The Effect of Rotor Blade Thickness and Surface Finish on the Performance of a Small Axial Flow Turbine

Richard J. Roelke
National Aeronautics and Space Administration
Lewis Research Center

and

Jeffrey E. Haas
Propulsion Laboratory
AVRADCROM Research and Technology Laboratories
Lewis Research Center

Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Vehicle and Engine R&D

Prepared for
1982 Gas Turbine Annual Meeting sponsored by
American Society of Mechanical Engineers
NOTICE

This report was prepared to document work sponsored by the United States Government. Neither the United States nor its agent, the United States Department of Energy, nor any Federal employees, nor any of their contractors, subcontractors or 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.
The Effect of Rotor Blade Thickness and Surface Finish on the Performance of a Small Axial Flow Turbine

Richard J. Roelke
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

and

Jeffrey E. Haas
Propulsion Laboratory
AVRADCOR Research and Technology Laboratories
Lewis Research Center
Cleveland, Ohio 44135

Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Vehicle and Engine R&D
Washington, D.C. 20545
Under Interagency Agreement DE-AL01-77CS51040

1982 Gas Turbine Annual Meeting sponsored by
American Society of Mechanical Engineers
THE EFFECT OF ROTOR BLADE THICKNESS AND SURFACE FINISH
ON THE PERFORMANCE OF A SMALL AXIAL FLOW TURBINE

by Richard J. Roelke
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

and Jeffrey E. Haas
Propulsion Laboratory
AVRADCOM Research and Technology Laboratories
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

An experimental investigation was conducted to determine the effect of blade profile inaccuracies and surface finish on the aerodynamic performance of a 11.15 cm tip diameter turbine. The as-received cast rotor blades had a significantly thicker profile than the design intent and a fairly rough surface finish. Stage test results showed an increase of one point in efficiency by smoothing the surface finish and another three points by thinning the blade profiles to near the design profile. Most of the performance gain between the as-cast thick and the thinned rotor blades, both with the same surface finish, was attributed to reduced trailing edge losses of the re-contoured blades.
THE EFFECT OF ROTOR BLADE THICKNESS AND SURFACE FINISH 
ON THE PERFORMANCE OF A SMALL AXIAL FLOW TURBINE
by Richard J. Roelke
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

and Jeffrey E. Haas
Propulsion Laboratory
AVRADCOM Research and Technology Laboratories
Lewis Research Center
Cleveland, Ohio 44135

INTRODUCTION

The efficiency of small (under about 15 cm tip diameter) axial turbines has not equaled that demonstrated in larger machines. The chief reasons for this are Reynolds number effects and compromises made in the aerodynamic design to accommodate limitations in mechanical design and fabrication processes. A practical small turbine design will almost always have a lower blade aspect ratio, higher trailing edge blockage, and a higher rotor tip clearance than a similar large turbine. Further performance degradation may also be caused by manufacturing imperfections because it is difficult to make the blade profiles with the same precision or relative surface smoothness as large turbines. The effect of these manufacturing imperfections on the performance of a small single stage turbine is the subject of this paper.

Few reports have appeared on the effect of these manufacturing imperfections in comparison to the other causes affecting the performance of small turbines. Bammert and Sandstede (1) reported on a series of cascade tests and a four stage turbine test where the surface roughness was changed and the blade profiles were either uniformly thinned or thickened to simulate manufacturing errors. Their results indicated dramatic changes in blade losses.

The results of the investigation described herein are an outgrowth of the automotive gas turbine technology program conducted at the NASA-Lewis Research Center. A part of that program consisted of a series of component performance tests of the compressor-drive turbine for the Department of Energy automotive gas turbine demonstrator engine. The engine and technology program are described in (2). The turbine blading used in the subject tests consisted of duplicates of the stator and rotor castings used in the demonstrator engine. Inspection of the blading made before the start of the turbine component tests showed significant deviations from design in the profile shape and a fairly rough surface. The initial tests were made to determine the performance of the as-cast blading. After these initial tests two subsequent turbine builds were evaluated. One build had reduced rotor blade surface roughness and in the other build the rotor blade profiles were reworked to more nearly approach the design profile.

