FATIGUE LOAD SPECTRA FOR UPWIND AND DOWNWIND ROTORS

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ABSTRACT

Effect of both alternating and mean load on the fatigue life of an upwind and downwind MOD-2 wind turbine system is presented. It was shown that the fatigue damage varies as the product of the stress range cubed and the maximum stress. Hence, the alternating flapwise load caused by tower shadow and wind gradient is an important factor in determining rotor blade life.

INTRODUCTION

The baseline MOD-2 wind turbine system is a downwind, cantilevered, zero precone rotor approximately 300 feet in diameter which will generate approximately 2500 KW. Boeing is presently in the configuration concept design phase of the program. The aim of this paper is to show the effect of both the alternating and mean load parameters on the fatigue life of an upwind and downwind MOD-2 rotor.

LOAD AND FATIGUE ANALYSIS DISCUSSION

The fatigue design goal is to operate thirty years in a given wind/gust spectrum with a safe life design concept, and yet meet minimum energy cost goal. Safe life design means that the maximum operating loads will be below the endurance limit. However, allowance for .5 percent of the total applied cyclic loads can be above this limit. These loads are the infrequent occurring cyclic loads (approximately 5,000 - 10,000 cycles).

The fatigue environment is composed of a wind spectrum, Figure 1, for any site which is independent of rotor orientation with respect to tower and some gust spectrum shown in Figure 2. This gust spectrum defines the load distribution relative to a nominal load, M_O, for a specific wind speed and is applied to the alternating load only. Figures 1 and 2 can be combined into a load exceedance curve of the form shown in Figure 3. There will be a number of these spectra for each given wind speed such that the total of the accumulative cycles will equal 2.11×10^8 cycles equivalent to 30 years of life. An upwind and downwind rotor will have different load exceedance plots.

The load time history of the flapwise bending moment at a spanwise blade station of $r/R = .385$ and at 52 mph for an upwind and a downwind rotor is shown in Figure 4. These are preliminary loads for MOD-2 due to a 30 degree tower shadow notch, wind gradient, and a 20 degree yaw wind. The C-60 computer program was used to establish these loads which would only allow input of the velocity reduction due to tower shadow in 15 degree azimuth increments which is quite conservative for the MOD-2 tower. For reference, the rotor blade is straight down at 180 degree azimuth. These flapwise alternating loads change with wind speed as shown in Figure 5. It can be seen that the tower shadow as represented has a large effect on the downwind rotor. The upwind and downwind steady state flapwise bending moment does not change much with wind speed as shown in Figure 6.

Now the question becomes, how do these loads relate to fatigue damage? Fatigue damage varies as the product of the stress range cubed and the maximum stress. The importance of this relationship with cut off wind speed is shown in Figure 7. An initial allowable stress for MOD-2 was established to be equal to the MOD-1 which was predicated on allowing .5 percent stress cycles to exceed the crack propagation threshold. The non-dimensional damage for the MOD-1 is shown in Figure 7 for comparison. A damage curve for the MOD-2 downwind rotor shown in Figure 7 indicates 4 percent exceedance of the crack propagation threshold. The reason for this is that the MOD-2 has a greater operating wind speed range between rated wind speed and cut off wind speed i.e., alternating loads are higher with a lower mean. Therefore, to meet the same fatigue criteria, the MOD-2 allowable would have to be reduced as shown in Figure 7 and spectrum testing would be required to establish the allowable since stress levels exceed the crack propagation threshold. Also noted in Figure 7 is the weight reduction available in an upwind rotor blade at this station based on the loads derived with this specified tower shadow and fatigue criteria.

CONCLUSIONS

The following conclusions were drawn from this study:

1. No direct linear relationship between alternating load and life.

2. Damage varies as the cube of alternating stress while it varies as maximum stress to the first power.

3. Damage will vary linearly with coning (max stress effect only).

4. Upwind rotor can produce dramatic reduction in damage depending on tower configuration.

5. Spectrum type fatigue test mandatory to establish allowables.

6. Fracture mechanics theory is to be an integral part of the fatigue test program to minimize number of specimens tested and to correlate with existing data.

DISCUSSION

Q. Why do you conclude that alternating loads have no direct effect on life?

A. Direct means linear and damage varies as the cube of the alternating loads.

Q. Have you looked at stresses at blade radii other than .385 radius?

A. Yes. The full radial stress distribution has been examined and this is one of the critical stations selected for this presentation.

