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Calculated Performance of the NASA Lewis Icing Research Tunnel

Larry A. Viterna
Lewis Research Center
Cleveland, Ohio

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Introduction

The Icing Research Tunnel (IRT) at the NASA Lewis Research Center in Cleveland, Ohio is used extensively to test many classes of aircraft under atmospheric icing conditions. Because of the need to test models at higher Reynolds numbers, a new fan rotor was being designed to increase test section wind speed. As a low cost alternative, a preliminary study was made of the present fan rotor to suggest possible methods to increase tunnel wind speed. This report presents the results of that study.

Analytical Approach

A computer program, WT (see Appendix A), was developed to calculate fan rotor power requirements and output thrust for a closed loop wind tunnel. WT uses blade element theory to calculate aerodynamic forces along the blade using airfoil lift and drag characteristics at an appropriate blade aspect ratio (reference 1). A tip loss model was also used which reduced the lift coefficient to zero for the outer 3 percent of the blade radius. The application of momentum theory is not necessary to determine the axial velocity at the rotor plane. Unlike a propeller, the wind tunnel rotor is prevented from producing an increase in velocity in the slipstream. Velocities at the rotor plane are known from measurements at the test section and the geometry of the tunnel. The rotational induced velocities were assumed to be counteracted by the stationary vanes immediately ahead of the rotor.

The geometry of the IRT fan rotor is given in Table 1 and Figure 1. The airfoil cross section is a Clark Y. The aerodynamic characteristics assumed are given in Figure 2 along with data from reference 2 for a Clark Y with a 12 percent thickness to chord ratio. Slight differences between the measured and assumed data are due to curvefit inaccuracies and adjustments for Reynolds number and aspect ratio. An aspect ratio of infinity was not assumed because the gap between the blade tip and the tunnel wall is not accounted for by an induced velocity calculation.

Table 1 IRT Rotor Characteristics

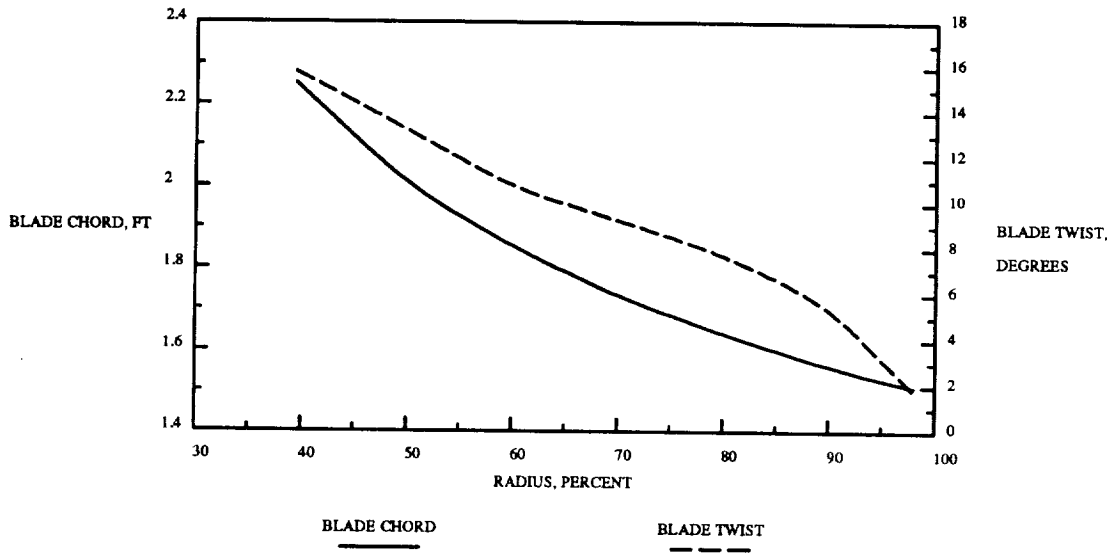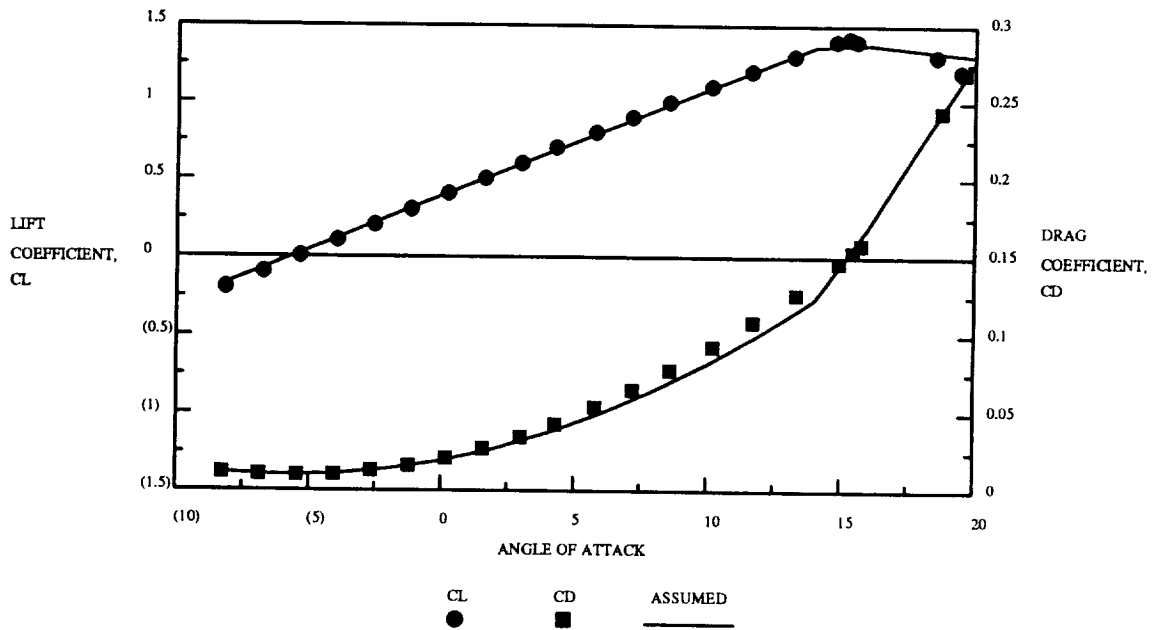|	
Blade Radius, ft.	12.7
Hub Radius, ft	5.0
Number of Blades	12
Rotor Swept Annulus Area, sq ft	428
Test Section Area, sq ft	54

