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James L. Tangler

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Golden, Colorado 80401

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AERODYNAMIC RESEARCH EFFORTS AT SERI WIND ENERGY RESEARCH CENTER AT ROCKY FLATS

James L. Tangler
Solar Energy Research Institute
Wind Energy Research Center
1617 Cole Boulevard
Golden, Colorado 80401, USA

The Solar Energy Research Institute (SERI) under contract to the U.S. Department of Energy (DOE) conducts in-house and subcontracted aerodynamic research studies. These efforts deal mainly with performance prediction and enhancement of horizontal axis wind turbines (HAWT's). Two levels of performance prediction theory are currently being used and refined while performance enhancement is being pursued through the development of new special purpose airfoils. A general purpose blade-element/momentum code (PROPSH) has been developed for rapid parametric studies and for use in annual energy calculations. A desirable feature of this code is a post-stall airfoil data synthesization routine that accounts for blade aspect ratio effects. A version of the performance code is also being developed to provide a better determination of dynamic stall effects on blade loads and performance as influenced by machine yaw angle, unsteady winds, tower shadow, and wind shear. For detailed wind turbine blade optimization, a more sophisticated lifting-surface/prescribed-wake analysis has recently been developed. This computer code is a transfer of current state-of-the-art helicopter theory into a wind turbine design analysis. The special purpose airfoil design effort is directed toward satisfying the need to tailor airfoil characteristics specifically for HAWT's. The design criteria and the current status of this effort are presented.

1. INTRODUCTION

In the late 1970s wind turbine aerodynamic design concerns centered on the issues of 1.) the accuracy and usefulness of the various performance prediction codes, 2.) the impact dynamic stall has on wind turbine performance and blade loads, 3.) the appropriate method of measuring rotor performance for establishing an accurate performance curve, and 4.) the need to consolidate low Reynolds number airfoil data into a catalog for wind turbine design. These issues were addressed through contracted and in-house research efforts at the Wind Energy Research Center (WERC) at Rocky Flats, which has recently been consolidated with the Solar Energy Research Institute (SERI).

To address the question of how well the various performance prediction codes predict net rotor performance, four contractors used their performance models to calculate the performance of two wind turbines and compared their results to test data. Three codes evaluated were based on blade-element/momentum theory and the fourth was a lifting-line/prescribed-wake model. Three objectives were addressed in this comparison: 1.) to evaluate the limitations and accuracies of the various analytical models; 2.) to identify areas where existing performance models were inadequate; and 3.) to identify where existing test methods are inadequate for correlation purposes. Documentation of this effort can be found in (1). Some of the more pertinent conclusions drawn from this study are:

- o Blade-element/momentum theory substantially underpredicts peak and post-peak power when two-dimensional (2-D) airfoil data tables are utilized after stall. Reasonable agreement can be achieved in this region using synthesized 3-D airfoil data (2).
- o In the windmill brake state, the Glauert empirical approximation has little influence on predicted performance for optimum blade pitch. At pitch angles toward stall the Glauert approximation predicts higher power coefficients than momentum theory.
- o In order to determine wind turbine power from measured generator power at high tip speed ratios (low windspeed), the elimination of hysteresis effects in measured power and accurate determination of the generator efficiency essential.
- o Based on this limited study, no definitive statement can be made on the relative accuracy of blade-element/momentum analysis versus analysis using discrete vortex-type wakes. Further study is needed to systematically compare differences in their respective blade element data.

Dynamic stall, as influenced by wind gusts and tower shadow, was investigated under contract (3) to determine its effect on predicted performance and blade loads for horizontal and vertical axis wind turbines. For fixed pitch horizontal axis wind turbines, the results showed that dynamic stall effects may increase a blade's normal loads and torsional moments by about 10 percent; for vertical axis machines, dynamic stall effects may increase normal blade loads marginally, but would likely result in a substantial increase in the blade's peak torsional moment. The consequence of these loads was indicated to be a reduction in fatigue life. An extensive literature review of dynamic stall is also included in this study. This work—one of the first investigations of dynamic stall effects on wind turbines—is by no means comprehensive. However, it does provide a good starting point, with recommendations for initiating new studies on the subject.

Evaluating the merit of aerodynamic performance prediction codes involves comparing predictions to measurements. However, measured performance data can include as much uncertainty as the predictions if certain precautions aren't observed in the data acquisition process. An awareness of the proper use of the "Method of Bins" in collecting data is essential to eliminate potential sources of error. Discussions of this subject can be found in (4) and (5). In addition, test data need to be accurately characterized by complete information on machine operating characteristics (i.e., blade pitch, yaw tracking, etc.) along with wind characteristics such as directionality, steadiness, and turbulence.

