ADVANCED WIND TURBINE BLADE STRUCTURE DEVELOPMENT PROGRAM AT MONTANA STATE UNIVERSITY

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Abstract

This paper presents an overview of the program centered at Montana State University (MSU) which is focused on the structural performance of wind turbine blades, and wind energy development in Montana. The program also has participants at three other Montana universities and colleges as well as cooperative efforts with local utilities, a manufacturing company, a wind industry partner, and a State agency. The program to advance wind turbine blade structural performance includes an iterative process of design/analysis, materials development, manufacturing, and laboratory and field testing. While this program addresses 8m fiberglass blades for the AOC 15/50 turbine (Atlantic Orient Corp., Norwich, VT), the capabilities and approach are generic in nature, intended to assist the U.S. wind industry in the structural/materials area. A major focus of the work is validation of the software and models available for prediction of blade structural performance including fatigue lifetime and buckling resistance. A second part of the program is involved with wind energy development in Montana, including distributed generation demonstration projects, an avian study, and wind development on Blackfeet Tribal Lands.

Introduction

This paper provides an overview of the program at Montana State University to develop advanced wind turbine blade composite material structures. The goal of this program is to develop generic approaches to blade materials and structural details which provide an improved, predictable blade lifetime and other structural characteristics at minimum weight and cost. The program integrates technologies in structural design/analysis, manufacturing, materials, and testing/evaluation, including laboratory and field testing. About seven faculty, two research associates, and seven graduate and undergraduate students are involved in the effort, with additional students in associated materials studies. The program in composite structures started about five years ago, with a major increase in effort over the last three years.

This program is expected to improve technologies important to blade structures in several respects of interest to the wind industry:

1. Improved materials and procedures and a database for materials selection.

2. Validation of methodologies for predicting blade lifetime, buckling resistance and strength.

3. Improved procedures for designing structural details such as ply drops, web or spar interface with blade skins, adhesive joints, and hub areas.

4. Improvements in blade manufacturing technology with emphasis on higher fiber contents, manufacturing for extended service lifetime, the incorporation of stiffening for buckling resistance, and lower cost, higher production rate manufacturing.

5. Enhanced testing capability available to industry including materials testing, full scale blade and substructure testing (up to 8m long), in-service testing on turbines up to 50kW capacity, nondestructive evaluation, and failure analysis.

It is the intention of this program to provide assistance to the wind industry in the structural area in terms of expertise, methodologies, and testing facilities. A related service is to

This work was supported by the U.S. Department of Energy and the State of Montana through the Montana DOE EPSCoR (Experimental Program to Stimulate Competitive Research) Program (contract # DE-FC02-91ER75681) and the National Renewable Energy Laboratory (NREL) under subcontract # X4F-5-14076-04.

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encourage and assist in the development of improved materials for blades, working in conjunction with materials manufacturers.

The DOE EPSCoR program also includes a component geared to assist in the development of wind energy resources in Montana and the surrounding region. This includes an avian study in a wind resource area, remote hybrid installations such as at ranches, a distributed generation demonstration project on a weak radial line, including studies of both power quality and economics, and a wind demonstration and educational program on Blackfeet Tribal Lands in northern Montana.

Materials

As part of both the NREL and EPSCoR programs, a systematic variation of materials parameters for the main structure of the blade as well as skin and web areas has been carried out. Some of these results were reported in Ref. 1. Selected versions of most U.S. manufactured E-glass fabrics were included, along with the systematic variation of the percent fiber and the percent 0° and ± 45° material. These parameters cover a much broader range than has been in the literature previously. Each laminate was tested for static ultimate and stiffness properties as well as a full fatigue S-N curve in tension (R=0.1, where R is the ratio of minimum to maximum stress, with the maximum stress varied systematically) and compression (R=10), with selected cases tested at R= -1 (reverse loading). These results are available in the MSU/DOE fatigue database[2].

