January 2002 • NREL/CP-500-31243

Conference Paper

The Nebulous Art of Using Wind-Tunnel Airfoil Data for Predicting Rotor Performance: Preprint

James L. Tangler

To be presented at the 21st ASME Wind Energy Conference
Reno, Nevada
January 14-17, 2002

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

NOTICE

The submitted manuscript has been offered by an employee of the Midwest Research Institute (MRI), a contractor of the US Government under Contract No. DE-AC36-99GO10337. Accordingly, the US Government and MRI retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

♻ Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

The Nebulous Art of Using Wind-Tunnel Airfoil Data for Predicting Rotor Performance

James L. Tangler
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado, 80401-3393

Abstract

The objective of this study was threefold: to evaluate different two-dimensional S809 airfoil data sets in the prediction of rotor performance; to compare blade-element momentum rotor predicted results to lifting-surface, prescribed-wake results; and to compare the NASA Ames combined experiment rotor measured data with the two different performance prediction methods. The S809 airfoil data sets evaluated included those from Delft University of Technology, Ohio State University, and Colorado State University. The performance prediction comparison with NASA Ames data documents shortcomings of these performance prediction methods and recommends the use of the lifting-surface, prescribed-wake method over blade-element momentum theory for future analytical improvements.

Introduction

Improvement to aerodynamic performance prediction codes based on comparisons with field-measured power curves has inherent limitations. In an unsteady field environment, turbulence induces error and wind shear alters the power curve relative to the steady state assumption on which the performance prediction methods are based. Turbulence-induced errors occur when using the method of bins for measuring power. For each wind speed bin, the sum of the wind speeds cubed is greater than the cube of the mean wind speed. This relationship results in the power curve rotating about some mean wind speed value, yielding too high a power value at low wind speeds and too low a value at high wind speeds as stall is encountered. Compounding this error is the hub-height wind speed measurement that, in the presence of wind shear, is not representative of the rotor disc average.

The need for an accurate measured steady state power curve for correlating with predicted performance has been a research priority difficult to achieve outside of a large wind tunnel. The opportunity to test a full-scale, 10-m (33-ft) diameter, wind turbine in the NASA Ames 24.4- x 36.6-m (80- x 120-ft) wind tunnel[1] represented a opportunity to acquire a unique data set. This data set should help advance the state of the art of more accurately predicting the aerodynamic performance of a wind turbine rotor.

A recent comparison[2] of predictions to measurements for the NASA Ames data set showed that in general blade-element momentum (BEM) theory overpredicts peak power. Reasons for this overprediction are also addressed in this study. Using this unique steady state performance database and two-dimensional wind tunnel data, two aerodynamic performance prediction methods were compared to the NASA data. One of these codes was the basic BEM method, WTPERF[3], while the second code was a more analytically rigorous lifting-surface, prescribed-wake approach called lifting-surface wind turbine (LSWT)[4].

Performance Prediction Codes

Blade-Element Momentum

Because of its simplicity, steady state performance prediction using BEM theory has been the mainstay of the wind industry for predicting rotor performance. Various versions of BEM exist, beginning with PROP[5] and followed by many other versions, such as PROP93[6], PROPID[7], and WTPERF[3]. For this paper, rotor performance predictions were acquired using a recent version of BEM theory, WTPERF.

Some limitations of BEM that affect its accuracy are related to simplifications that are not easily corrected. These error-producing simplifications begin with the assumption of uniform inflow over each rotor disc annulus and no interaction between annuluses. Also, the tip loss model accounts for blade number effects, but not effects due to differences in blade planform, which must be modeled with lifting-surface theory. Finally, a two-dimensional (2-D) assumption relates effective angle of attack to local blade loads for a three-dimensional (3-D) environment. In addition, some versions of BEM numerically model the blade with equally spaced radial segments, which results in poor resolution of loading in the tip region where it should rapidly drop to zero. Insufficient resolution of the tip region typically leads to an overprediction of the tip loading and peak power.

Lifting-Surface, Prescribed-Wake

Modeling the rotor blades with a lifting surface and the resulting vortex wake (Fig.1) eliminates errors resulting from the simplifications mentioned for BEM theory. The local inflow for each annulus is now greater at each blade than the average of the annulus because of induced effects from the blade trailing vorticity. Greater local induction leads to lower angle of attack distributions and greater induced drag. Lifting-surface wake theory also allows interaction between the rotor annuluses and blade surface chordwise panels. This formulation eliminates the need for a tip loss model and provides a more accurate radial load distribution. A lifting surface that includes chordwise panels[8] results in lower outboard loading relative to a simpler lifting line formulation.