Figure 1 Rotor Blade Chord and Twist Distributions

DATA AT REYNOLDS NUMBER 3.5E6, ASPECT RATIO 6
ASSUMED CHARACTERISTICS FOR REYNOLDS NUMBER 5E6
  AND ASPECT RATIO 9

Figure 2 Clark-Y Airfoil Characteristics

Results

Results from the model were first compared to measured power versus wind speed for the IRT. Power data was available for rotor speeds of 50 through 466 rpm along with the test section wind speeds under empty tunnel conditions. For convenience, the measured electrical power was converted to shaft horsepower at sea level density assuming an 87.5 percent motor efficiency. This data is shown in Figure 3. Test section wind velocities were
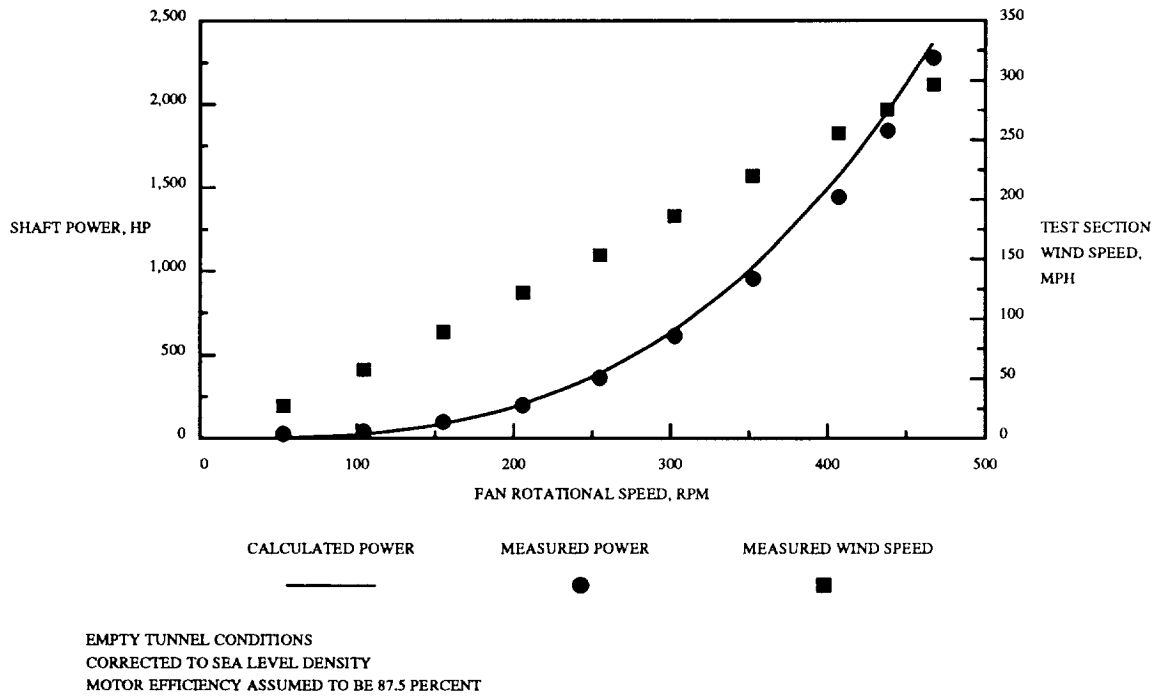
<figure>

SHAFT POWER, HP

TEST SECTION WIND SPEED, MPH

FAN ROTATIONAL SPEED, RPM

| CALCULATED POWER | MEASURED POWER | MEASURED WIND SPEED |

EMPTY TUNNEL CONDITIONS
CORRECTED TO SEA LEVEL DENSITY
MOTOR EFFICIENCY ASSUMED TO BE 87.5 PERCENT

</figure>

Figure 3 Measured and Calculated Power versus Rotor Speed

converted to velocities at the rotor plane based on tunnel cross–sectional area and used as input to the model. Calculated power from the analytical model is also shown in Figure 3 and was found to be in good agreement. Though not apparent due to the scale, at low power, the calculated power is less than the measured power. At these power levels a more realistic variable motor efficiency model would improve agreement.

With some confidence in the model's ability to calculate the aerodynamic forces on the rotor, changes to the rotor geometry were investigated.

Several possible rotor modifications were conceptually considered including reducing tunnel radius, increasing hub radius, increasing pitch angle or rotor speed, changing airfoil cross– section, etc. Of these, rotor speed or blade pitch angle were considered to be of

minimal impact on the present design while still being effective in modifying performance. They are thus studied in detail here.

For the pitch angle study, the rotor speed of 466 rpm was chosen as a baseline. This is above the original design rpm, however, test experience had demonstrated successful operation and lower shaft torque would result at the higher rotor speed. Rotor thrust was chosen to be the principle figure of merit in evaluating the effect of pitch angle on improving tunnel performance due to its relationship to pressure and thus mass flow rate. Figure 4 shows the
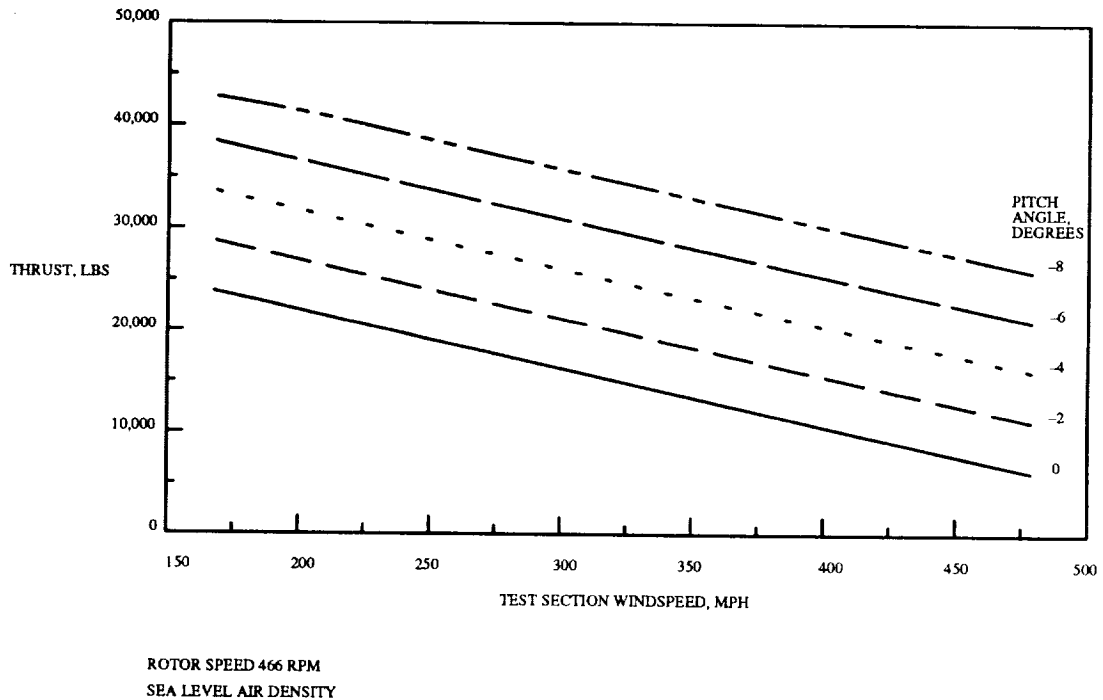

ROTOR SPEED 466 RPM
SEA LEVEL AIR DENSITY

Figure 4 Effect of Blade Pitch Angle on Rotor Performance

calculated thrust as a function of wind speed for pitch angles of 0, –2, –4, –6, and –8 degrees. A pitch angle of 0 is currently used. Negative pitch angles increase angle of attack of the airfoil. As seen in Figure 4, pitch angle has a significant effect on rotor thrust. At a test section wind speed of 300 mph, for example, a pitch change of 6 degrees almost doubles rotor thrust.

