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WIND TURBINE DESIGN CODES: A PRELIMINARY COMPARISON OF THE AERODYNAMICS

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ABSTRACT

The National Wind Technology Center of the National Renewable Energy Laboratory is comparing several computer codes used to design and analyze wind turbines. The first part of this comparison is to determine how well the programs predict the aerodynamic behavior of turbines with no structural degrees of freedom. Without general agreement on the aerodynamics, it is futile to try to compare the structural response due to the aerodynamic input.

In this paper, we compare the aerodynamic loads for three programs: Garrad Hassan's *BLADED*, our own WT_Perf, and the University of Utah's YawDyn. This report documents a work in progress and compares only two-bladed, downwind turbines.

INTRODUCTION

The National Wind Technology Center (NWTC) of the National Renewable Energy Laboratory (NREL) is comparing several computer codes used to design and analyze wind turbines. Before we can compare the structural-response predictions of the codes, we must first compare the predictions of the aerodynamic forces applied to the structure. To do this, we disabled all structural degrees of freedom (DOF).

We modeled two turbines with *BLADED* from Garrad Hassan and Partner's Limited, the NWTC's WT_Perf, and the University of Utah's YawDyn. One turbine is a nonexistent, two-bladed turbine with a simple configuration that makes it easy to analyze turbine aerodynamics. The other is similar to the commercial, two-bladed AWT-27. We modeled both turbines without any structural flexibility for this study. We eliminated all degrees of freedom and the only turbine motion allowed was a constant rate of rotor rotation.

In the paper, we will list the aerodynamic features found in each of the three programs. We started our comparison with the simplest set of aerodynamic features that all three codes could simulate. We then gradually added features until we were using the codes with all their available options enabled.

For wind input, we used both steady and time-varying winds. Because WT_Perf models only steady winds, we did not use it in the later comparisons.

One of the side benefits of this study was that we found and fixed errors in the programs. We think this study enhanced the accuracy of all three codes.

Although the programs do not produce identical responses, the agreement between them is quite reasonable. These differences will make a comparison of their structural responses more difficult, but still possible.

SOFTWARE

We used three wind-turbine design codes for this study. They were *BLADED*, WT_Perf, and YawDyn. See Table 1 for a comparison of the aerodynamic features of the three codes. We discuss some of the impacts of the various features below.

BLADED is a performance, structural response, and analysis code from Garrad Hassan and Partners

Table 1. Aerodynamic Features of the Codes

Feature	*BLADED*	WT_Perf	YawDyn
Induction, Axial	optional	optional	optional
Induction, Tangential	optional	optional	optional
Loss Factor, Hub	optional	optional	not available
Loss Factor, Tip	optional	optional	always enabled
Wind Shear	optional	optional	optional
Tower Shadow	optional	not available	optional
Beddoes Dynamic Stall	optional	not available	optional

Limited. We used version 3.2 of this commercial code for this study. See Reference [1] for the theory used in *BLADED*.

WT_Perf is a wind-turbine performance code developed by the NWTC. It was derived from Aerovironment's PROP code. The PROP code was based upon work done by Robert Wilson and Stel Walker of Oregon State University [2]. We used version 2.04 of WT_Perf. There is no documentation for WT_Perf, but the algorithms used are those for PROP-PC [3].

YawDyn, using the AeroDyn aerodynamics package, is a structural response code developed by the University of Utah for the NWTC. FAST_AD and ADAMS, which we will use for a future structural-response comparison, also use the AeroDyn routines. We used the 10.31 alpha version of YawDyn for this analysis. The changes made to the released version 10 of YawDyn allowed us to start the simulation with Blade 1 up so we could synchronize YawDyn with *BLADED*. We also added new output capabilities to YawDyn to make this study possible. The University of Utah will include these new features in the next release of YawDyn. The theory used for YawDyn and AeroDyn can be found in [4] and [5]. Greater detail on the Beddoes-Leishman dynamic-stall model can be found in [6].

We processed some of the results from the simulators with GPP version 5.09. Although the user's manual [7] for this NWTC-developed postprocessor is for an earlier version, most of the information is still valid.

The latest beta versions of GPP, WT_Perf, and YawDyn are available on the NWTC Design Codes web page and are free to the public. Our address is http://www.nrel.gov/wind/codes.html.

We used Microsoft Excel 97 for some simple postprocessing and to plot the results.