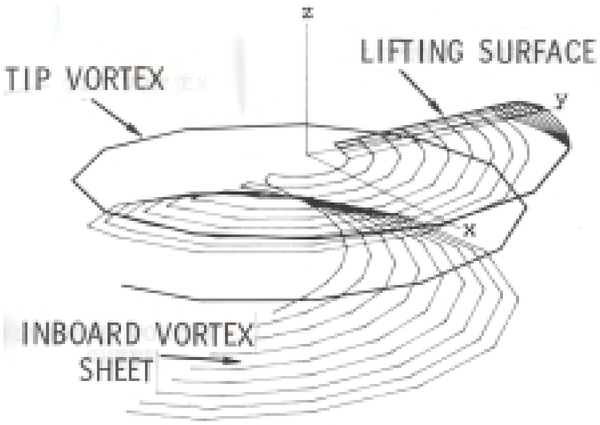


Fig. 1. Blade and wake model for LSWT [8].

With lifting surface, the 3-D relationship between effective angle of attack and local blade loads is reflected through an inner-loop iteration that modifies the 2-D linear lift curve slope to ensure compatibility between the resulting effective 3-D linear lift curve slope and the potential flow circulation.

Numerically modeling the blade tip and root regions of the blade with the cosine radial segment distribution option in LSWT better follows the large gradients in loading that are present as a result of the shed tip and root vorticity. Probably the biggest unknown of the LSWT method is how closely the prescribed wake geometry represents reality. Recent wake studies[1,9] should provide better calibration of the wake equations, which in turn influences the predicted performance.

This study focused on axis-symmetric, steady state performance prediction. The LSWT method also includes inputs for a wind shear profile, tower shadow, and off-axis rotor shaft alignment. These influences add additional asymmetric displacement to the wake model. Computer execution time for LSWT is about 10 times greater than a comparable case with BEM. Using a 700 MHz Pentium III required about 7 seconds for a 15-point wind speed sweep versus less than a second for BEM.

NASA/CER Experimental Data

Wind-Tunnel CER Test

Rotor test data were acquired in the NASA Ames 24.4- x 36.6-m (80- x 120-ft), wind-tunnel test section. The test configuration for the comparison with predictions was a constant-speed (72 rpm), two-bladed, upwind, stall-regulated rotor. Rotor blades[10] for this test had a linear chord taper with a nonlinear twist distribution as shown in Fig. 2, and operated with a 3 degree tip pitch toward feather relative to the airfoil chord line. The radius from the center of rotation, which includes both blade and hub, was 5.03-m (16.5-ft). The S809 airfoil was used from blade root to tip for simplicity and because of the availability of 2-D wind-tunnel data from several wind tunnels.

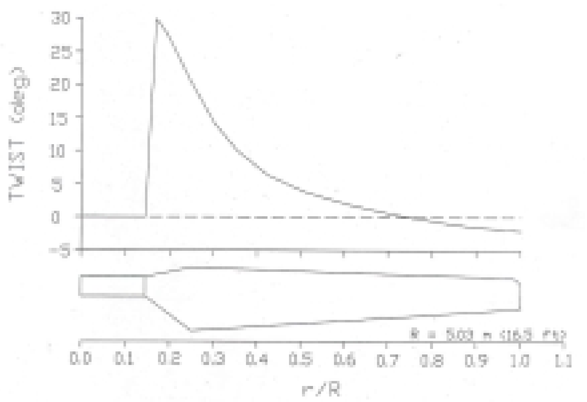


Fig. 2. Chord and twist distribution for the CER blade[10].

Rotor Performance Data

This unique data set is considered to be the only comprehensive, steady state, wind-tunnel data set in existence for a 10-m (33-ft) diameter rotor. Comparisons in this paper were limited to rotor power, inflow distributions, and normal and tangential force coefficients (C_n, C_t). These force coefficients are perpendicular and parallel to the airfoil chord line. Measured rotor power used for these comparisons was based on low-speed-shaft torque measurements. The inflow measurements at five spanwise stations (r/R = 0.30, 0.47, 0.63, 0.80, 0.95) were acquired using five-hole pressure probes. Although no correction was applied for converting the inflow angle to angle of attack in this study, a 3-D correction[11] is recommended in lieu of a 2-D correction. Values of C_n and C_t at the five spanwise stations were derived from 22 pressure taps per station. Integration of the average pressure between adjacent taps projected onto the chord line provided values of C_n. Integration of the same average pressure projected onto an axis orthogonal to the chord line provided values of C_t. Rae and Pope[12] describe this procedure in *Low-Speed Wind Tunnel Testing*.

