigue striations. "Rubbing" is seen at the lower left of both photos. (90 X)
- (b) Higher magnification view showing spacing of striations. (180 X)

The cracks running down the leading edge were also fatigue cracks. One such crack from Blade No. 2 is shown in Figure 11. The fracture surface was generally badly rubbed, but the striations that were visible were parallel to the surface with a spacing of about 10×10^{-3} mm per striation. The crack was longer on the inside surface of the leading edge. No pre-existing cracks were found along either the inside or outside of the leading edge.

DISCUSSION

Chemical analysis confirmed that the skin of the Millville blades was made of 5052 Aluminum, as reported by the manufacturer. The Handbook of Aerospace Materials states that 5052 is a material normally considered to have good high-cycle fatigue strength compared to other aluminum alloys. However, the rate of growth of the cracks observed in this investigation was very high, leading to low-cycle fatigue failures after only a few thousand cycles or so. This would indicate that the loading was severe. Also, the cracks started in buckled areas where the stress was concentrated further. The buckling was probably caused by large deflections of the blades in the wind storm, indicating insufficient stiffness of the blades to withstand the wind velocities encountered. The initial growth rate of the cracks in the buckled region was high, but they slowed down slightly as the cracks extended. When a crack reached the leading edge, the growth rate increased as the crack propagated through the heavily cold-worked leading edge.

Dr. David W. Hoepfner, Professor of Engineering Design at the Cockburn Centre, University of Toronto, Toronto, Canada, concurs with the metallurgical evaluation.⁽²⁾ In addition, he believes the cold forming of the leading edge may be quite excessive in this material and there is a high probability the material is cracked during forming. Also, the blade clearly contains an extremely high residual stress - particularly at the leading edge - which could be detrimental from a fatigue point of view. The material/manufacturing operation controls

Figure 11 - (a) Scanning electron micrograph of the area near the start of the fracture of the leading edge of Blade No. 2. Some coarse striations are visible in the center. (140 X)

(b) An area near the tip of the same crack. The lower area in the photograph shows ductile rupture produced when the crack was pulled open during preparation. The upper area is the fracture surface of the crack, near the tip of the crack growing down the inside surface of the leading edge.

did not prevent cracking or the introduction of detrimental residual stresses.

Given the two above conditions, it appears that a high vibratory stress is set up in the blade due to aerodynamic excitation. This could be the result of several factors including improper thickness of blade, improper spacing of spanwise splices, lack of chord reinforcement, and improper connection of splices.

Two "rough" calculations of crack growth rates were made from fractographs provided by Metallurgy. The "rough" determinations were 8.4×10^{-5} in. per cycle and 2.5×10^{-5} in. per cycle.

ANALYSIS CONCLUSIONS

1. The Millville blades failed due to low-cycle fatigue of their aluminum skins.
2. Fatigue cracks initiated in buckled areas of the blade skin. This buckling was caused by large deflections of the blades which occurred during the wind storm.
3. The large deflections were a result of aerodynamic excitations.

MANUFACTURER MODIFICATION

The consulting report from Dr. D. Hoepfner was sent to Mr. Devon Tassen of Millville Windmill Company,⁽³⁾ and discussed on the phone.

Recommendations were made to modify the blade design to avoid the cracking problems observed at Rocky Flats. The areas reviewed were: (1) skin material; (2) forming techniques and specifications; and (3) blade stiffeners.

The blades were shipped to Millville for reskinning and design modification.

The following changes were made in the blades returned for testing.

1. The skin material was changed to 3003 H-14 aluminum which contains only 1-1/2% magnesium as compared to 2-1/2% for the 5052. This should result in a more ductile bend radius on the leading edge.
2. The leading edge radius was increased, thus reducing residual stresses and possible cold form cracking.
3. For stiffness, an "M"-shaped sheet metal section was added and riveted to the skin. The stiffener runs the full length of the blade.

Figure 12 shows views of the added stiffeners and the blade skin sections which have been preshaped. The rivets are installed in rows parallel to the main spar. On the upwind surface one row is forward and two are aft. On the downwind surface there is only one row and it is aft of the spar. A nonattached section is bent around the spar to give added skin support.

This blade structure configuration is currently under test at Rocky Flats, and during calibration of bending bridges it was noted that no oilcanning was produced. The bridges are located on the main spar and were installed prior to shipment to Millville for rework.

Figure 12 - (a) View of stiffener "M" Section.

(b) View of installed stiffener and skin sections ready for installation.

COMMENTS

As of this report, no winds equal to the December 4, 1978 storm have been experienced by the new blades. Continued testing is planned, and at least one equivalent wind storm is expected during the next wind season.

Millville has informed Rocky Flats that an additional design change has been incorporated into the blades they now manufacture.⁽⁴⁾ The following is the current configuration.

1. A 1-in. diameter x 0.083 wall thickness tube runs the length of the leading edge, thus giving this edge a 1/2-in. radius.
2. Four (4) "C" Section stiffeners are now used. These run the full length of each blade and are riveted to the skin, one forward of the main spar and three aft. This leaves only about 3 in. of open space between stiffeners and should totally eliminate the possibility of buckling. This has also resulted in a higher survival wind speed rating by Millville.

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