SIMPLE TURBINE

Description

We created models of a simple, nonexistent turbine to make it easy to understand some of the basic aerodynamics involved. The two-bladed, downwind turbine was given round numbers for all physical parameters. The blades have no twist or taper and use a single airfoil. The airfoil's lift coefficient has a constant slope of 2π and the drag coefficient is zero. The rotor has no precone, the blade pitch is set to zero (flat to the wind), and there is no shaft tilt. In this case, the airflow angle and angle of attack are the same. This completely rigid turbine has no DOFs and runs at a constant 60 rpm.

Blade-Element Analysis

First, we compared blade-element data predictions for the three design codes. We ran them with three constant wind speeds: 6, 10, and 14 m/s. To see how well the codes agreed, we plotted the induction factor (Figure 1), the angle of attack (Figure 2), and the normal force (Figure 3) against blade station.

For this part of the evaluation, we turned off many aerodynamic features to make the comparison easy. These included hub losses (YawDyn doesn't model them), wind shear, downwind tower shadow, and dynamic stall. We also used an equilibrium wake.

BLADED uses a slightly different induction model than the other two codes. All three codes compute the tip-loss factor using the same algorithm, but *BLADED* applies it differently. The difference is that *BLADED* uses the linearized correction model and WT_Perf and YawDyn use the Wilson and Lissaman method as described on pages 22–23 of [8]. The a(1-a) term in the induction equation is transformed by the tip-loss factor, F, to aF(1-a) for the linearized model and to aF(1-aF) for the Wilson and Lissaman model. The calculation of the tangential induction is the same for all three codes.

Our early work in the study showed the need for good definition of aerodynamic properties near the blade tip. With only a few points in the outer portion of the blade, one would lose much of the character of the tip loss. One should have at least one point in the outer 3% of the blade. Our first *BLADED* model had points at 90% and 100%, so its predictions were drastically different from the other codes that originally had their outer-two points at 85% and 95%. The more points a model has, the better the predictions. The cost is greater processing time.

WT_Perf and YawDyn calculate the aerodynamic force on each blade element and apply this force at the center of the element. *BLADED* calculates the aerodynamic force per unit length at each of a number of stations along the blade, which must include the root and tip. It assumes a linear variation between blade stations when integrating along the blade. The force per unit length is necessarily zero at the blade tip. Thus, if the choice of elements or stations is too coarse near the tip, *BLADED* will underpredict the forces while the other codes will overpredict them. With sufficient blade stations to remove this inaccuracy, the remaining difference between the codes is due to the choice of induction model.

AWT-27

Description

After the blade-element analysis with the simple turbine, we moved on to time-series analyses using *BLADED* and YawDyn models of a turbine with properties similar to the Advanced Wind Turbines AWT-27. We chose the AWT-27 because we already had YawDyn, FAST, and ADAMS models of the AWT-26. We needed to make only simple changes to convert the models to an AWT-27.

Our AWT-27 models differ in several ways from the real turbine, so our model predictions will not agree with test data. We are grateful that Advanced Wind Turbines, Inc., has agreed to let us publish the results of these studies.

For the analyses used in this paper, we turned off all structural DOFs in our AWT-27 models. This allowed us to concentrate on the differences in the aerodynamic models.

Wind Shear

The first new aerodynamic feature we added to the models used in the blade-element analysis was wind shear. Although the mean values for parameters such as power and bending loads were slightly different due to the different induction models, the effect of shear seems to be the same in *BLADED* and YawDyn.

Downwind Tower Shadow

Our initial studies were carried out with an earlier version of *BLADED*, which had a rather simple model for tower shadow in the downwind case. It had a cosine-shaped wake with a fixed user-specified width and intensity. While the same wake shape is used by YawDyn, the width and intensity vary with the square root and inverse square root of the distance from the tower, respectively. At our suggestion, and with the consent of the University of Utah, Garrad Hassan incorporated this modification to the model into the latest version of *BLADED*. This allowed us to compare the codes with the same wake model.

From our studies, we found that we need a high integration rate in order to get reasonable definition of the tower shadow. For an upwind turbine, one might use a dozen time steps per rotor rotation. However, with a downwind machine, one might completely miss the tower shadow with such a low rate. Good definition of the tower shadow requires more than 200 time steps per rotation. This has a significant impact on processing time.