Prediction and Measurement Comparisons

S809 Airfoil Data Sets

A comparison of three, 2-D, S809 airfoil data sets of section lift and profile drag coefficients (C_l, C_d) are shown in Fig. 3. Two of these data sets, the Delft[13] and the Ohio State University[14] (OSU) data, are for a Reynolds number of 1,000,000, while the Colorado State University[15] (CSU) data set is for a Reynolds number of 650,000. The tip-region Reynolds number for the NASA Ames test was close to 1,000,000. Noticeable differences are seen between these 2-D airfoil data sets that will have a significant influence on the predicted performance with WTPERF as seen in Fig. 4. For these predictions 2-D airfoil data was used only up to an angle of attack of 16 degrees without any stall delay model.

The zero angle of attack, lift-coefficient of the OSU data is noticeably lower than the other two data sets and the Eppler[16] code prediction. This leads to a lower predicted power at 5 m/s (16 ft/s) compared to that predicted with the Delft and CSU data sets. The CSU data have a maximum lift coefficient lower than the other two data sets, largely as a result of its lower Reynolds number. The predicted peak power is also the lowest largely as a result of the low maximum lift coefficient. The minimum drag of the CSU data is unreasonably low relative to the other two data sets, and relative to Eppler code predictions. The low minimum drag results in a higher predicted power at 5 to 7 m/s (16 to 23 ft/s).

The deficiency in predicted power from 7 to 10 m/s (23 to 33 ft/s) is largely due to the omission of a stall delay model for modifying the 2-D wind tunnel data. Differences in the three airfoil data sets clearly manifest themselves in different predicted power curves, particularly around peak power. The over prediction in peak power for all three airfoil data set is largely due to using 2-D data only up to 16 degrees without the following rapid drop in C_l resulting from flow separation. After 16 degrees flat plate theory is used for determining values of C_l and C_d. Although this procedure results in an over prediction of peak power it does illustrate the significant differences due to the three airfoil data tables.

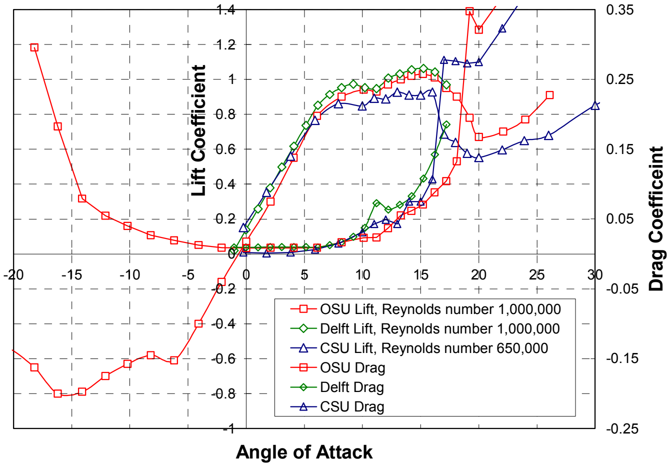


Fig. 3. Comparison of S809 wind tunnel data sets.

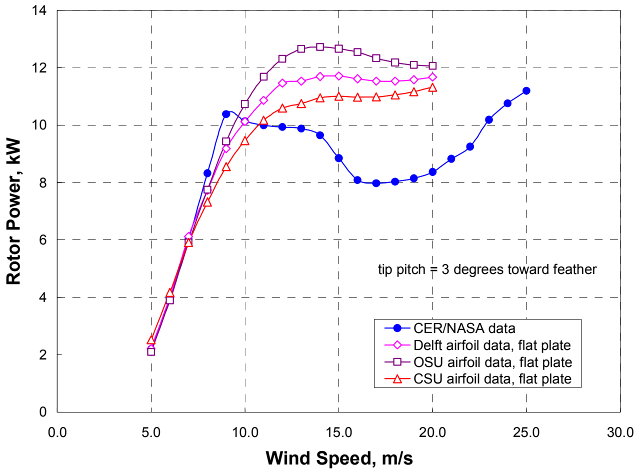


Fig. 4. Predicted performance using WTPERF and different wind-tunnel data sets.