Required power must also be considered as more thrust is developed. Figure 5 shows the effect of pitch angle on shaft power. The present pitch angle configuration requires about 2400 horsepower over the range of wind speeds modeled. The present motor in the IRT has a rated power of about 5000 horsepower. A pitch angle of –6 degrees provides the greatest thrust while not exceeding the rated power of the present motor.

To further verify the WT model and test its ability to predict performance over a wide range of conditions, subsequent tests were made in the IRT. The measured data shown in Figure 5
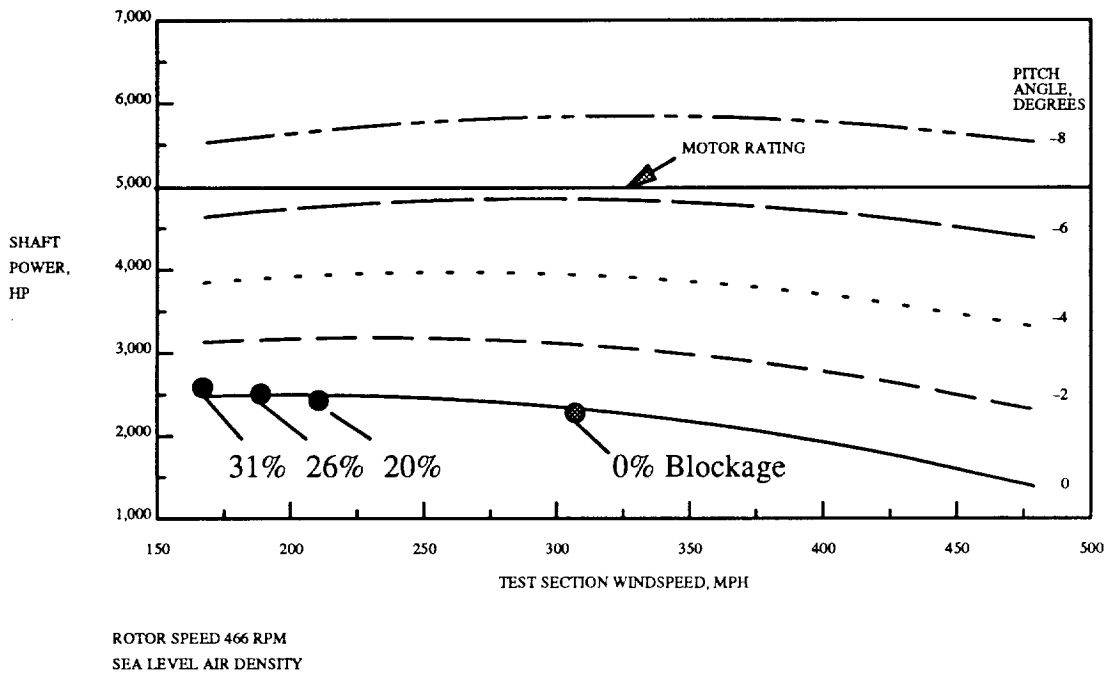
Figure 5 Effect of Pitch Angle on Required Power

shows good agreement between the predicted power calculated by WT and the measured power for 20, 26, and 31% tunnel blockage conditions. The 0% blockage case is shown for reference with the data from Figure 3.

Stall margin is another important consideration. Figure 6 shows the calculated angle of attack at the 75 percent blade radius for a range of tip speed to wind speed ratios and pitch angles of 0 (present configuration) and –6 degrees. The expected open tunnel operating curve is given for reference. Pitching the blade 6 degrees decreases the stall margin by 6 degrees. The 75 percent radius remains in the unstalled region over the normal operating tip speed ratios. At high tip speed ratios, such as during start up, blade sections inboard of the 75 percent radius might operate stalled. This is not expected to prevent the rotor from producing thrust nor cause rapid changes in the aerodynamic forces on the blades. This is because the angle of attack along the radius is not a constant for moderately twisted blades and thus stall is approached gradually. The results of studies of wind turbine rotors, for example, has found no rapid drop in performance during stall. In fact torque remains nearly constant, see for example reference 3. Still it is not recommended that the rotor operate in stall even during startup. It should also be noted that the exact point of stall of an airfoil is often difficult to predict and depends on variables such as surface roughness.

While rotor thrust was used as the figure of merit to evaluate pitch changes, improvement in test section wind speed is of primary concern. It is thus important to relate increased thrust to increased wind speed. To do this, calculated thrust as a function of test section wind
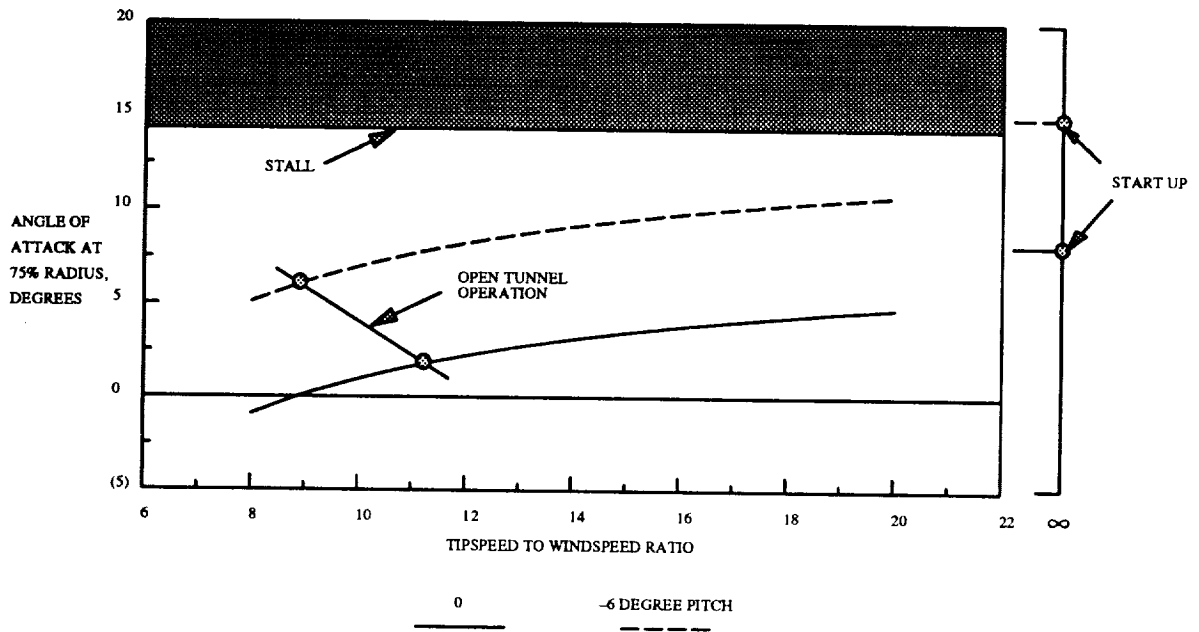
–5–