Figure 1 shows typical S-N curves, while Figure 2 shows the variation in slope of the normalized S-N curve, b, for various fabric constructions as a function of fiber content (percent fiber by volume). The fatigue coefficient, b, represents the fatigue sensitivity of the laminate. The best glass fiber laminates have a value of b in the range of 0.10 (10% of the initial strength, S_0, per decade of cycles to failure, so that a maximum stress, S, of half of S_0 would produce failure in 10^5 cycles). The most fatigue sensitive laminates at R=0.1 have a b value around 0.14, which produces on the order of 10 to 1,000 times shorter lifetime over most of the tensile stress range. Compression fatigue has also been characterized, but much less sensitivity to fabric type and fiber content is observed [1].

Figure 2 shows a transition in tensile fatigue sensitivity from the best to the worst as the fiber content increases. The tightly stitched triax fabrics show poor behavior over the entire range, while unidirectional fabrics are the best, particularly with the fabric stitching removed. Unfortunately, the selection of materials even at fiber contents below 40% is further compromised because the stitched fabrics with good static compressive strength, D092 and D155, are not available with fibers in the "warp" direction, the long direction of the roll of fabric, which is usually oriented lengthwise on a blade. Only the A fabrics (Fig. 2), which are woven, are "warp" unidirectionals, and typical of woven fabrics, their compressive strength is only 50 to 75% of the values for the D fabrics [2]. Solutions to this dilemma are currently being sought with the manufacturer, as well as new fabrics with improved tensile fatigue resistance at high fiber contents.

Buckling

The problem of predicting and designing for buckling in turbine blades has been a major concern in many blade development efforts. This problem is now being addressed under the NREL and EPSCoR programs at MSU in a systematic fashion. Linear and nonlinear buckling is predicted using the ANSYS finite element analysis (FEA) software, and validated with laboratory tests for a variety of geometries. Standard and novel approaches to stiffening to improve buckling resistance are being pursued, first at the column and beam flange level, then later for the AOC 15/50 blade.

Figure 3 shows a beam with buckled and failed flanges, as well as strain data from each side of the compression flange, which defines the buckling condition. Figure 4 shows FEA results for an initial design of the AOC 15/50 blade in buckling.

While the buckling phenomenon is difficult to define and predict precisely in a structure, current results for the beams show a generally good correlation between predicted and observed buckling and post-buckling conditions. One of the key questions is the extent to which skin buckling can be tolerated at high wind (shut down) conditions without compromising the integrity of the blade. The avoidance of buckling at all load conditions may impose a major weight penalty for the AOC 15/50 blade and other industry blades.

Finite Element Analysis

Previous work [3] has demonstrated that strains and stiffness of wind turbine blade structures can be accurately predicted using available FEA packages. Current studies support these findings, and will extend them to validation on the AOC 15/50 blade in full scale tests.

Questions which arise in applying FEA to blade structures revolve around the mesh sizes and element types which give adequate treatment at minimum cost, as well as the treatment of complex structural details such as stiffeners and joints. One goal of this program is to demonstrate and validate the level of analysis required for blade design and analysis. Specific, generic design detail questions will also be explored.

A type of detail which has been studied in current work is

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ply drops. As the thickness is tapered along the blade, plies of fabric are typically dropped. The location, number, and spacing of ply drops is critical to the strength and fatigue performance, as both stress concentrations and delaminations occur at these points. A number of guidelines for ply drops have already been developed, and a more detailed study is ongoing, as reported in an associated paper [4].

Manufacturing Technology

Under the DOE EPSCoR program, MSU has a subcontract with Headwaters Composites, a startup company in Three Forks, MT, near MSU, to manufacture 8m fiberglass blades for the AOC 15/50 turbine. Charles Hedley, owner of the company, did his graduate studies at MSU on composites manufacturing [5]. The current status of the blade manufacturing project is that fiberglass molds are under construction using a plug supplied by AOC. Blades for testing will first be fabricated by hand layup in an open mold, and the process will then be extended to resin transfer molding (RTM) in the following year. As part of the iterative design/materials/manufacturing/testing approach being pursued, sections of blades and complete blades will be fabricated for full scale and substructure testing at MSU. The resulting optimized blades will then be used on the AOC 15/50 turbine being purchased under the program.