Of these three data sets, the OSU data set was chosen for the comparison between the BEM and LSWT performance prediction codes, and their comparison with NASA Ames data. This choice does not imply the OSU data set to be more accurate than the Delft data. For this study, the absolute values of the predictions are less important than the relative differences that were used to draw most conclusions.

Most experts agree a stall delay model is needed for the highly 3-D inboard region, which normally precludes the use of the rapid drop in C_l that is associated with 2-D data. However, over the outboard part of the blade, 2-D data including the rapid drop in C_l after 16 degrees

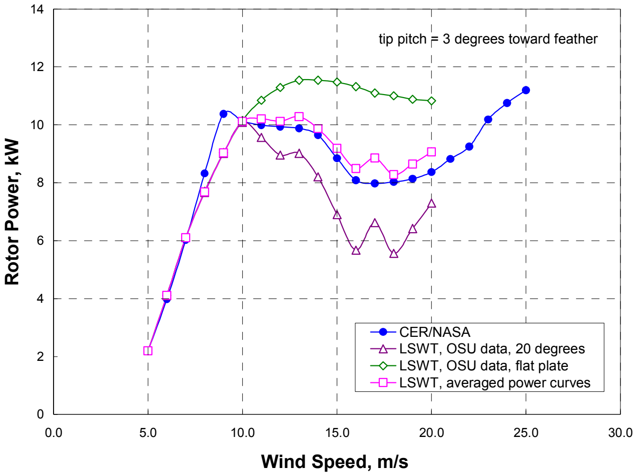


Fig. 5. Error in predicted performance resulting from 2-D stall.

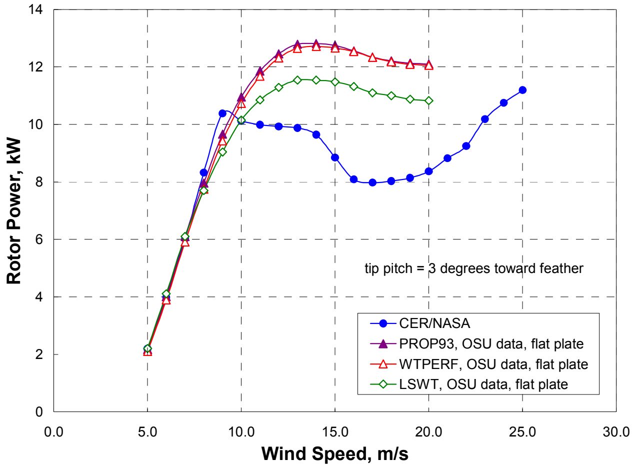


Fig. 6. Predicted performance comparison and NASA Ames data.

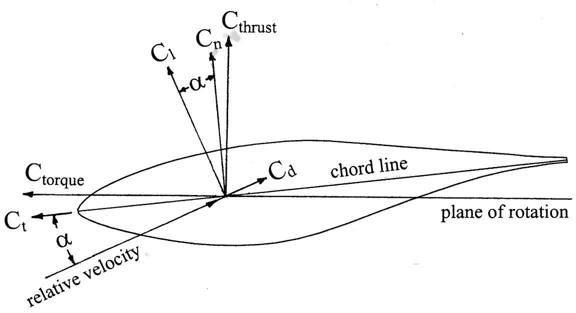
may give better correlation with test data. Some evidence of this can be seen in the power curve of Fig. 5. The power was predicted with LSWT using the 2-D OSU airfoil data with and without the abrupt drop in lift coefficient at 20 and 16 degrees, respectively. The abrupt drop in C_l results in an abnormally rapid fall off in peak power relative to measured data. A gradual transition to flat plate theory at 16 degrees results in an overprediction of peak power. When both of the predicted power curves are averaged together the resulting curve follows the measured data reasonably well after 10 m/s (33 ft/s). This tends to provide some credibility for using 2-D data out to 20 degrees over the outer part of the blade or some modification thereof. Again, the discrepancy between predicted and measured power between 8 to 10 m/s (26 to 33 ft/s) is attributed to the omission of a stall delay model.