STALL

OPEN TUNNEL
OPERATION

ANGLE OF
ATTACK AT
75% RADIUS,
DEGREES

START UP

TIPSPEED TO WINDSPEED RATIO

0   −6 DEGREE PITCH

Figure 6 Calculated Angle of Attack at 75 Percent Radius versus Tip Speed to Wind Speed Ratio

speed was determined from the analysis presented in Figure 3 for empty tunnel conditions. A second order regression analysis relating thrust, T, to empty tunnel wind speed, V was found to be

$$T = -141.1 + 8.855xV + 0.155xV^2 \qquad (1)$$

This thrust represents drag loss in the tunnel under empty tunnel conditions and is plotted in Figure 7. Calculated rotor thrust at a constant 466 rpm is also shown in Figure 7 for 0 and −6 degree pitch angles. The intersection of the tunnel drag and rotor thrust curves represents empty tunnel wind speed conditions. The present design has an empty tunnel wind speed of 299 mph and requires 2355 horsepower. The −6 degree pitch modification would increase tunnel speed to about 385 mph or about 29 percent. Required power would increase to about 4860 horsepower but this is still within the capability of the present motor.

Under loaded tunnel conditions the required thrust to overcome the tunnel and test model drag will result in a similar but lower curve in Figure 7. It is expected that the effect of pitch angle on tunnel wind speed will decrease somewhat as the tunnel becomes very heavily loaded.

A similar study was made of increasing rpm to increase thrust while limiting power requirements to 5000 horsepower. This approach has the advantage of no modification to the rotor structure, however, it runs risk of operating at rotor speeds with unknown dynamic response of the blades.
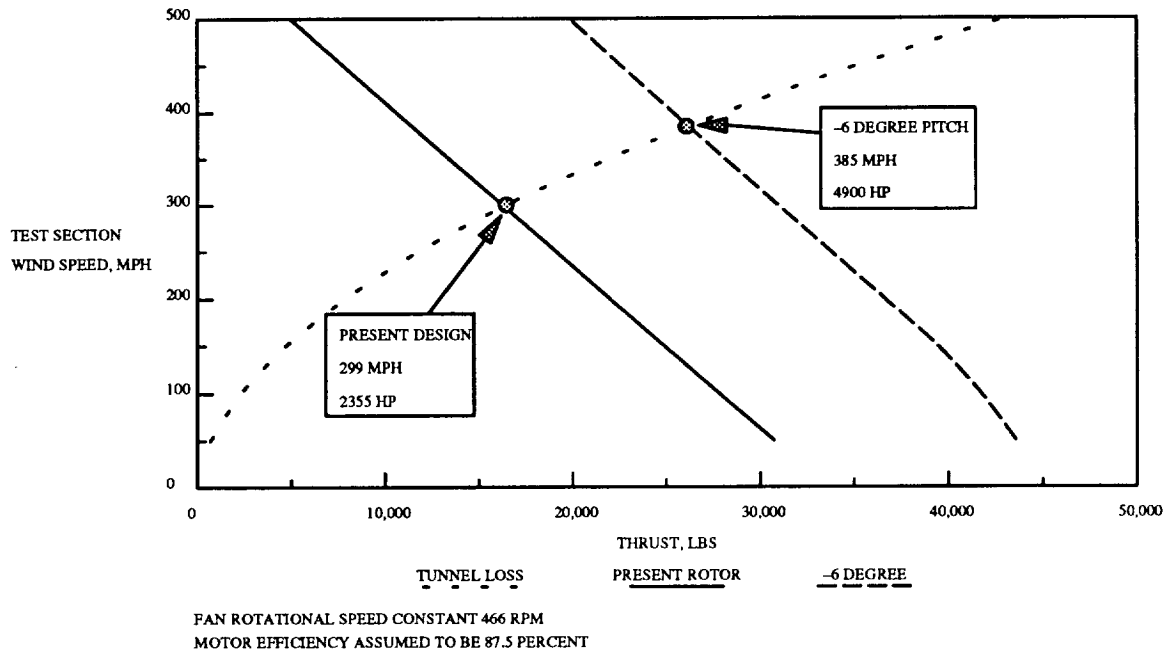
Figure 7 Effect of 6 Degree Blade Pitch Change on Empty Tunnel Maximum Wind speed

An increase in rotor speed of 25 percent to 582 rpm was found to require 4900 horsepower. Figure 8 shows the resulting increase in wind tunnel speed to 375 mph or 26 percent.

Further studies of pitch angle and rotor speed are presented in Table 2. A pitch angle of –3 degrees and a rotor speed of 518 rpm provides good performance as well as good stall margin. This is the recommended configuration based on aerodynamic considerations. While the actual IRT rotor has operated at higher rotational speeds than 518 rpm, structural analysis of the rotor should be made before selecting the design rpm and pitch angle.

Conclusions

With a pitch angle change of about 6 degrees, the present IRT fan rotor could produce sufficient thrust to increase tunnel wind speed by about 29 percent to 385 mph. This increase is at the expense of increase power requirements to about 4860 horsepower. However, this is still within the capability of the present motor. At this pitch angle, most of the rotor will be operating stalled at very low wind speeds such as during start up.

Increasing the rotor speed to 582 rpm with no changes in rotor geometry increases tunnel wind speed by about 26 percent to 377 mph while requiring 4860 horsepower. This rpm exceeds the maximum operating rpm to date.

A pitch change of 3 degrees and a rotor speed of 518 rpm results in an open tunnel wind speed of 383 mph while providing good stall margin even during start up.
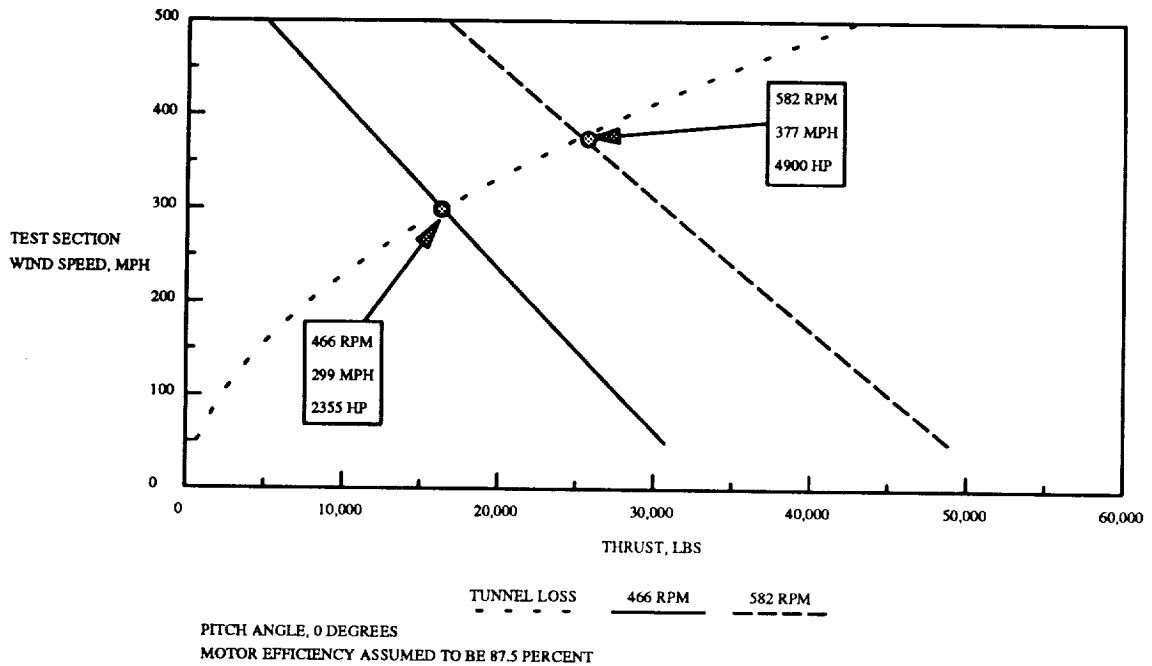
Figure 8 Effect of Rotor Speed on Empty Tunnel Maximum Wind speed