Performance prediction for wind turbines requires airfoil data at relatively low Reynolds numbers. Available airfoil data for this purpose are in a variety of publications not readily known to most designers. To facilitate the location and use of these data, a contracted effort was undertaken with Texas A&M University to consolidate them in a single source (6). The resulting catalog includes data up to a Reynolds number of 3,000,000. Airfoil series in the catalog include those by Eppler, the Wortmann FX-series, the Gottingen-Go series, and NACA four-digit, five-digit, and six-digit airfoils. A cautionary note on the use of the catalog concerns those airfoils having a sharp drag rise at stall such as for the Eppler and FX-series airfoils. These data possess excessive smoothing of the drag data in this region due to the cubic spline curve fitting routine used in generating the curves from discrete data. An addendum containing corrected curves for these data is available (7).

As with any research, it tends to uncover as many new issues as it resolves. Past aerodynamic studies concentrated on accurately calculating net rotor performance for determining annual energy output and the cost of energy. Recent work has recognized the importance of determining the cyclic aerodynamic blade loads for dynamic and fatigue analyses, which strongly affect machine reliability. A meeting of aerodynamic specialists, sponsored by the Wind Energy Research Center at Rocky Flats and the NASA Wind Energy Project Office, focused on current needs and provided recommendations for future aerodynamic research work (8). The present aerodynamic research activities at WERC are based on these observations and recommendations. High priority items from this list that are currently being pursued are:

o Post-stall airfoil characteristics need to be better understood to explain why fixed pitch rotors perform better in high winds than can be predicted using 2-D post-stall airfoil data.
o A more comprehensive study of dynamic stall to include the effects of yawed flow, tower shadow, wind shear, unsteady winds, or any combinations of these factors is needed to quantify its effect on blade loads and performance.
o Blade pressure measurements under controlled conditions with an anemometer array windspeed measurements are needed before performance prediction codes can be further developed to account for unsteady effects.
o Development of special purpose airfoils to improve the aerodynamic and structural performance of horizontal axis wind turbines.

The first three activities support an ongoing in-house task to verify and improve our general purpose blade-element/momentum performance prediction code (PROPSH) and our special purpose lifting-surface/prescribed-wake code used for detailed aerodynamic optimization. The fourth activity supports our in-house task devoted to performance enhancement. The remainder of this paper discusses the two performance prediction codes and related activities along with our special purpose airfoil design activities.

2. BLADE-ELEMENT/MOMENTUM CODE (PROPSH)

At WERC, the standard blade-element/momentum code used for routine performance predictions is called PROPSH. This code was developed in-house from the nondimensional AeroVironment blade-element/momentum PROP code (1). A desirable feature of the AeroVironment PROP code is that it is an efficiently written short code that can sweep tip speed ratio and blade pitch in one computer run. The code includes the Glauert empirical approximation (9) for low windspeed analyses and can accommodate different airfoil data tables for each blade element. Because of these features, the AeroVironment PROP code was considered an ideal building block from which a more useful code, PROPSH, could be developed for general engineering purposes.

The key features that distinguish the WERC PROPSH code from the AeroVironment PROP code are:

o The suffix "SH" in the PROPSH name stands for shaft because yawed flow effects were added to analyze machines operating off the wind axis or with shaft tilt.
o A 3-D post-stall airfoil data synthesization routine was added for better performance prediction at high windspeeds.
o The code was reprogrammed in a dimensional format for practical engineering use.
o Variable blade segment number and airfoil data input (up to 20) was added.

The development of PROPSH was motivated by the need for an easy to operate performance prediction code. The routine use of such a code is not only desirable for rotor blade design but also for performance verification and blade pitch determination for maximum energy extraction at a given wind site. Due to the recent proliferation of microcomputer systems, the PROPSH code has been made available to the wind industry for a nominal fee. The code is available in either Fortran or an IBM operational compatable Microsoft Basic language. Computational time for the Fortran version on an IBM PC is approximately 7 seconds per performance point (i.e., one blade pitch angle at a given tip speed ratio). This version of the code is available directly from SERI WERC. Similar computational times are associated with the Microsoft Basic version, which is offered by JETSTREAM wind systems designers (10).