Q. Is the repeated loads design going to be carried out primarily by the fracture-mechanics methodology now being used for USAF aircraft?

A. Yes, as this is our standard practice at The Boeing Company.

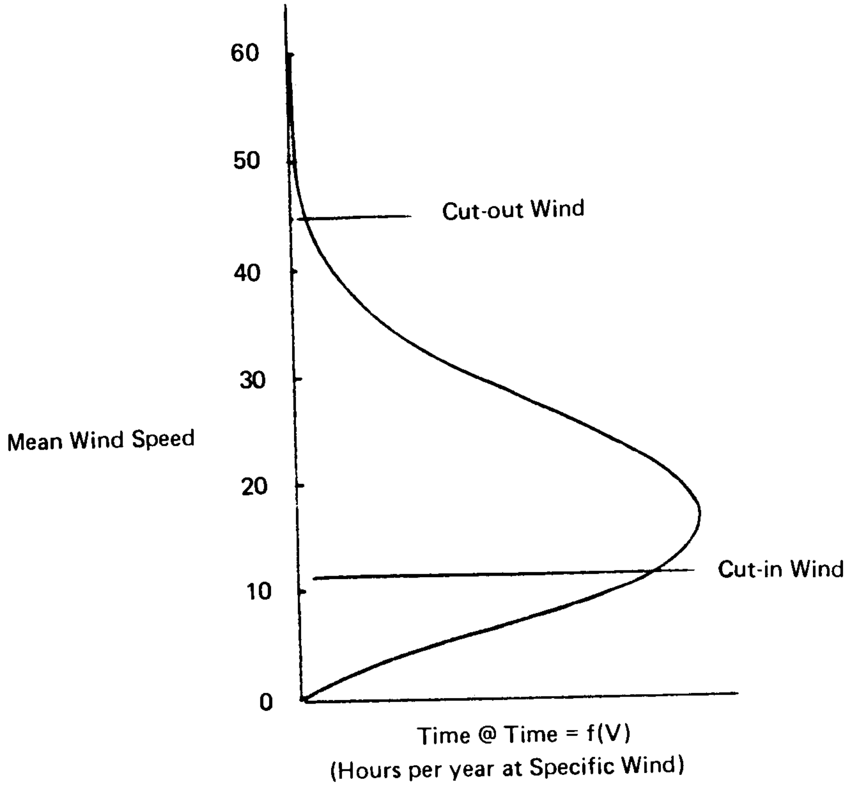

Figure 1. - Wind spectrum - upwind and downwind rotor.