Table 2 Summary of IRT Performance Study

Pitch Angle, Degrees	Rotor Speed, rpm	Shaft Power, hp	Test Section Wind Speed, mph	Comments
0	466	2355	299	Present Rotor
0	582	4860	377	No Structural Changes
−1	560	4900	380	
−2	538	4890	382	
−3	518	4880	383	Best Aero. Compromise
−6	466	4860	385	No Increase in RPM Rotor stalled during startup

The present motor rating of 5000 horsepower and tunnel drag losses limit maximum wind speed in the IRT. From measured data, the rotor fan requires 2355 horsepower at 299 mph. Based on a calculated rotor efficiency of 69.7 percent, the power required to overcome the tunnel drag is 1641 horsepower at 299 mph. Since the power lost to the tunnel increases with the third power of wind speed, the maximum wind speed is 433 mph for even a 100 percent efficient rotor.

Appendix A: The WT Computer Program

This appendix describes how to use the WT computer program. WT, was developed to calculate fan rotor power requirements and output thrust for a closed loop wind tunnel. The program uses blade element theory to calculate aerodynamic forces along the blade using airfoil lift and drag characteristics at an appropriate blade aspect ratio. A tip loss model is also used which reduces the lift coefficient to zero for the outer 3 percent of the blade radius. The application of momentum theory is not used to determine the axial velocity at the rotor plane. Unlike a propeller, the wind tunnel rotor is prevented from producing an increase in velocity in the slipstream. Instead, velocities at the rotor plane are used as input. Other input for WT includes rotational speed, rotor geometry, and airfoil characteristics.

Computer Requirements and Installation

WT exists as a stand–alone program for DOS. WT is provided on 5.25 inch high density floppy diskettes containing the following three files:

> wt.exe
> example_.wts
> wt.dir

The example_.wts file can be read from within WT and contains input data for the example in this appendix.

The wt.dir file is optional and will be created by the WT program if it is missing. It provides for long file name capability under DOS.
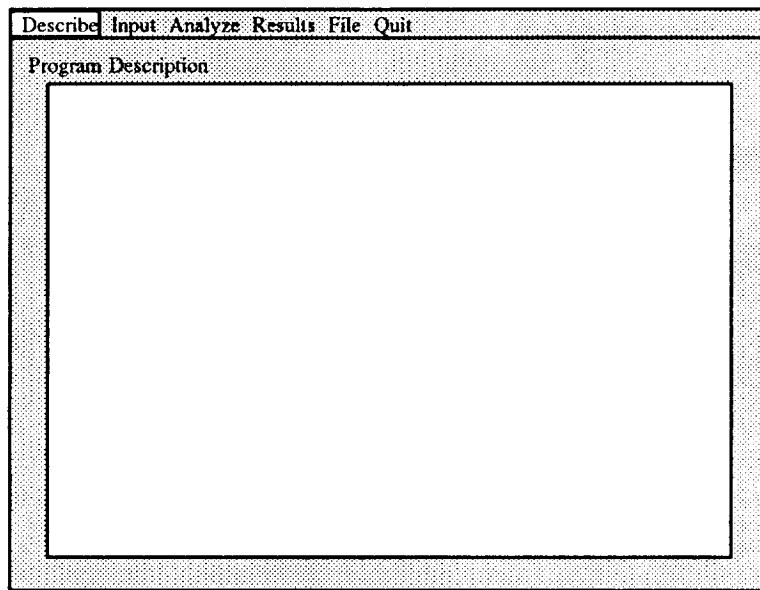
For this version, WT requires an IBM PC or compatible with at least 640 K of memory and DOS 3.1 or higher.

To install WT, simply create a directory and copy the files to it.

To run WT, change to the directory containing the wt.exe file and type "WT" at the DOS prompt.