BEM and LSWT Power Curves Comparisons

Comparisons of BEM (WTPERF and PROP93) and LSWT predictions with the measured power curve are shown in Fig. 6. At low wind speeds (high tip-speed ratios) up to 8 m/s (26 ft/s) both BEM and LSWT are in good agreement with measured power. At moderate wind speeds, both BEM and LSWT underpredict the power, largely because of the omission of a stall-delay model. At high wind speeds, predicted peak power with LSWT is closer to measured peak power. In this region, BEM theory can be expected to result in excessive angle of attack distributions at high wind speeds as a result of the uniform inflow assumption. The slight difference in peak power between the two BEM codes, WTPERF and PROP93, is due to different versions of the Prandtl tip loss models.

Blade-Element Data Comparisons

Blade-element data comparisons prove to be invaluable in helping to understand the reasons for the discrepancy between the predicted and measured power curves. In this study, comparisons of angle of attack (α) distributions relative to the airfoil chord line, normal force coefficient (C_n), and tangential force coefficient (C_t), provided insight for the discrepancies between performance prediction codes, and discrepancies between predictions and measured results. The following equations were used to calculate the values of C_n and C_t.



$$C_n = C_l(\cos\alpha) + C_d(\sin\alpha) \qquad \text{(Eq. 1)}$$

$$C_t = C_l(\sin\alpha) - C_d(\cos\alpha) \qquad \text{(Eq. 2)}$$

A comparison of predicted angle of attack distributions and measured inflow distributions are shown in Fig. 7 for wind speeds from 5 to 19 m/s (16 to 62 ft/s). At low wind speeds little difference is seen between WTPERF and LSWT, other than at the tip, where the radial cosine distribution of blade segments used in LSWT results in a prediction close to the tip (r/R = 0.99). However, as the wind speed increases above 10 m/s (33 ft/s), WTPERF predicts an increasingly higher angle of attack relative to LSWT. The reason for this higher angle of attack is the uniform inflow assumption associated with BEM theory[2,16]. LSWT is also seen to

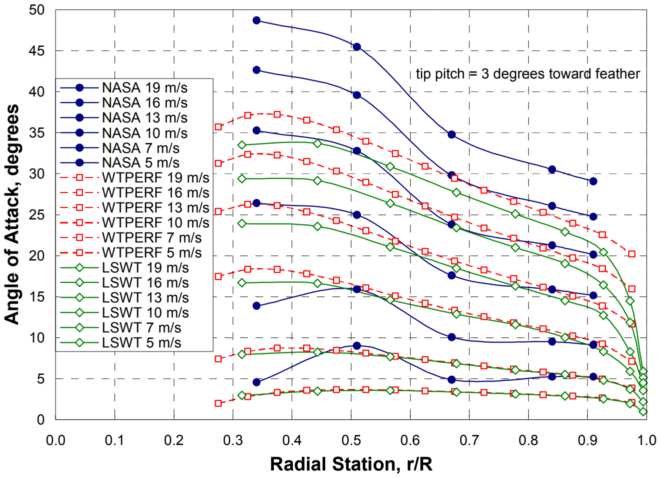


Fig. 7. Comparison of predicted angle of attack and measured inflow distribution.

have a much lower angle of attack distribution in the tip region with increasing wind speed, due largely to the strong tip vortex induced effect. Neglecting this induced effect in BEM leads to additional error in the prediction of peak power.

Only a qualitative comparison of the measured inflow distribution can be made with the predicted angle of attack distributions because no correction has been applied to the measured inflow angles in front of the blade. An interesting observation in the inflow distribution is the high angle of attack or blade induced upwash at 50% radius for low wind speeds. This high induced upwash extends toward the hub at higher wind speeds. The cause of the upwash may be due to a vortex that lies just above the blade surface in this region. A delta wing at high angles of attack exhibits similar behavior.

The comparison of predicted and measured C_n is shown in Fig. 8 for wind speeds of 7, 10, and 13 m/s (23, 33, and 43 ft/s). At 7 m/s agreement between predictions and measurements is reasonably good. A noticeable discrepancy at all three wind speeds is that the measured C_n outboard of 80% radius is lower than predictions. An expected observation is the much greater measured C_n inboard at 10 and 13 m/s (33 and 43 ft/s), which correspond to angles of attack above stall. No stall-delay model was included in the predictions that would reduce this discrepancy.