As with the wind shear, the difference in the induction models causes differences in the mean loads. Still, the tower shadows seem to be quite similar. See Figure 4 for the impact of tower shadow on out-of-plane bending moments.

Full Aerodynamics

In the next phase of the study, we turned on all available features in the aerodynamic models. For *BLADED*, we turned on hub losses, Beddoes dynamic stall, and the dynamic-inflow wake model. For YawDyn, we turned on the Beddoes dynamic stall model, but retained the equilibrium-wake model because of problems with the dynamic-inflow model. The next version of YawDyn will contain an improved dynamic–inflow model and we will redo this analysis. YawDyn does not include a hub-loss model.

Extreme Operating Gust

To drive the full aerodynamics, we blew an IEC Extreme Operating Gust on the turbine and observed its impact on rotor power. Figure 5 shows a difference in the predictions. Although the pre-gust and post-gust portions of the power curves have approximately the same level, YawDyn seems to dip down more during the gust. We believe this disagreement is due to the difference in the induction models.

One can also see in Figure 5 that there must be a difference in the dynamic-stall models. The excursions caused by the passage of the blades through the tower shadow seem to be somewhat larger in the YawDyn predictions. Because the tower shadow models are the same, we believe this difference lies in the dynamic stall models. A possible explanation is that for YawDyn, we applied the dynamic stall model to the entire blade, but to only the outer 20% in *BLADED*. We would like to explore this in detail before we proceed to our comparisons of the structural models.

SUMMARY

In our aerodynamic comparison of three wind-turbine design codes, we found differences in their predictions. Many were due to coding errors that were fixed before the final simulations. Others are caused by differences in the algorithms themselves. The use of the tip-loss correction factor in the axial-induction equations seems to be the main culprit. This difference makes all subsequent comparisons more difficult. The Beddoes dynamic stall models also seem to differ some.

FUTURE WORK

Garrad Hassan has implemented the Wilson and Lissaman model for tip losses in a noncommercial version of *BLADED*; they confirm that the observed differences between the results with the different codes can be attributed to this choice of model. It is not clear which model gives a better match to reality. We may try to eliminate the use of the tip-loss correction factor on the axial flow in the plane of the rotor in WT_Perf and YawDyn in order to facilitate our forthcoming comparison of structural models. We hope this will be only a minor effect.

We have talked to some of the leading aerodynamicists in the wind-turbine field. There is some consensus that there is room for improvement in tip-loss models. Dr. Michael Selig of the University of Illinois at Champagne-Urbana is under contract to NREL to derive a better model. We will likely include the new model in future versions of YawDyn/AeroDyn and WT_Perf.

The next major step in our code side-by-side comparison will be the structural comparison. In it, we will compare predictions from *BLADED*, YawDyn, Oregon State's FAST_AD, and Mechanical Dynamics' ADAMS. FAST_AD and ADAMS share the AeroDyn aerodynamics package that is used by YawDyn. We will take a similar approach in which we gradually add degrees of freedom.

We hope to repeat these studies with models of a commercial, three-bladed, upwind turbine. We would also like to eventually compare the model predictions to test data.

ACKNOWLEDGEMENTS

We would like to thank the folks at Garrad Hassan and Partners Limited for all their help, advice, and patience in working with us in our study. We especially thank Ervin Bossanyi and David Quarton for all the time they took to help us. Without their cooperation, this study would have been nearly impossible.

We are grateful to Advanced Wind Turbines, Inc., for allowing us to publish results of our studies using a model of their AWT-27. David Malcolm provided us with properties of a preliminary version of their turbine.