3. LIFTING-SURFACE/PRESCRIBED-WAKE CODE

The lifting-surface/prescribed-wake performance prediction code being developed by Computational Methodologies is based on state-of-the-art theory (11,12) used in the helicopter industry. A sophisticated design code as this is suitable both for blade geometry optimization and to support research efforts requiring a more accurate estimation of the blade loading in both the spanwise and chordwise directions. A noteworthy feature of this approach is that lifting-surface theory provides the flexibility to account for performance differences due to tip shape geometry, due to aerodynamic surfaces mounted perpendicular to the blade such as dynamic inducers, and resulting from gaps or different pitch in the case of two piece blades. In addition, real wake induced effects on the blade are represented that account for radial and axial wake expansion as influenced by the blade loading.

A lifting-surface blade representation accounts for induced effects associated with aspect ratio or blade geometry. No tip loss correction is applied to the blade loading. Unlike lifting-line theory, both the chordwise distribution of induced velocity and the chordwise variation of freestream velocity are accounted for at each blade station. An accurate estimate of induced drag is dependent on these chordwise properties. Being a thin surface theory, airfoil thickness effects are reflected through the airfoil data tables used in the analysis. The lifting surface blade grid can consist of up to 20 spanwise panels and 5 chordwise panels.

A prescribed-wake geometry provides a rational approach for calculating wake induced effects at the rotor blade. A free wake representation is impractical because of the associated numerical problems and the extensive computer time. Past helicopter research studies (11) have shown that a rotor's wake geometry, in terms of contraction rate and pitch, is related to key rotor parameters such as blade number, twist, and thrust coefficient. In a similar manner, a wind turbine's wake is also governed by these parameters. However, unlike a helicopter wake, flow visualization studies suggest the geometry is dominated by freestream displacement and that distortion due to induced effects are secondary. Based on these considerations, the blade wake interface and near wake region can be defined. The far wake, which begins after the fourth tip vortex passage beneath the blade, is best represented using a generalized vortex cylinder model.

The computer implementation of this code is written in Fortran 77 and was developed on a fixed-disk based microcomputer system with floating point hardware. The source code is 4600 lines, of which 40 percent are comments, and requires 300kb of RAM. Depending on the size of the problem selected (i.e., number of spanwise and chordwise stations), execution time varies from 2 to 7 minutes per performance point.

4. CURRENT PERFORMANCE PREDICTION RESEARCH

A weakness of performance prediction codes is their inability to consistently predict peak power and blade loads on which the machine structural design and cost are strongly dependent. In many cases these quantities are much higher than can be predicted using current performance analyses. In any performance code, peak power and associated blade loads are dependent on an accurate assessment of the airfoil's static and dynamic stall characteristics. The relative importance of each of these has yet to be fully quantified. In an attempt to resolve the influence of each, two studies were undertaken. One of these efforts was to further validate the post-stall (static) synthesization routine of (2) against a comprehensive airfoil data base acquired in the Texas A&M University wind tunnel. The second effort was to develop a version of the PROPSH code with a time variant dynamic stall routine.

The post-stall synthesization routine of (2) is based largely on empirical relationships shown to provide good correlation for the larger NASA machines. This routine was chosen for use in PROPSH because it accounts for post-stall aspect ratio effects and because of its user friendly nature. Without any required user interaction, the routine automatically provides a smooth curve fit from where the airfoil 2-D data leave off up through the highest angle of attack experienced by the blade. A comparison of this synthesization routine to wind tunnel test results is presented in (13). For this comparison, nonrotating wing sections were tested in the Texas A&M wind tunnel. Post-stall performance characteristics were established as a function of aspect ratio, airfoil thickness, and Reynolds number. The test models had a 0.30-m chord and were of the NACA 44XX family of airfoils. Blade aspect ratios of 6, 9, 12, and ∞ were tested for airfoil thicknesses of 9, 12, 15, and 18 percent at Reynolds numbers of 250,000, 500,000, 750,000 and 1,000,000.