The comparison of predicted and measured C_t is shown in Fig. 9 for wind speeds of 7, 10, and 13 m/s (23, 33, and 43 ft/s). Below stall, at 7 m/s (23 ft/s), WTPREP and LSWT are in agreement with the measured C_t distribution over most of the span. In the root region some difference is seen between prediction and

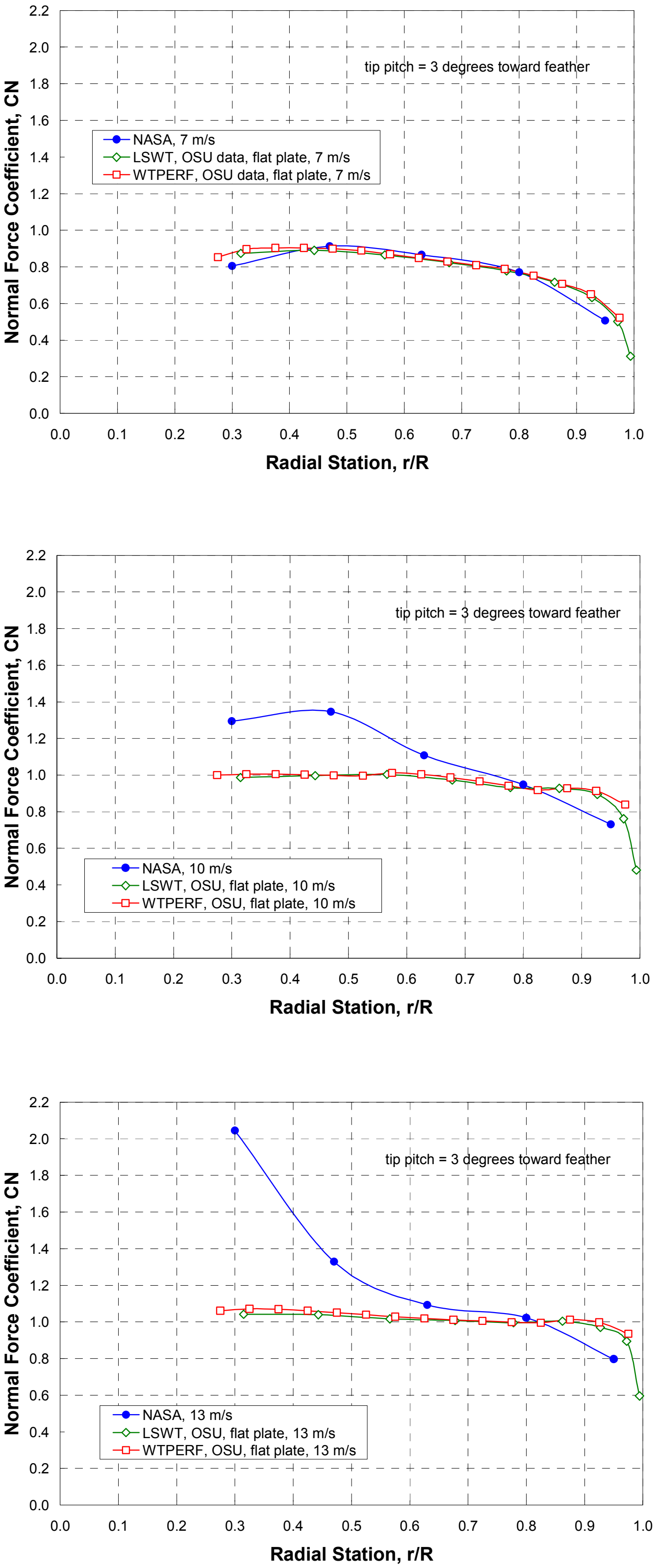


Fig. 8. Comparison of predicted and measured normal force coefficients, 7, 10, 13 m/s (23, 33, and 43 ft/s).