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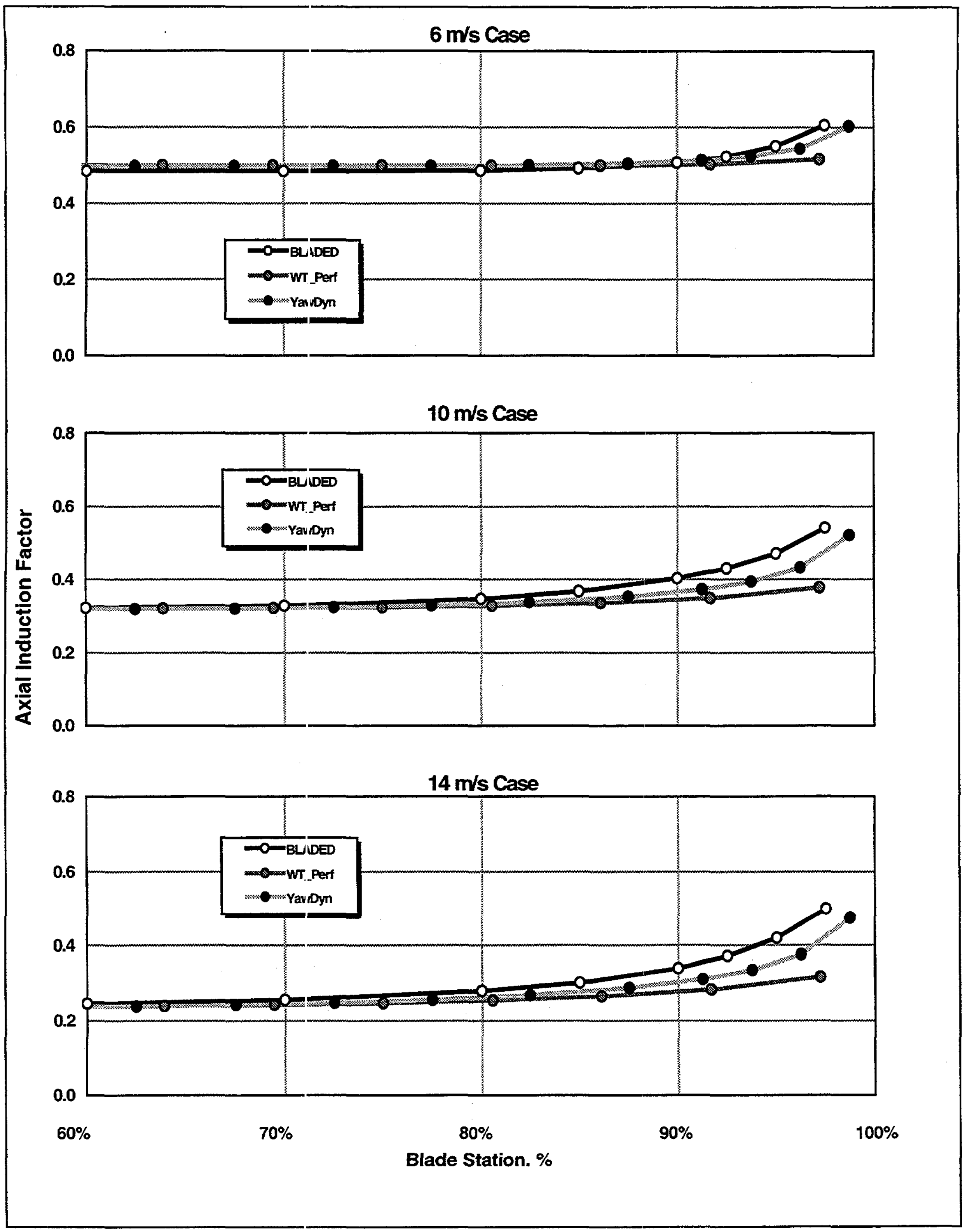

Figure 1. Axial Induction Factor for the Simple Turbine.