Results of the wind tunnel tests (14) showed that in the light stall region, from 15 to 30 degrees, the thinner airfoils acted more as flat plates and produced higher drag, while aspect ratio effects could not be discerned. In this region, the higher induced drag associated with lower aspect ratio is neutralized by the lower pressure drag associated with lower aspect ratio. Aspect ratio effects are not seen to have a net effect on C_D until the angle of attack exceeds 27 degrees. Above this angle, the post-stall airfoil characteristics of C_L and C_D are a strong function of aspect ratio (as expected) and a weak function of airfoil thickness. In the post-stall region, the influence of Reynolds number was negligible for the range tested. Comparison of the equations of (2) showed that they provided substantially higher L/D ratios after stall than could be substantiated by the C_L and C_D test data of Figures 1 and 2. Because of the more optimistic post-stall L/D ratio, when used in blade-element/momentum type analyses, these equations provide a better peak power prediction than is achieved by using equations based on the wind tunnel test. Potential causes of the differences are the inability of nonrotating wind tunnel tests to represent the influence of radial flow effects, which are thought to delay stall, and possible elastic twist effects resulting from the divergence of the post-stall moment coefficent.

The purpose of developing a dynamic stall version of the PROPSH code was to provide a useful tool that would allow dynamic stall to be studied in greater depth than in previous investigations. The new code, being developed under contract by Aerovironment Inc., includes the four causes of dynamic stall: wind shear, tower shadow, yawed flow, and unsteady winds. This code is being exercised for both two- and three-bladed wind turbines to determine the magnitude of dynamic stall effects in terms of rotor blade loads, torsional loads, and power output. Results of the dynamic stall effort to date show a very small loss in peak power. Dynamic stall for HAWT's appears to pertain more to fatigue through its contribution of cyclic loads.

The analysis of the static and dynamic stall effects on blade loads and performance raises many new questions that can only be answered through intensive experimental studies to better quantify the characteristics of the wind as seen by the rotor (15,16) and the causual relationship to both steady and unsteady blade loads. Anemometer arrays are needed to establish the spatial and temporal distribution of the wind inflow while aerodynamic blade loads need to be acquired through the use of pressure transducers encircling the airfoil at one or more blade stations. The response to these loads can then be acquired with strain gages located to measure bending, inplane, and torsional loads. The resulting steady and cyclic loads provide the critical inputs for determining rotor fatigue life and reliability (17); they also provide the basis for the next level of analytical refinements to the theory.

5. PERFORMANCE ENHANCEMENT

In the continuing effort to reduce the cost of energy, various means of enhancing the aerodynamic performance of horizontal axis wind turbines have been proposed and tested. Performance augmentation devices attached to the blades such as dynamic inducers (18) and stationary ones such as concentrators and diffusers (19) have shown substantial power ouput gains. However, when compared to conventional rotors of increased size for comparable power output, their relative cost and reliability is questionable. At WERC, performance enhancement is being pursued through the development of special purpose airfoils, in which performance gains and increased machine reliability are believed possible without impacting machine cost.

Airfoils currently used on horizontal axis wind turbines vary from cambered plates, to well-known airfoils of the NACA 44XX and 23XXX series, to recently designed, special purpose general aviation airfoils such as the LS(1)-0417 Mod. Early airfoil design, during the 1930s, used an empirical design approach to develop the NACA 44XX and 23XXX series airfoils. Over the years, airfoil design theory has progressed to where new airfoils can be designed analytically as was done for the LS(1)-0417 Mod. airfoil currently used on such wind machines as the Carter 250 and EST 80/200. Validated analytical design codes such as the low Reynolds number Eppler code (20) allow airfoils to be tailored for specific applications.

For horizontal axis wind turbines, better performance can be achieved with airfoils designed to be more machine specific in terms of Reynolds number, rotor solidity, mean annual windspeed, and machine operational mode. For low solidity rotors, better performance is achieved when L/D_{max} occurs at medium-to-high values of C_L, while for high solidity rotors lower values of C_L are desired for L/D_{max}. In a similar manner, the higher the mean annual windspeed for which the rotor is being designed, the more desirable it is to shift L/D_{max} to higher values of C_L. Machine operational modes such as fixed blade pitch versus variable blade pitch and constant rpm versus variable rpm also govern the airfoil design. For fixed pitch machine operation, designers have expressed the need for airfoils having a predictable $C_{L_{max}}$ insensitive to airfoil roughness effects. This quality provides for more consistent power output and helps eliminate unexpected operating characteristics that may be detrimental to rotor life. For variable pitch machines, this requirement can be relaxed since the blades can be feathered to avoid stall during high winds. However, for variable rpm machines, the airfoil must be designed to operate effectively over a wider Reynolds number range.

Acknowledging the general airfoil design dependency on rotor solidity, mean annual windspeed, and machine operational mode, the first family of special purpose airfoils was directed toward a class of wind turbines having the following properties:

- Fixed pitch 10-m diameter rotor
- Low solidity rotor with twist and taper
- Mean annual windspeed of 5 to 7 m/sec.