Preparing the Input

The user interface to WT consists of a cursor/keystroke driven menu along the top of the screen, a data input editor and a file management system. After starting WT the title screen appears followed by the menu screen shown in Figure A1. Menu choices are selected by using left and right cursor motion followed by the [Enter] key. Alternatively, the first character of the selection can be typed with immediate execution of that selection.

```
┌─────────────────────────────────────────────────────┐
│ Describe  Input  Analyze  Results  File  Quit         │
│ ┌───────────────────────────────────────────────────┐ │
│ │ Program Description                                │ │
│ │ ┌───────────────────────────────────────────────┐ │ │
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Figure A1: WT Main Menu Screen

Data entry screens consist of one or more fields. The [Tab] key provides movement between fields and the [Enter] key causes execution of the input data assignments and a return to the previous menu. Note that in the following input fields **all input is assumed to be in metric system mks units, unless specified by the user.**

Operating Conditions

Choosing the *Input* option displays the menu shown in Figure A2. Pressing the [Enter] key will select the operating *Conditions* input option and display the screen shown in Figure A3. Enter the rotor rotational speed in the first field. This may be more than one real number optionally followed by the units. Similarly, the wind speed at the rotor plane is entered in the second field. For the screen shown, two cases are specified (1) 466 rpm with 37.7 mph wind speed and (2) 530 rpm with 43.15 mph wind speed. If either the rotational speed or the wind speed is specified with more than one number the other parameter must be a single number or have just as many numbers as the other. The final field contains the altitude above sea level which can be used to model effects of air density.
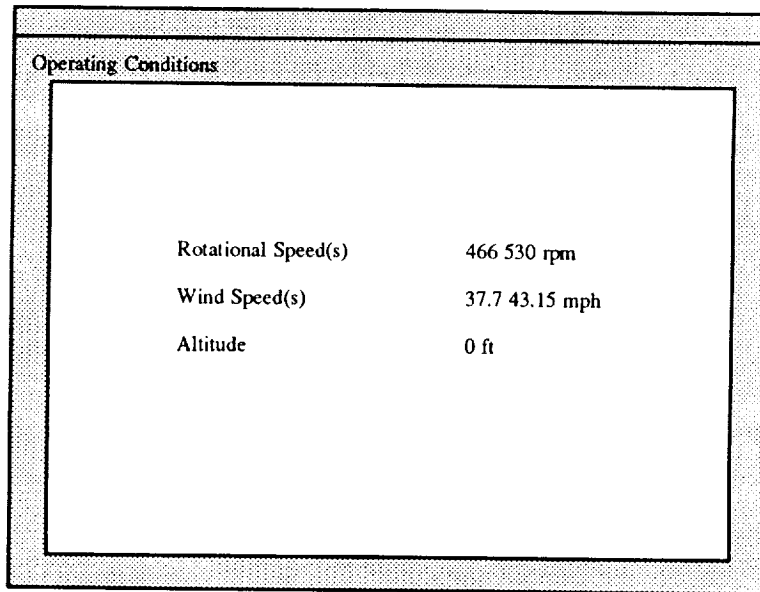
Rotor Geometry

Choosing the *Geometry* option in Figure A2 will select the rotor and blade geometry option and display the screen shown in Figure A4. Enter the rotor blade radius (from rotational centerline to the tip) in the first field. In the next field enter the hub radius. The hub radius is the portion of the blade near the rotor centerline which does not contribute to the production
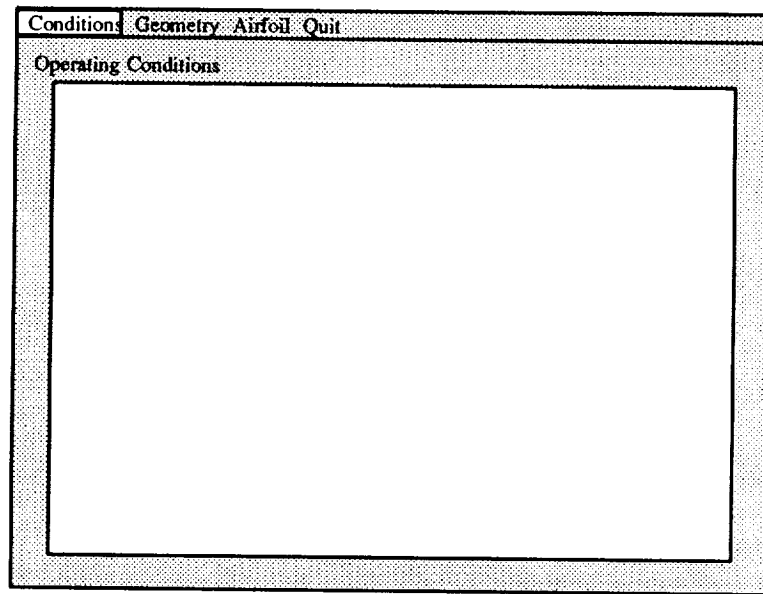
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Figure A2: Input Menu Screen

Rotational Speed(s)	466 530 rpm
Wind Speed(s)	37.7 43.15 mph
Altitude	0 ft

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Figure A3: Operating Conditions Input Screen

Rotor and Blade Geometry

Blade Radius	12.7 ft	Hub Radius	5 ft
Number of Blades	12	Pitch Angle	0 deg

Radius r/R	Chord	Twist
0.394	2.25 ft	15.8 deg
0.5	2	13.25
0.6	1.85	10.7
0.7	1.73	9.3
0.8	1.64	7.8
0.9	1.56	5.6
0.98	1.51	1.8

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Figure A4: Rotor and Blade Geometry Input Screen

of thrust (or axial air flow). The number of blades and the blade pitch angle are entered next. Finally, the blade chord and twist distributions are entered in three column fields. A pictorial display of these geometric parameters is given in Figure A5. Note that the pitch angle can be thought of as a change in angle from the prescribed twist distribution. Negative pitch angles increase the angle of attack of the airfoil.

Airfoil Characteristics

Choosing the *Airfoil* option in Figure A2 will select the airfoil aerodynamic input screen shown in Figure A6. A pictorial display of these parameters is given in Figure A7. Note that the *Lift Curve Exponent Near Stall* parameter effects the rate of change in the lift curve slope near stall.

Performing the Analysis