The blade manufacturing effort is supported by a continuing research effort at MSU which is focused on RTM process modeling and validation experiments [5,6]. In addition to basic research, the RTM process at MSU has been used to fabricate materials with a broad range of characteristics, described earlier, as well as to prepare dozens of substructure beam elements for testing [3]. The fabrics and resins used in these studies are the same as those used by some U.S. blade manufacturers. The RTM effort at MSU allows the preparation of a very broad range of materials and characteristics, such as fiber content, for study as compared with other processes. Processing research and development can be carried out at MSU on smaller sections, with the capability to fabricate full scale blades in cooperative efforts with Headwaters Composites or other manufacturers.

Laboratory Testing

MSU has developed a broad materials and structures testing facilities and expertise over the past seven years of wind energy research. With the support of Sandia National Laboratory (SNL), NREL, and DOE EPSCoR, four servohydraulic materials test systems are available with various special features such as very high frequency and high load and displacement. A structural test system capable of full scale testing of the 8m AOC 15/50 blades is presently being assembled; this facility will also be used to test smaller blade and substructure sections for systematic study of parameters such as buckling.

The test facilities are state-of-the-art, equipped with high speed data acquisition and machine control, with spectrum loading as well as constant amplitude fatigue capability. An array of accessory equipment such as extensometers, hydraulic grips, ultrasonic inspection, microfocus X-Ray and digital oscilloscopes are available.

Service Testing

The Rice Ridge Renewable Energy Park near MSU was developed for wind energy research with the cooperation of Montana Power Co. and the State of Montana Department of Environmental Quality. The site now contains one modified, instrumented 10 kW Bergy turbine, with a second turbine with 20kW capacity under construction. The Bergy turbine, modified for yaw and speed control at Montana Tech (Dave Westine), is being used to test special blade sections to failure under service conditions. Figures 5 and 6 show the special blade section and the turbine, and Figure 7 shows output from the first instrumented run. The purpose of these experiments is to validate the lifetime prediction methodologies used for blades, as well as to test experimental materials and structures. The site also provides a cold, high altitude wind resource area with about an 18 mph average annual wind speed.

The special test apparatus shown in Figure 6 has several functions:

1. To contain blade sections safely after failure
2. To limit the maximum bending moments on the section
3. To remove the high axial loads when the Bergy is run at high RPM, so that the loads spectrum better approximates larger machines

The test section used in the initial experiments is a circular, tapered diameter hollow tube. This section was chosen for simplicity and due to limitations imposed by the small size of the turbine. Larger, more blade-like airfoils with realistic wall thicknesses could not be designed to fail at the load levels of the Bergy. A larger system (20kW) capable of testing larger sections is under construction, and the AOC 15/50, being installed this year, will raise the loads capability to where more representative airfoils can be considered.

The tube section and apparatus has been through several fabrication, testing, and redesign iterations, and is now generating data, with an apparatus on all three blades. The data acquisition system developed at Montana Tech is also providing continuous loads data, with the number of 400 Hz channels currently being expanded from four to nine. As data are obtained for blade failure under measured loads spectra, the results will be compared with predictions using the MSU/DOE database, finite element analysis, and life prediction codes including SNL's LIFE2, (see Ref. 7). Laboratory simulations using the measured loads spectra will also be run as part of the validation process.

As noted earlier, an AOC 15/50, 50kW turbine is scheduled to be installed next year. This turbine is of a size which will allow testing of airfoils and blade structural characteristics which are representative of larger turbines, but sufficiently small (with tilt-down tower), safe, and easy to inspect. This turbine is the focus of the Advanced Blade Structure Development effort described earlier, and the blades which result from that effort will be flown on this turbine, with full instrumentation.

Wind Energy Development In Montana

Several projects within the DOE EPSCoR program are geared to wind energy development in Montana and the region. These are summarized briefly below:

1. Avian study at Norris Hill (Al Harmata, MSU). An avian study of the wind resource area surrounding the Rice Ridge Renewable Energy Park (Norris, MT), was initiated with a combination of funds from EPSCoR, Montana Power Co., Windmaster, and the State of Montana Department of Environmental Quality. This study is now funded under NREL contract, and is focused on an assessment of avian activity prior to wind farm development. The study includes the innovative use of radar for bird counting and tracking.

2. Blackfeet Community College (BCC) Program (Marty Wilde and R. Michael Reed, BCC). This program includes a demonstration 100kW turbine installed in 1996 near the college, in cooperation with the Blackfeet Tribe, Zond, Glacier Electric Co., and DOE Title XXVI funding. An educational program focused on wind energy has been implemented at the college. This effort takes place in the major wind resource area around Browning, MT on the Blackfeet Tribal Lands.

3. Distributed Generation Demonstration Project (Don Pierre, MSU and Dan Trudnowski, Montana Tech). The AOC 15/50 turbine will be installed this year with the cooperation of Montana Power Co. on a weak radial line near MSU and MT Tech to demonstrate its use in distributed generation. A study of power quality issues will be carried out on the line. A related capability to model economics of distributed generation is also underway (John Duffield, Univ. of Montana).

4. Stand Alone Systems (Victor Gerez, Hashem Nehrir, Giri Venkataramanan, MSU). This program has included wind and solar availability measurements at several sites around Montana, economic modeling of individual loads, and hardware development. A demonstration project including a 3kW turbine is planned for this year.

References

1. Samborsky, D., and Mandell, J.F., "Fatigue Resistant Fiberglass Laminates for Wind Turbine Blades" Wind Energy 1996, ASME, pp 46-51 (1996).

2. Mandell, J.F., et. Al., "MSU/DOE Wind Turbine Blade Composite Material Fatigue Database" Released November 1995.

3. Mandell, J.F., Combs, D.E., and Samborsky, D., "Fatigue of Fiberglass Beam Substructures" Wind Energy 1995, W.D. Musial, S.M. Hock, D.E. Berg (eds), SED-Vol. 16, ASME, pp 99-106 (1995).

4. Cairns, D.S., Mandell, J.F., Scott, M.E., and Macagnano, J.Z., "Design Considerations for Ply Drops in Composite Wind Turbine Blades" Wind Energy 1997, January 1997 (to be published).

5. Hedley, C.W., "Mold Filling Parameters in Resin Transfer Molding" M.S. Thesis, Department of Chemical Engineering, Montana State University, 1994.

6. Humbert, D.R., "Modeling of Resin Transfer Molding of Composite Materials With Oriented Unidirectional Plies" M.S. Thesis, Department of Chemical Engineering, Montana State University, 1996.

7. Sutherland, H.J., and Mandell, J.F., "Application of the U.S. High Cycle Fatigue Database To Wind Turbine Blade Lifetime Predictions" Wind Energy 1996, ASME, pp 78-84 (1996).

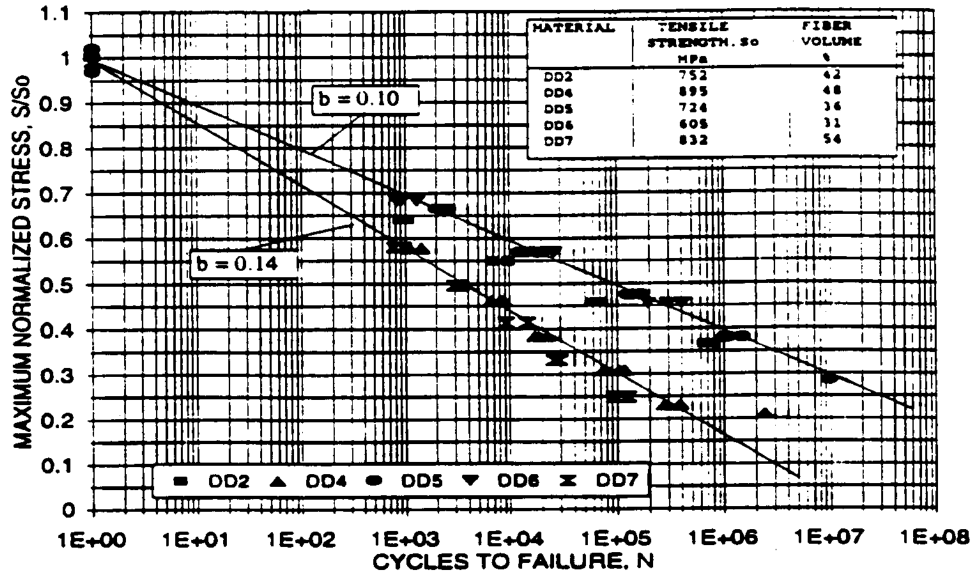


Figure 1. Normalized tensile fatigue data for DD materials $[0/\pm45/0]_S$, S/S=1-b log N.

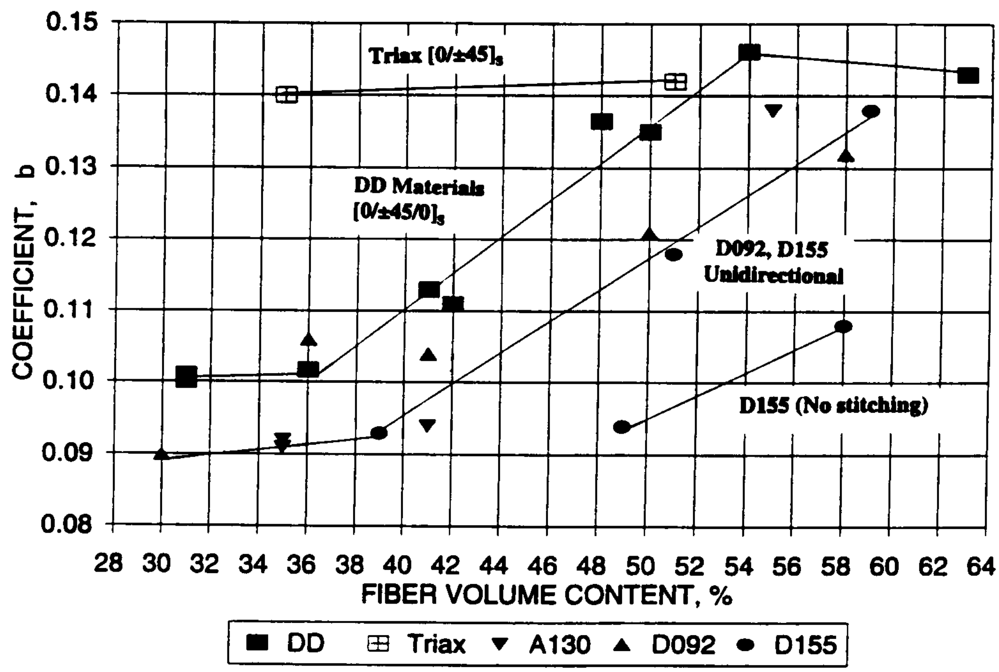
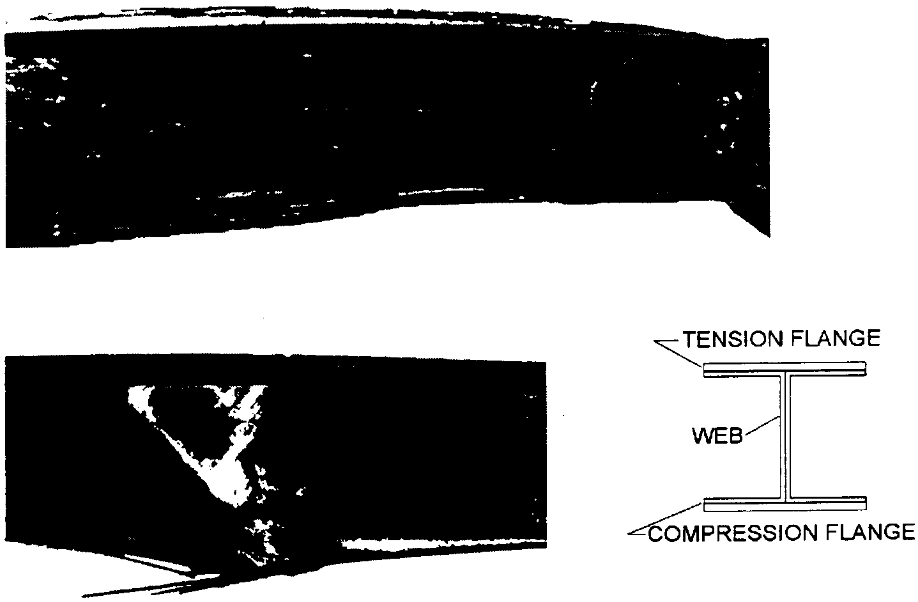


Figure 2. FIBER CONTENT VS. FATIGUE SENSITIVITY COEFFICIENT, b
S/So = 1 - b LOG N, A130, D092, D155, DD AND TRIAX MATERIALS
R = 0.1



Beam buckling and failure

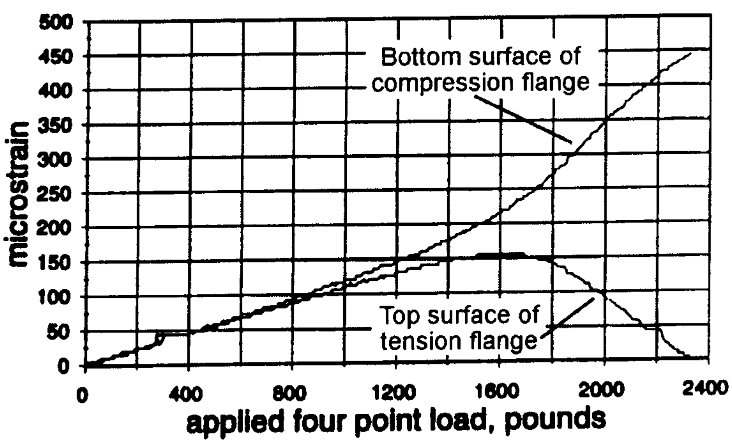


Figure 3. Beam Buckling and Failure (Top) and Experimental Strain at top and bottom surfaces of the compression flange vs. load showing the buckling event at the divergence of the curves.

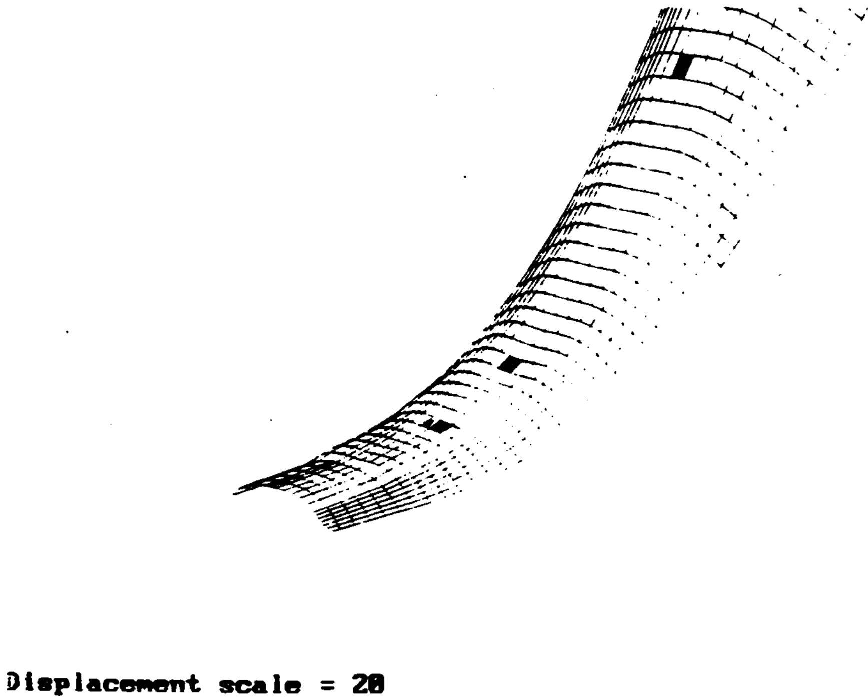


Figure 4. Finite Element Prediction of Buckling in AOC 15/50 Blade (Mesh Distortion)

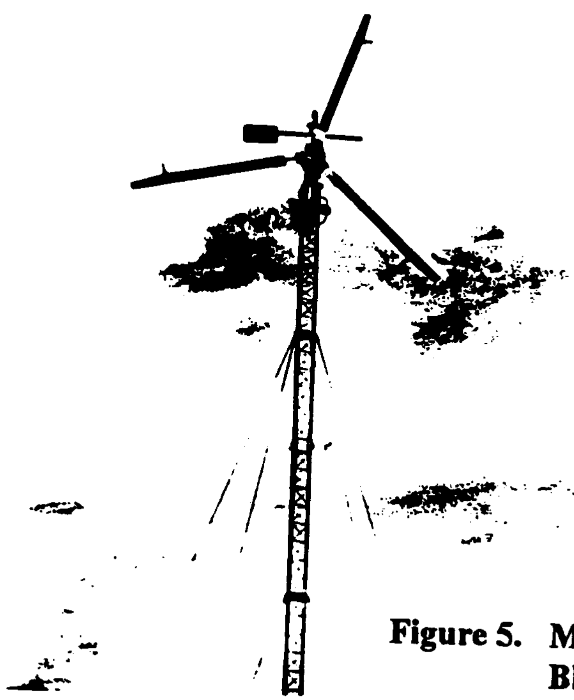


Figure 5. Modified Bergy 10kW Turbine with Special Blade Section

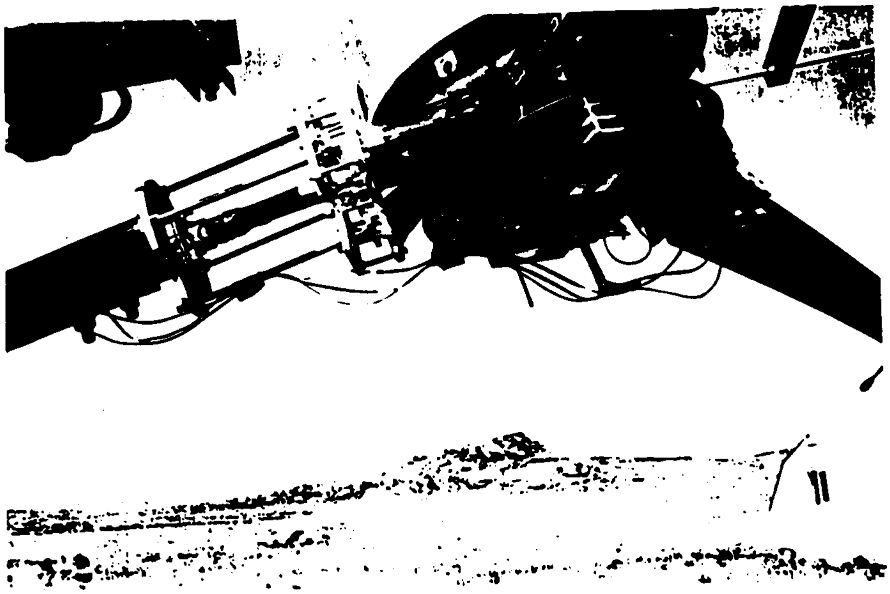


Figure 6. Close-up of Special Blade Section and Containment Apparatus, also showing Instrumentation

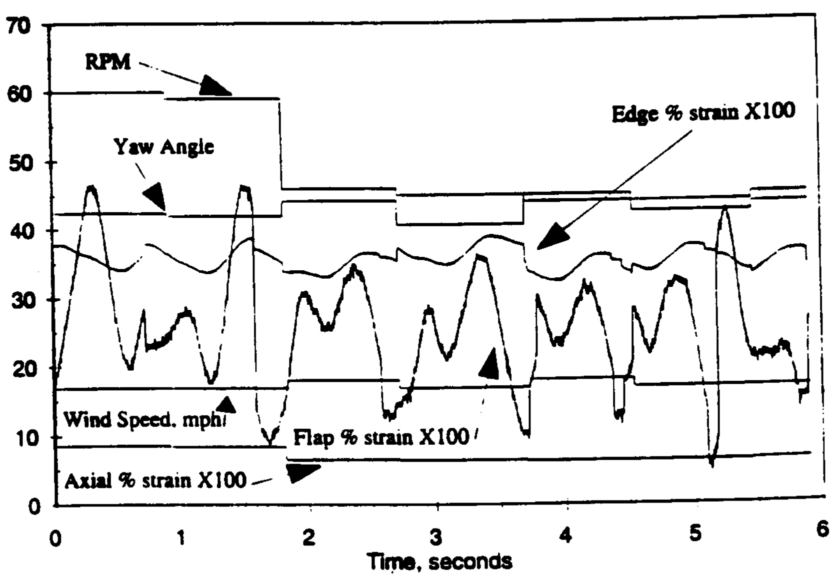


Figure 7. Typical Data Acquisition Output for Special Blade Section