The airfoil family was to consist of three airfoils. The primary airfoil was to be designed for a radial station of (r/R = 0:75), while secondary airfoils would be designed for r/R = 0.40 and 0.90. The thickness of the airfoil for r/R = 0.40 and 0.90 would be expected to be thicker and thinner than the primary airfoil, respectively. To achieve the designed rotor operating characteristics, substantially different design criteria might be required for the inboard airfoil versus the outboard airfoil.

Specific design criteria established for the primary airfoil (r/R = 0.75) were that it have:

- High L/D through laminar flow
- $C_{L_{max}}$ insensitive to surface roughness
- Airfoil thickness of 12 to 15 percent.

With respect to the high L/D, the question arises as to whether it should occur at low, medium, or high lift coefficient. To answer this question, a C_L versus C_D airfoil polar was modified to simulate these hypothetical cases as shown in Figure 3. In cases 1, 2, and 3, a laminar flow bucket was assumed to exist between the C_L values of 0.0 to 0.4, 0.4 to 0.8, and to 0.8 to 1.2, respectively. Rotor performance was calculated using these three cases. The influence on the power coefficient versus tip speed ratio curve is shown in Figure 4. For case 1, the laminar flow bucket at low C_L resulted in some performance improvement at high tip speed ratios (low windspeeds) but contributes little to annual energy output. For case 2, a substantial increase in performance is achieved at medium to high tip speed ratios. Whereas case 3 results in substantial performance improvement at low tip speed ratios (high windspeed). Based on this comparison, a laminar bucket covering the C_L range of 0.4 to 0.8 showed the greatest potential for enhancing annual energy output. The midpoint of the bucket ($C_L = 0.6$) was chosen as the point for which L/D was to be maximized. Associated with this bucket placement, it was also discovered that C_{Lmax} over the outboard portion of the blade had to be restrained so that power output at high windspeeds would not be excessive. This restrain also helps hold down the airfoil moment coefficient, which can contribute to high control loads or elastic twist during stall.

Using this design philosophy, Dan Somers of Airfoils Incorporated is in the final design phase of the first family of special purpose airfoils. Upon completion of this task the primary airfoil of the family is scheduled to be wind tunnel tested to verify its performance characteristics—particularly its C_{Lmax} roughness sensitivity. A diagram of the primary airfoil (r/R = 0.75) is shown in Figure 5. The airfoil geometry is characterized by a rather sharp leading edge with very little forward camber. A moderate amount of laminar flow is present on the upper surface and extensive laminar flow is present on the lower surface. Trailing edge camber is held to a minimum in an effort to restrain C_{Lmax} and minimize the airfoil's pitching moment coefficient. Also illustrated in Figure 6 is an approximation of one of the secondary airfoils designed for the blade root. This thicker airfoil is designed to have its L/D_{max} at a slightly higher value of C_L. The airfoil is designed for a C_{Lmax} as high as possible without any restrain put on the pitching moment coefficient. The combination of these two airfoils designed to the same camber family is expected to improve the performance at low windspeeds and limit peak power at high windspeeds, independent of roughness effects.

6. CONCLUDING REMARKS

Performance prediction methods at WERC have evolved from the relatively simple blade-element/momentum approach (PROPSH), which is ideal for rapid parametric type analyses, to the more rigorous lifting-surface/prescribed-wake approach used for detailed blade optimization. Current and future embellishments of these codes include refinements to the post-stall 3-D airfoil data synthesization routine, the incorporation of dynamic stall unsteady effects, and inclusion of sophisticated turbulent wind input models. Completion of these efforts will establish the need for a more rigorous level of validation characterized by detailed time dependent measurements of wind input, blade airfoil pressure distributions, and strain gauge measurements of cyclic loads. From these data current theory can then be evaluated and refined to provide design codes that better characterize the aerodynamic loads upon which dynamic and fatigue analyses are based. In turn, machine reliability should improve and help provide the needed energy cost reduction that will insure the survival of this viable energy source.

Performance enhancements of HAWT's is being pursued through the development of special purpose airfoil families. It is recognized that rotor airfoil requirements are unique in terms of Reynolds number, rotor solidity, mean annual windspeed, and operational mode. Accounting for these factors, new airfoil families are being developed for fixed and variable pitch wind turbines with consideration of both the constant and variable rpm operational modes. The first of these airfoil families is for the 10-m, constant rpm, fixed pitch class of machines. Desired performance characteristics being sought are enhanced performance at low-to-medium windspeeds through laminar flow and predictable C_{Lmax} independent of roughness effects at high windspeeds. Properly incorporating these characteristics into new machines should also reduce energy cost through improved annual energy output and machine reliability.