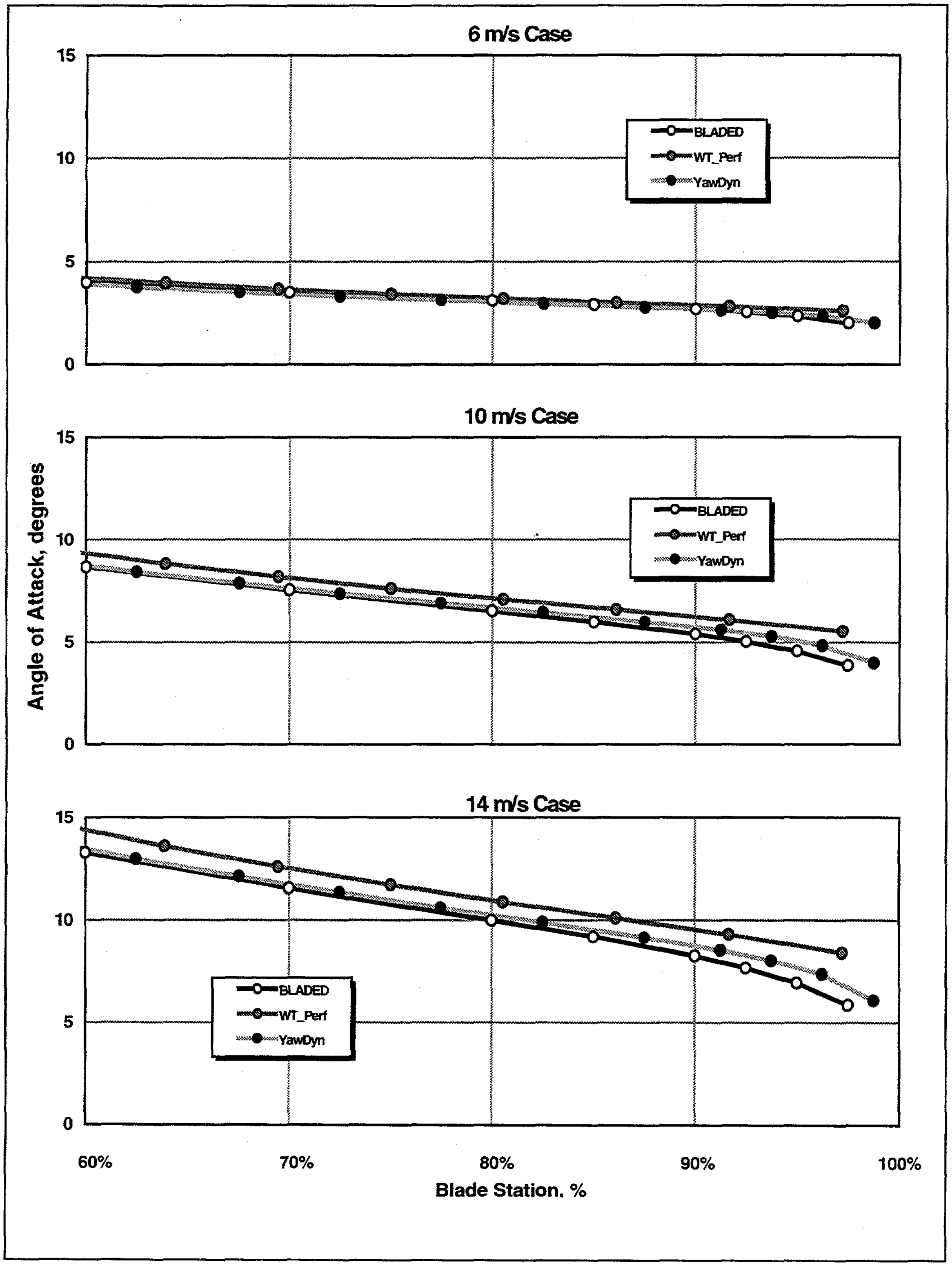

Figure 2. Angle of Attack for the Simple Turbine.