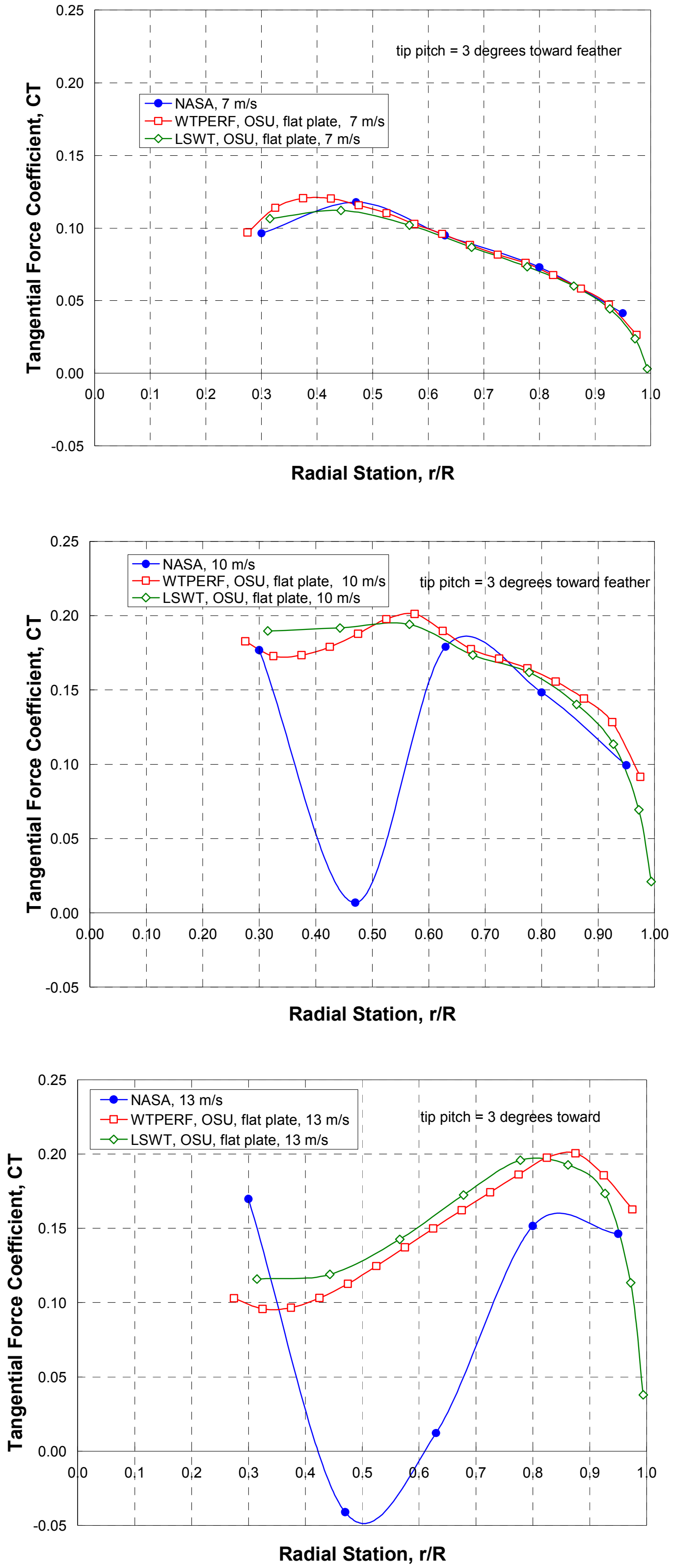


Fig. 9. Comparison of predicted and measured tangential force coefficients, 7, 10, 13 m/s (23, 33, and 43 ft/s).

measurement. At 10 and 13 m/s (33 and 43 ft/s) the inner half of the blade is predicted to be largely stalled and is not in agreement with the measured data. The drop in C_t to negative values implies much higher than predicted drag values associated with an inflow phenomenon not modeled in the predictions. This large drop in C_t may be the result of an attached vortex above the blade that contributes substantial drag.

Conclusions

The BEM performance prediction method has several inherent shortcomings that are overcome through the use of the LSWT performance prediction method.

At medium wind speeds, the uniform induction assumption for each annulus in BEM results in an over-prediction of the angle of attack distribution that worsens with increasing wind speed. The more physically accurate approach provided by LSWT should provide more realistic angle of attack distributions.

Another BEM shortcoming, not easily corrected, is the inadequate tip loss model. The LSWT formulation replaces the tip loss model with a lifting surface to accurately account for both blade number and planform induced effects.

Numerical modeling of the blade root and tip region in both BEM and LSWT is best done using a cosine distribution of the radial blade segments. Equal-size blade element results in excessive tip loading due to poor numerical resolution of the large tip gradient.

The discrepancy between predicted and measured C_n out to 60% radius is due largely to the omission of a stall-delay model. The formulation of this model should be further explored. Measured results toward the root that include a large upwash, high C_n, and a large drop in C_t may result from a standing vortex attached to the suction surface of the blade.