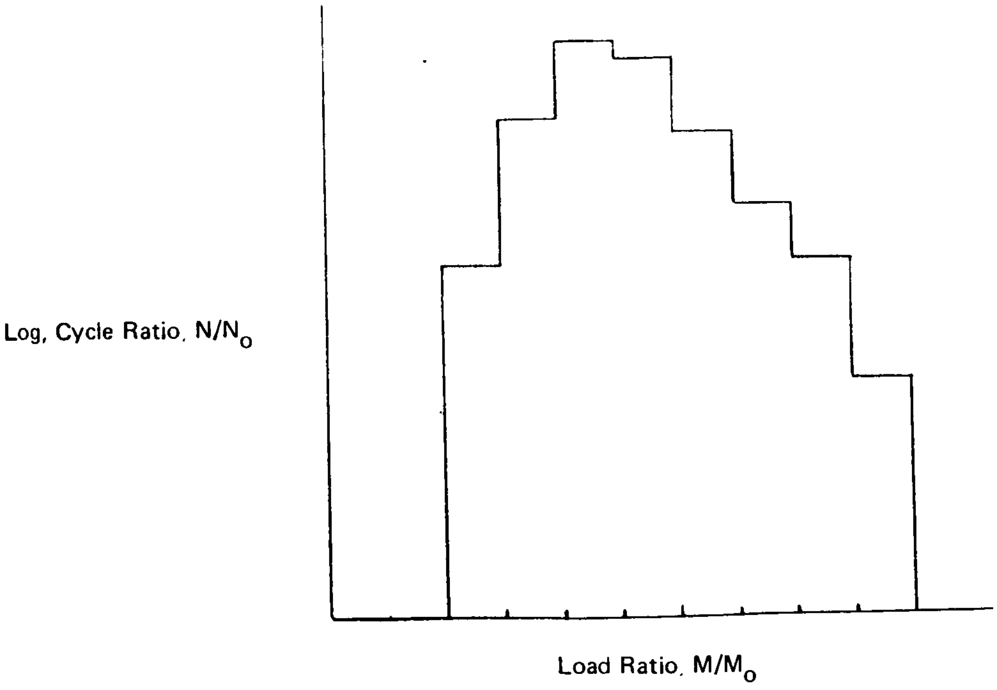

Figure 2. - Gust spectrum.

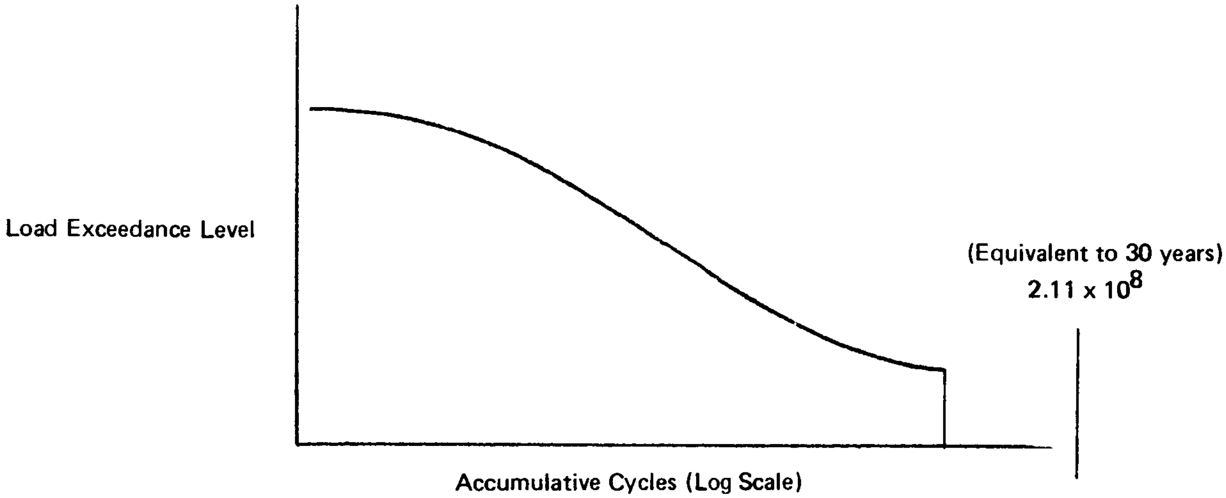

Figure 3. - Load spectrum for given wind speed.

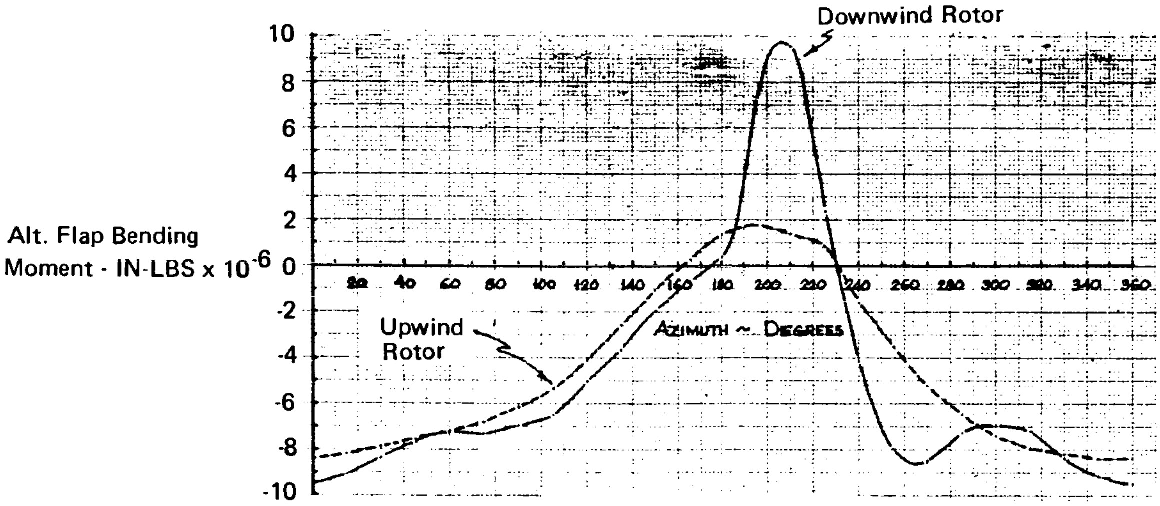

Figure 4. - Alt. flap bending moment at 52 mph and blade station r/R of 0.385.