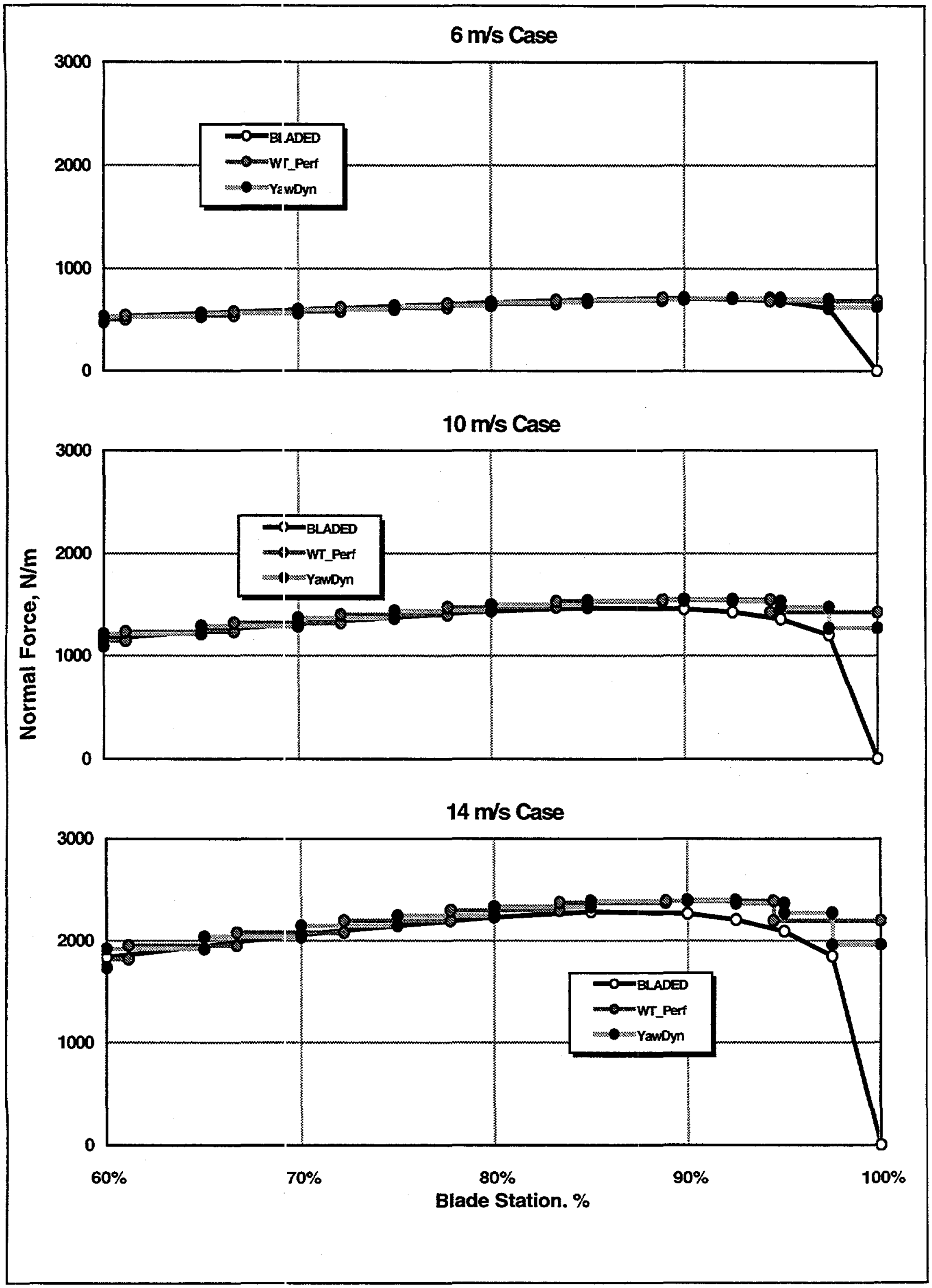

Figure 3. Normal Force for the Simple Turbine.