Once the input has been entered or loaded from a previously stored system, the analysis can be performed. Choosing the *Analyze* option in the menu in Figure A1 begins the analysis. After a short time the analysis is complete and user control of the menu returns.
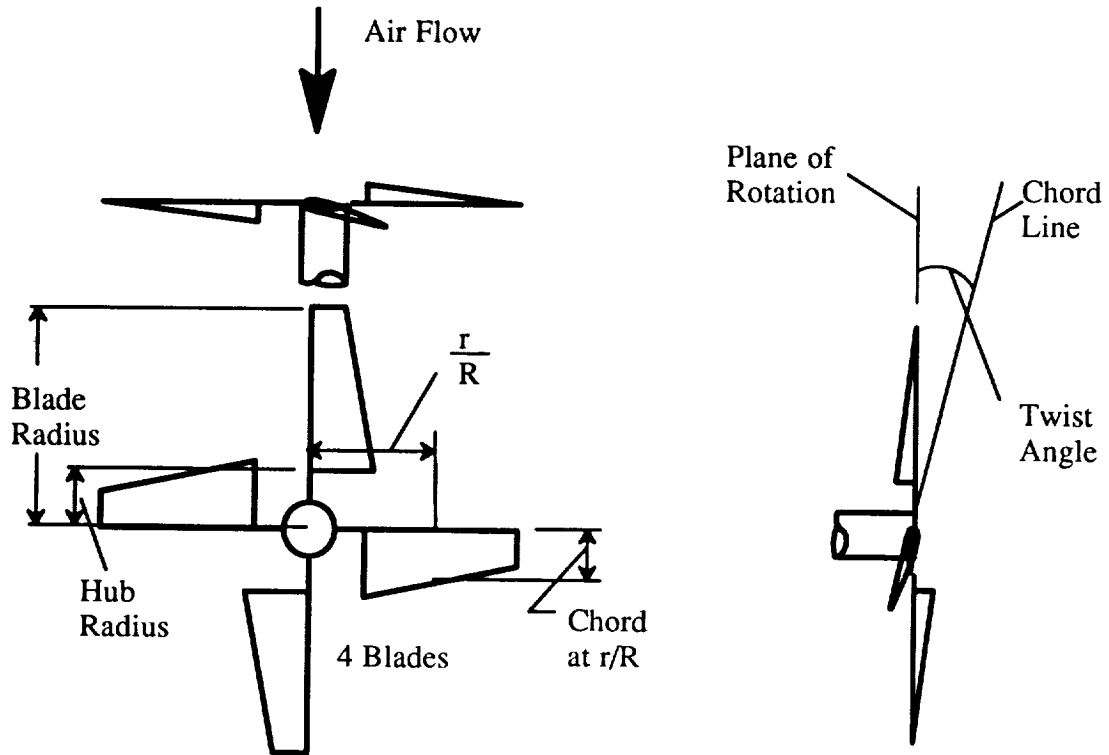
Figure A5: Rotor and Blade Geometric Parameters

Airfoil Lift and Drag Characteristics

Angle at 0 Lift Coef.	–5.7 deg.
Inverse of the Lift Curve Slope	10.46 deg
Positive Stall Angle	9 deg
Lift Curve Exponent Near Stall	5
Reduction in CL at Stall	0
Angle of 0 Lift After Stall	90 deg
Drag Coef. at 0 Lift Coef.	0.01
Drag Coef. at Stall	0.12

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Figure A6: Aerodynamic Parameter Input Screen
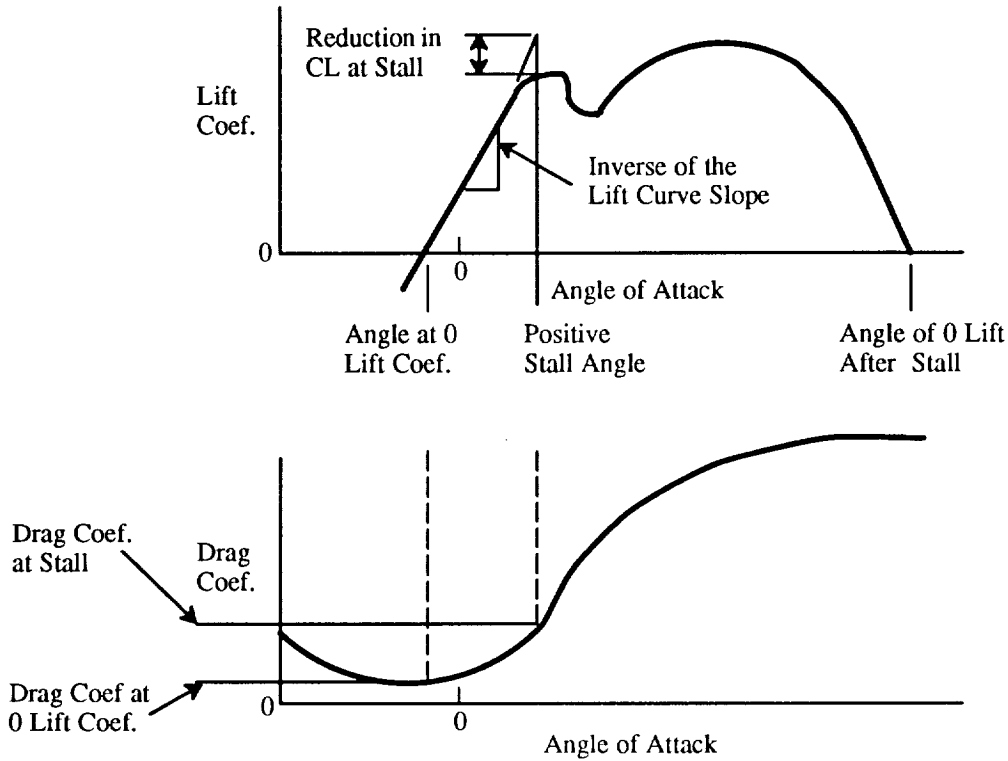
– 14 –

**Figure A7: Aerodynamic Input Parameters**

Results

Choosing the Results option in the menu in Figure A1 displays the menu screen shown in Figure A8.

Performance

Selecting the *Performance* option in Figure A8 displays the power, thrust and efficiency results shown in Figure A9.

Aerodynamics

Selecting the *Aerodynamics* option in Figure A8 displays the aerodynamic conditions along the blade. For this example, the input specified two cases to run (37.7 mph, 466 rpm and 43.15 mph,530 rpm). The user is requested to enter the case number. The results for case 1 are shown in Figure A10.

Power, Thrust and Efficiency Results
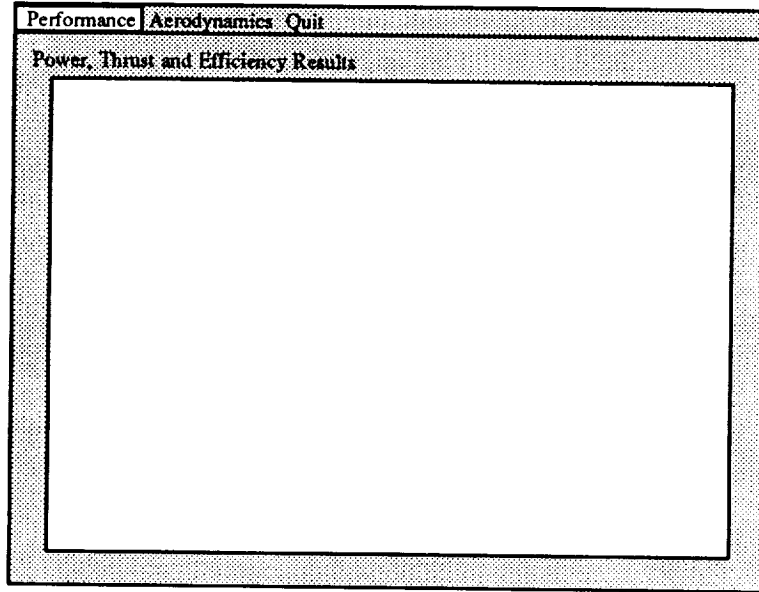
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Figure A8: Results Menu Screen

Power, Thrust and Efficiency Results

Case	Mph	Rpm	V Ratio	Pitch, deg.	Power hp	Thrust lbs	Efficiency
1	37.7	466	11.208	0	2354.9	16329	.69679
2	43.15	530	11.138	0	3456.5	20982	.69817

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Figure A9: Performance Results Screen

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r/R	Alpha Deg.	CL	CD	In-plane Lbs/in	Out-Plane Lbs/in
0.3937	3.0388	0.6047	0.032321	2.3044	8.1284
0.43159	3.216	0.61696	0.033236	2.5143	9.5409
0.46949	3.2242	0.61753	0.33278	2.6637	10.808
0.50738	3.0888	0.60816	0.032577	2.7591	11.914
0.54528	2.803	0.58838	0.031133	2.8211	12.916
0.58317	2.431	0.56264	0.029324	2.8322	13.698
0.62106	2.2303	0.54875	0.028382	2.8999	14.732
0.65896	2.164	0.54417	0.02076	3.0177	16.026
0.69685	2.0482	0.53615	0.027547	3.1058	17.197
0.73474	1..8554	0.52281	0.026685	3.1686	18.258
0.77264	1.6235	0.50677	0.025677	3.2038	19.171
0.81053	1.2868	0.48347	0.024268	3.1785	19.722
0.84843	0.73162	0.44505	0.022091	3.0372	19519
0.88632	0.15285	0.405	0.020013	2.8677	19.013
0.92421	−1.064	0.3208	0.016282	2.3828	16.098
0.96211	−2.6481	0.21118	0.012722	1.7378	11.297
1	−4.2483	0	0.010616	0.60713	−0.054167

Aerodynamic Characteristics and Loads Along Blade for Case: 1

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Figure A10: Aerodynamic Results Screen

Input File Management

Selecting the *File* option from the input menu screen shown in Figure 2 displays the file management menu screen of Figure A11.

Saving Input Files

Selecting the *Save* option displays the file save screen of Figure A12.

WT supports long filenames. The list of previously stored input files are displayed in reverse chronological order according to the times there were saved. The size, date, and time saved are displayed along with the names. Near the top of the screen, WT prompts for a name to store the current input. The name can consist of any alphanumeric characters, with the exception that the first character must be alphabetic. Pressing the [Enter] key stores the current input data. Pressing the [Esc] key exits all file menus without completing the file operation.

Loading Input Files

Selecting the *Load* option displays the file load screen of Figure A13. Again WT displays the list of previously stored input data. The specific file is selected with the up and down cursor keys and pressing [Enter] when the desired file is highlighted.
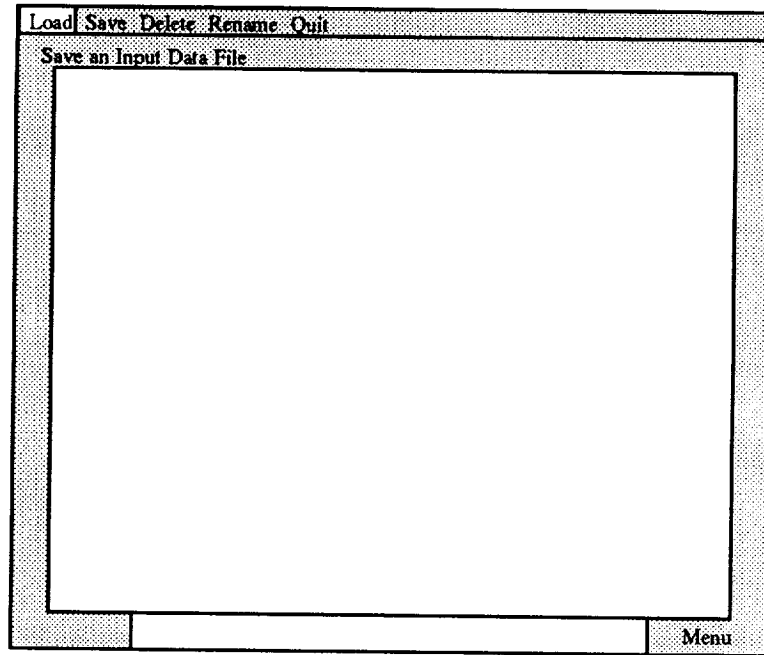
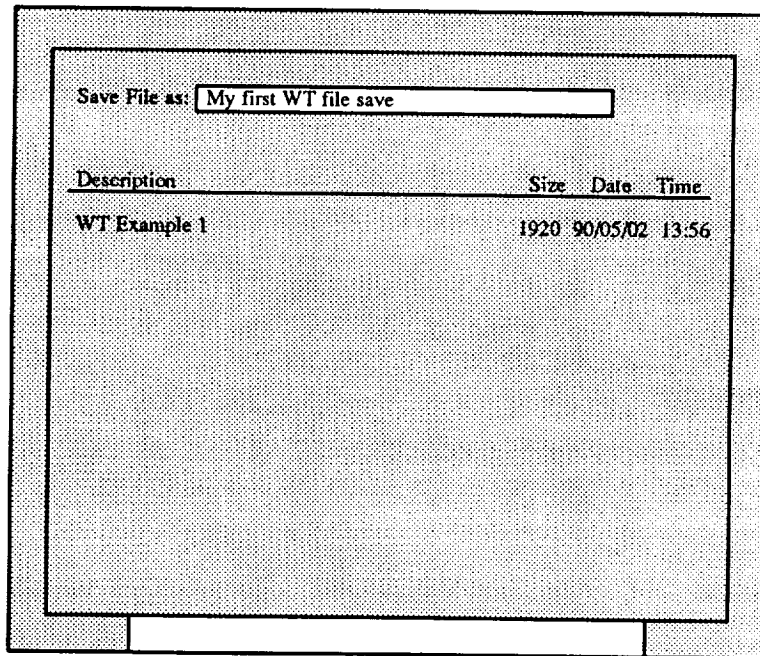**Figure A11: Input File Management Input Menu Screen**

Figure A12: File Save Screen

Figure A13: File Load Screen

Renaming Input Files

A file can be renamed similarly by first selecting the old file name using the cursor keys and then entering the new name at the prompt.

Deleting Input Files

A file can also be deleted by selecting and pressing [Enter]. To prevent deleting a file, the [Esc] key must be pressed before leaving the delete file menu.

Conclusions

WT provides a fast and easy way to evaluate power requirements and thrust output from a multi–bladed wind tunnel rotor. It requires input data of operating conditions, rotor geometry, and airfoil characteristics. Because it is based on simple blade element theory, care should be taken to avoid complex flow conditions such as recirculating flow at the rotor plane. In addition, the calculated performance is highly dependent on the assumed airfoil characteristics, especially when significant portions of the blades are stalled.

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3.   Viterna, L. A., "Theoretical and Experimental Power from Large Horizontal–Axis Wind Turbines," *NASA TM–82944,* 1982.

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13. ABSTRACT (Maximum 200 words)

The Icing Research Tunnel (IRT) at the NASA Lewis Research Center in Cleveland, Ohio is a unique and important facility for testing aircraft under adverse weather conditions. Because of the need to test models at higher Reynolds numbers, a new fan rotor was being designed to increase test section wind speed. As a low cost alternative, a preliminary study was made of the present fan rotor to suggest possible methods to increase tunnel wind speed. An analysis based on blade element theory was used to calculate the required power and the rotor thrust for various configurations over a wide range of tunnel wind speeds. The computer program used to conduct the analysis is described in an appendix. Calculated power was found to be in good agreement with measured power versus wind speed for both open and blocked tunnel conditions. Studies were made of the effect of blade pitch angle and rotor speed on tunnel performance. A change in pitch angle of 6 degrees while maintaining the current rpm was found to increase maximum tunnel wind speed from 299 mph to 385 mph at the test section. Required power increases to 4860 horsepower, which is within the capability of the present motor. This pitch modification could be accomplished by reshaping the root section of the present blades. This configuration results in a rotor which passes through stall at start up, however. An alternative approach would be to increase rotor speed to 582 rpm. This would increase tunnel wind speed to about 377 mph while requiring 4860 horsepower. This approach has the advantage of no modifications to the rotor structure but exceeds the rpm of operation to date. A pitch change of 3 degrees and increasing rpm to 518 increases tunnel speed to about 383 mph while providing good stall margin. Further analysis is required to ensure stresses in the rotor do not exceed allowables at these higher blade leadings. The

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13. Abstract (continued)

present motor rating of 5000 horsepower and tunnel drag losses limit maximum wind speed in the IRT. Since the power lost to the tunnel increases with the third power of wind speed, the maximum wind speed is 433 mph for even a 100 percent efficient rotor.

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Lewis Research Center
Cleveland, Ohio 44135

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