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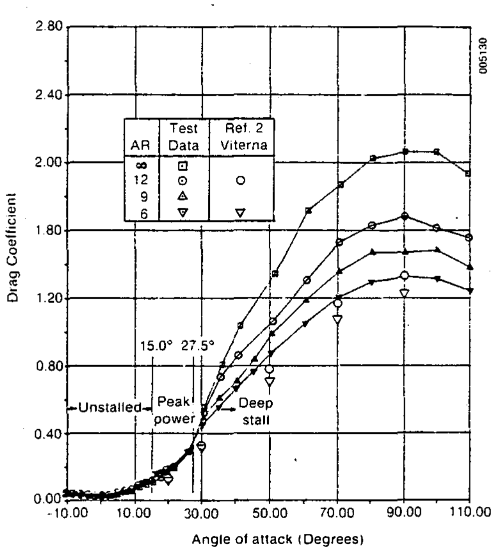

Fig. 1. Effect of Aspect Ratio on Drag Coefficients of the NACA 4418 Airfoil at RN = 0.25 x 10^6.

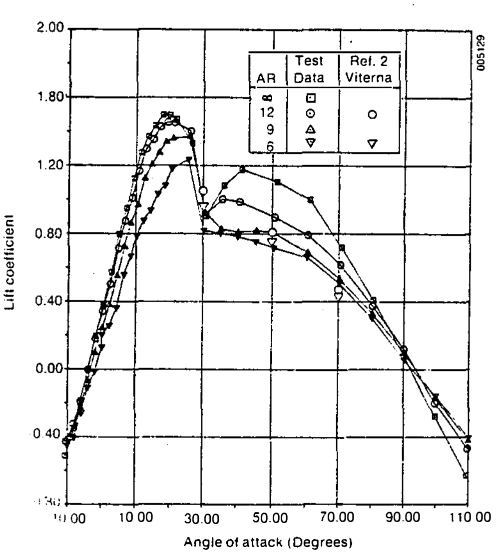

Fig. 2. Effect of Aspect Ratio on Lift Coefficients of the NACA 4418 Airfoil at RN = 0.25 x 10^6.

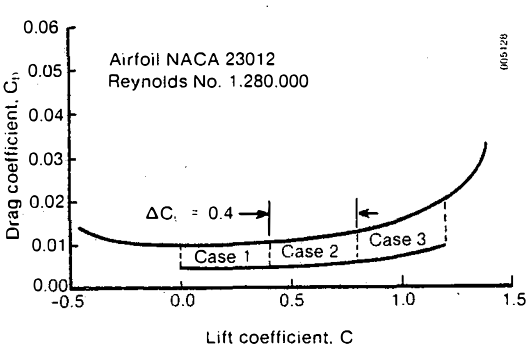

Fig. 3. Evaluation of Laminar Flow Drag Bucket Placement.

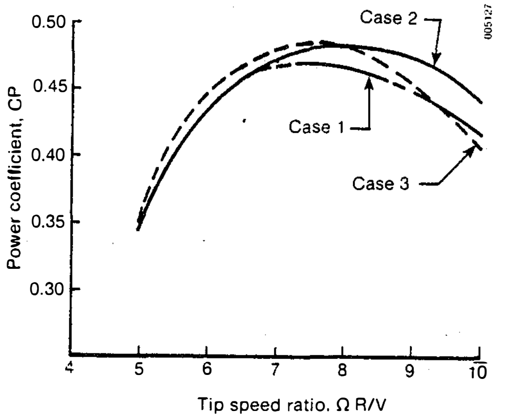

Fig. 4. Effect of Laminar Flow Bucket Placement on Rotor Performance.

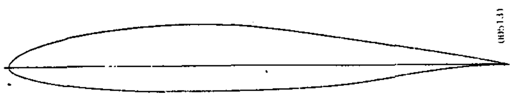

Fig. 5. Special Purpose Airfoil Designed for Blade Outboard Region.

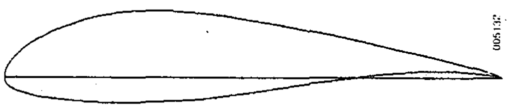

Fig. 6. Special Purpose Airfoil Designed for Blade Root Region.