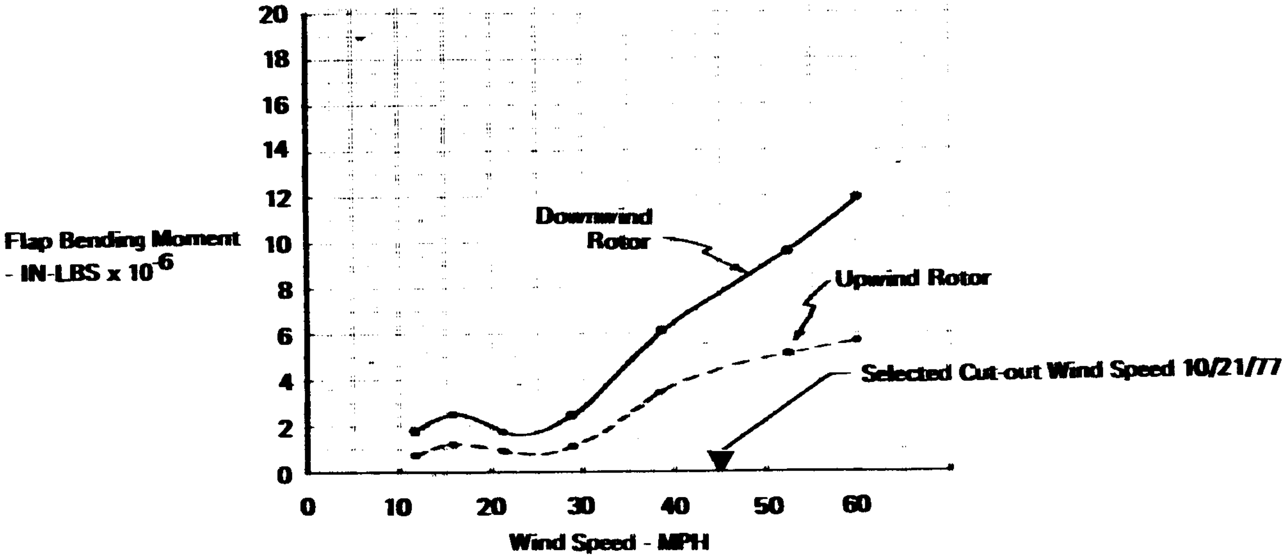

Figure 5. - Flap bending moment at blade station r/R of 0.385.

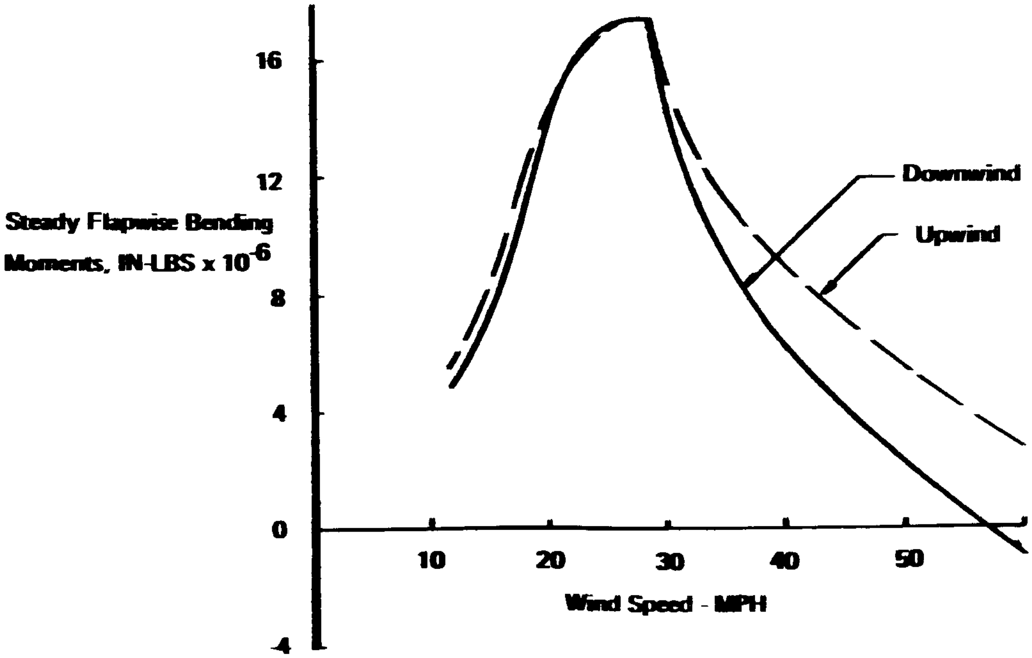

Figure 6. - Steady flapwise bending moments at blade station r/R of 0.385 - upwind and downwind conditions.

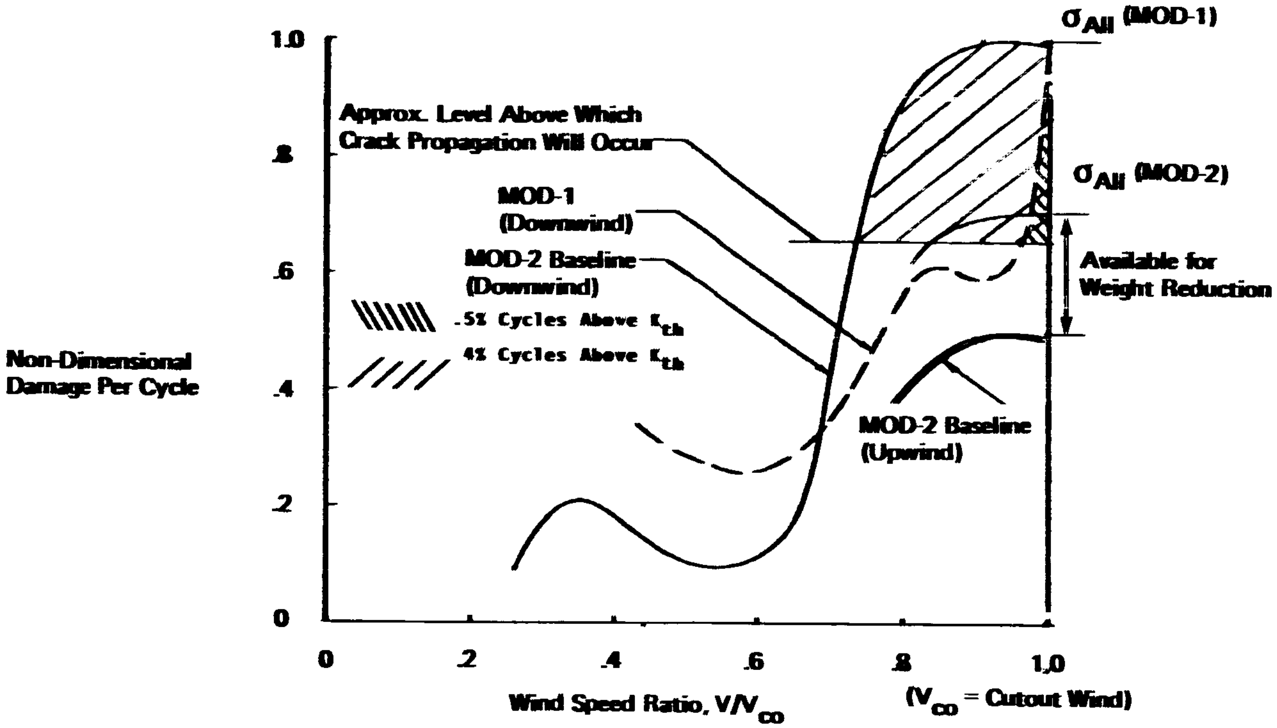

Figure 7. - Effect of wind direction on fatigue damage - damage cycle $\propto (\Delta\sigma)^3 \left(\frac{\Delta\sigma}{2} + \sigma_m\right)$.