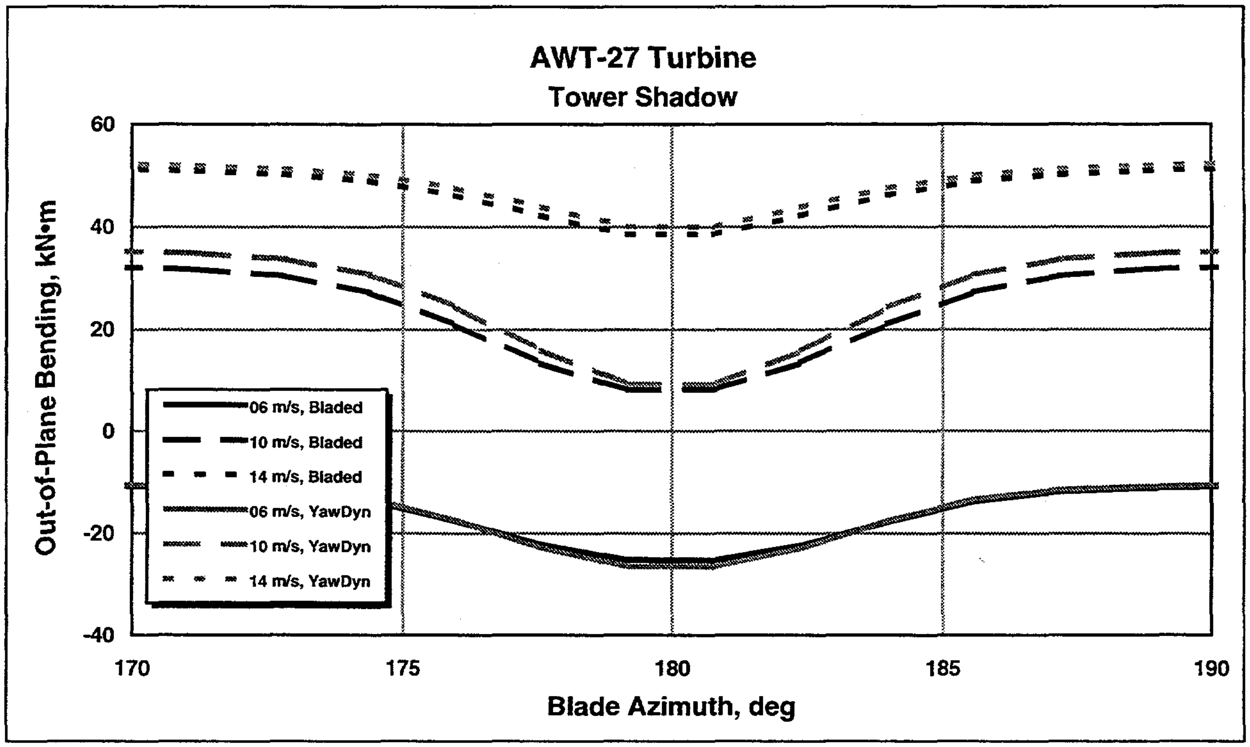

Figure 4. The Effects of Tower Shadow on Out-of-Plane Bending Moments.

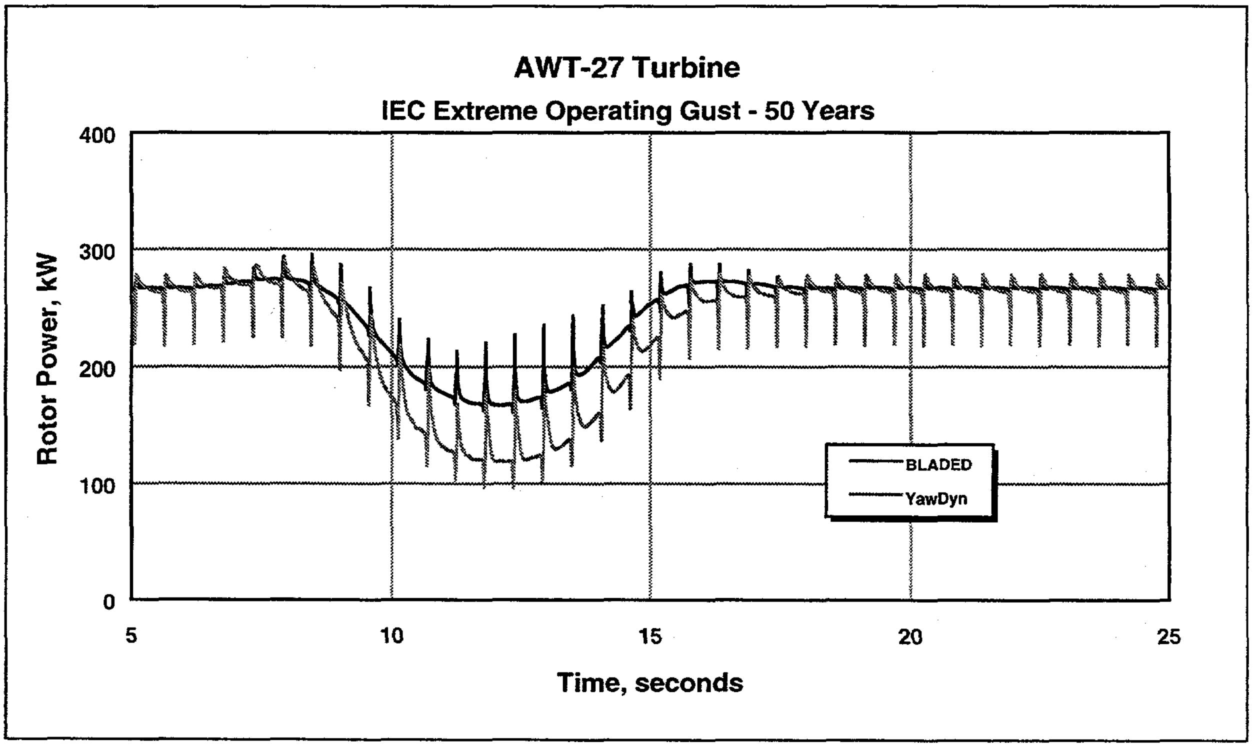

Figure 5. Rotor Power Excursion due to Extreme Operating Gust.