Further study of the LSWT performance prediction method should include verification of the prescribed wake geometry against new model rotor and full-scale NASA Ames wake data. Accurate prescribed wake equations are necessary for accurate angle of attack distributions.

Acknowledgments

This work was supported under a DOE contract. The assistance of M. Hand and L. J. Fingersh in preparing the CER data is gratefully acknowledged.

References

[1] Hand, M., et.al., "Unsteady Aerodynamics Experiment Phase VI: Wind Tunnel Test Configurations and Available Data Campaigns," NREL Report to be published 2001.

[2] Simms, D., et al., "Unsteady Aerodynamics Experiment in the NASA-Ames Wind Tunnel: A Comparison of Predictions to Measurements," NREL/TP-500-29494, June 2001.

[3] Buhl, M.L., "WT_PERF User's Guide," NREL, 2000.

[4] Kocurek, D., "Lifting Surface Performance Analysis for Horizontal Axis Wind Turbines," SERI/STR-217-3163, 1987.

[5] Wilson, R.E., and Walker, S. N., "Performance Analysis Program for Propeller Type Wind Turbines," Oregon State University, 1976.

[6] McCarty, J., "PROP93 User's Guide," Alternative Energy Institute, 1993.

[7] Selig, M.S., and Tangler, J.L., "Development and Application of a Multipoint Inverse Design Method for Horizontal Axis Wind Turbines," *Wind Engineering*, Vol.19, No. 2, 1995, pp 91-105.

[8] Kocurek, D.J., "Hover Performance Methodology at Bell Helicopter Textron," 36th Annual Forum of the American Helicopter Society, Washington D.C., May 1980.

[9] Fisichella, C.J., "An Improved Prescribed Wake Analysis for Wind Turbine Rotors," PhD Thesis, M.E. Dept., Univ. of Ill., 2001.

[10] Giguere, P., and Selig, M.S., "Design of a Tapered and Twisted Blade for the NREL Combined Experiment Rotor," Subcontract No. XAF-4-14076-03, June 1998.

[11] Whale, J., et al. "Correcting Inflow Measurements from HAWT's Using a Lifting Surface Code," ASME Wind Energy Symposium, Reno, NV, January 1999.

[12] Rae, W.H., and Pope, A., "Low-Speed Wind Tunnel Testing," Wiley & Sons, 1984.

[13] Somers, D.M., "Design and Experimental Results for the S809 Airfoil," NREL/SR-440-6918, 1997.

[14] Reuss, R.R., et al. "Effects of Grit Roughness and Pitch Oscillations on the S809 Airfoil," NREL/TP-442-7817, 1995.

[15] Butterfield, C.P., Musial, W.P., and Simms, D.A., "Combined Experiment Phase I Final Report," NREL/TP-257-4655, 1992.

[16] Eppler, R., "Airfoil Program System, PROFIL98," User's Guide, 1998.

[17] van Bussel, G.J.W., "The Aerodynamics of Horizontal Axis Wind Turbine Rotors Explored with Asymptotic Expansion Methods," PhD Thesis, Technical University Delft, ISBN 90-9008848-2, 1995.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB NO. 0704-0188*

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE January 2002	3. REPORT TYPE AND DATES COVERED Conference paper

4. TITLE AND SUBTITLE The Nebulous Art of Using Wind-Tunnel Airfoil Data for Predicting Rotor Performance: Preprint	5. FUNDING NUMBERS WER21120
6. AUTHOR(S) James L. Tangler	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	8. PERFORMING ORGANIZATION REPORT NUMBER NREL/CP-500-31243
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The objective of this study was threefold: to evaluate different two-dimensional S809 airfoil data sets in the prediction of rotor performance; to compare blade-element momentum rotor predicted results to lifting-surface, prescribed-wake results; and to compare the NASA Ames combined experiment rotor measured data with the two different performance prediction methods. The S809 airfoil data sets evaluated included those from Delft University of Technology, Ohio State University, and Colorado State University. The performance prediction comparison with NASA Ames data documents shortcomings of these performance prediction methods and recommends the use of the lifting-surface, prescribed-wake method over blade-element momentum theory for future analytical improvements.

14. SUBJECT TERMS wind energy; wind-tunnel airfoil data; rotor performance; wind research	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL