Design, analysis and testing of a wind turbine blade substructure
by David Wright Combs

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering
Montana State University

Abstract:
This thesis presents the development of a substructure test for wind turbine blade materials (E-glass and polyester resin) and the initial experimental results obtained from this testing procedure. On going research at MSU has established baseline data for the fatigue response of rotor blade materials using coupon geometries to 10^8 stress cycles. The necessity for substructure testing is based on the accepted engineering procedure of incremental scaling towards full scale testing. In the case of composite wind turbine blades the necessity for this approach derives additional motivation due to the lack of experience with dynamic structures design for the expected lifetime of wind turbines, approaching 10^9 fatigue cycles in a 30 year service life, and the lack of experience with E-glass composite material applications at this level of cycling.

A four-point bending fixture was designed and fabricated that allowed static and fatigue testing of composite I-beams using a servo-hydraulic material testing machine. The I configuration was chosen to represent the region of the shear web and skin immediately above and below the web, of a rotor blade. Four-point bending was selected for the loading configuration due to the simplified stress state in the gage section of the beam, i.e, no shearing stress. The beams were manufactured using two resin transfer molds: one mold for the C-channels and the other for flat plates from which flanges and beam details were fabricated.

Fatigue testing of the beam pointed to the significance of structural details in fatigue design. Load and support pad failure, adhesive failure of the flange joints due to shear stress concentrations, ply-drop delaminations and shear web failure were the major developmental problems encountered. All were satisfactorily resolved except ply-drop delaminations and shear web failure. It is believed that thickening the web of the C-channels will eliminate shear web failure. Ply-drop delaminations warrant further investigation as they are commonly used in composite structures where a change in thickness is required.

The final beam design withstood over 2.2 million cycles at or above 6000 microstrain in the flanges. Of those cycles, 285,735 were at approximately 9000 microstrain. Both the static and cyclic beam flange strains at failure are close, slightly above, values predicted by coupon S-N data coupled with the finite element analysis.

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APPROVAL

of a thesis submitted by

David Wright Combs

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

4/11/95 — Date

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Date 4-11-95

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CHAPTER 1

INTRODUCTION

A Brief History of Wind Turbines

Human kind has employed the wind, for both commerce and recreation, since antiquity. The inception of the windmill, or in present day terminology, wind turbine, precedes recorded history [1]. Throughout history there have been two main configurations for wind machines, horizontal and vertical axes. Fig. 1 is a conceptualization of today's horizontal axis wind turbine, HAWT, and vertical axis wind turbine, VAWT.

Vertical axis windmills appear first in historical records [1], A.D. 600-800. The rotor assembly of these machines resembled paddle wheels found on steam driven paddle boats of Sammuel Clemen's day. These machines relied upon momentum transfer or drag to produce mechanical work. In order for a moment to be created about the axis of rotation it was necessary to shield part of the rotor assembly from the wind (Fig. 2).

HAWT's, incorporating a 90^o angle in the drive train appeared in the 9th-10th century [1]. This shift in axis orientation necessitated the inclusion of an oblique orientation of the blades with respect to the wind. While the designers of the day certainly did not understand the principles, aerodynamic lift was being employed, albeit rather crudely [1, 2]. This genre of windmill was prevalent in the United States, starting in the mid to late 1800's. As a testament to the basic design, it is

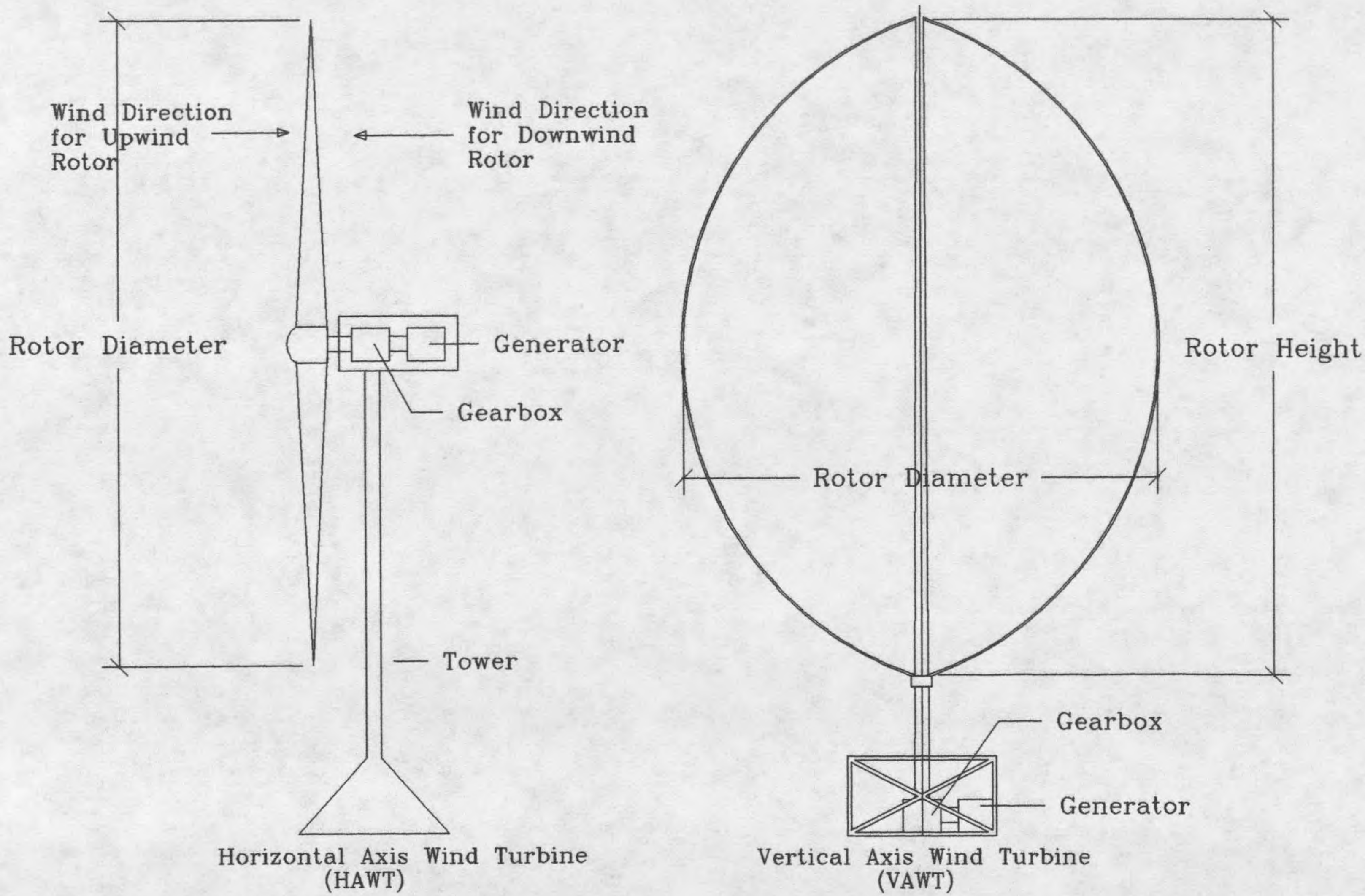

Figure 1: Wind turbine configurations.

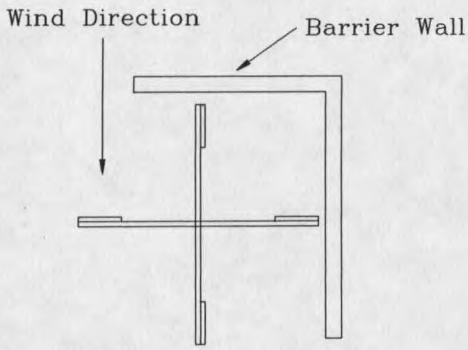

Figure 2. Configuration of original VAWT's.

estimated that there are 100,000 windmills of this variety operating in the United States today [3].

Wind Turbines as Electrical Generators

Modern wind turbines are a sophisticated synthesis of materials, aerodynamics, structural dynamics, electronic control and electrical generators. As of 1993 there were 1600 megawatts (MW) of wind energy capacity in the United States [4]. The American Wind Energy Association has set a goal of 10,000 MW of installed wind energy capacity in the United States by the year 2000 [4]. The size range of the most common wind turbines is 100-1000 kilowatts. To add perspective to these wattage numbers, at present there are approximately 16,000 wind turbines in the state of California. While California accounts for a majority of the wind turbines in the United States, wind energy is expanding throughout the United States and is a significant source of power in Europe as well.

The economic viability of wind turbines is, in part, dependent on a life expectancy of 20 to 30 years. A conservative estimate for fatigue cycles vs time for a

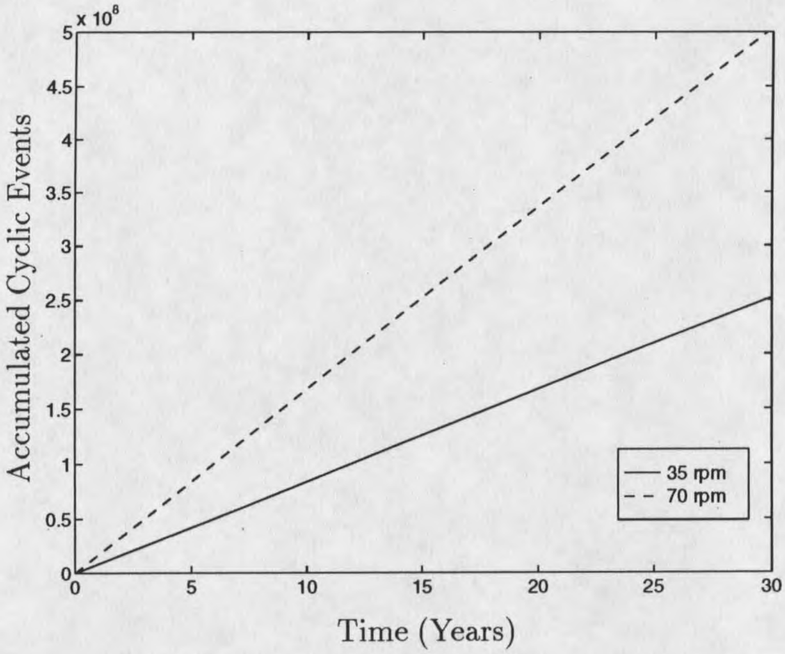

Figure 3. Conservative estimate of fatigue cycles.

wind turbine [5] is given by the equation,

$$N = 60\ k\ \omega\ H_{op}\ t. \tag{1.2}$$

N is number of accumulated cyclic events, k is the number of cyclic events per revolution, H_{op} is the operating hours per year and t is time in years.

Fig. 3 is a plot of Equation 1.2) using $k = 1$, $H_{op} = 4000$, typical values range from 3000 to 4500 hours/year, and 35 and 70 rpm values for ω. Small wind turbines may operate at angular frequencies approaching 100 rpm while large turbine speed is approximated by 35 rpm. The use of $k = 1$ is the most conservative choice available, representing only the periodic influence of tower shadow for HAWT's. The actual loading regime experienced by a wind turbine is extremely complicated making this forecast an absolute minimum, although most cycles may experience stress amplitudes that are below levels where damage occurs in the rotor material. Wind turbines are one of the first large scale machines to be designed with a fatigue life of 10^8 to 10^9