All performance tests were conducted with air at a nominal inlet temperature of 320 K and an inlet pressure of 0.827 bars. The results reported in this paper were obtained by measuring the overall stage performance for a range of pressure ratios with the turbine operating at design speed. Rotor-exit radial surveys of angle, total pressure and total temperature were taken at design equivalent values of speed and specific work. Results are presented in terms of efficiency and mass flow for each of the three turbine builds. Also included is the effect of the blading changes on the static pressures within the stage and the calculated changes in local efficiency based on the rotor-exit surveys. The results of the complete series of performance tests conducted with this turbine are reported in (3).

SYMBOLS

\( m \) mass flow rate, kg/sec
\( r \) radius, m
\( U \) blade velocity
\( V \) absolute gas velocity, m/sec
\( W \) relative gas velocity, m/sec
\( a \) absolute gas angle measured from axial direction, deg
Turbine aerodynamic performance tests were made using the as-cast blading. After these tests were made, two modifications were made to the rotor blading. The first modification consisted of reducing the blade surface roughness. This process consisted of polishing the suction surface of each of the blades (reducing the average suction surface roughness to 0.33 microns) and applying a thin coat of lacquer to the pressure surfaces. The average pressure surface roughness was 0.85 micron resulting in an average surface roughness for the blade of 0.64 microns. Tests were then made on this configuration. The second modification consisted of electric discharge machining the rotor profiles to the design profile. The process consisted of slowly removing metal from the rotor profiles until inspection traces at the mean and tip agreed closely with the design profile. Rotor throat measurements indicated that the hub section was still thick. However, any further hub machining may have resulted in undersized profiles away from the hub, and perhaps in the blade thickness. Measurements made indicated local regions of the blade profiles fell outside the profile tolerance band by up to 0.05 mm. The profile tolerance was ±0.1 mm. The average trailing edge thickness based on these and other inspection tracings and the hub throat measurement was 0.053 cm resulting in a trailing edge blockage of 16.5 percent. Surface roughness measurements were made on the pressure and suction surfaces of several blades and averaged 1.35 microns.

Surface velocity distributions were not generated for the as-cast rotor blades primarily because the rotor was not a typical as-cast profile. The inspection tracings made showed profile variations from blade to blade. Also tracings of the hub section profile could not be obtained.

Profile tracings for the stator were not generated since the blades were cast individually with the endwalls. However, stator throat measurements indicated that the stator flow area was undersized by 4.1 percent. The reduced flow area was caused by the size of the fillets and draft angles used in casting the stator. The as-cast stator trailing edge blockage was nominally 4.5 percent.
A probable explanation for a major portion of the configuration is the reduced trailing edge losses. An increase in performance of the reworked rotor configuration between it and the reworked blade. To test this hypothesis an estimate of the effect of the blade surface finish and profile near the hub. With the blade surface roughness of this rotor was the same as the original rotor. The highest surface finish of the rotor and stator blades. Rotor kinetic energy loss coefficients were calculated for three values of trailing edge thickness; design, as-cast and reduced roughness rotor had the lowest mass flow.

For each rotor configuration a rotor exit radial survey was first conducted at design equivalent values of speed and specific work. Mass averaged values of flow angle, total temperature, and total pressure were obtained for each of the three survey locations. These mass-averaged values were then arithmetically averaged to obtain overall values. The survey probes were then positioned with one near the hub so that the average flow angle from these three positions could correspond closely to the overall mass-averaged value obtained from the survey. The radial positions of the survey probes, so determined, were not changed during the remainder of the testing of that rotor configuration. Performance data were then obtained over a range of turbine exit total pressures were calculated from mass flow measurements. The ideal work was based on the manifold inlet-to-rotor exit total pressure ratio at design equivalent speed. Data were obtained at nominal inlet flow conditions of 320 and 0.7 and 0.827 bars. The turbine Reynolds number, \( \frac{\text{m} \cdot \text{ft}}{\text{sec}} \), at these conditions was about 2.44\times10^6.

The rotor exit survey data together with the overall stage measurements and the results of a stator exit survey (5) were used to calculate the stage velocity diagrams for the three turbine builds at the design work condition. Selected results from those calculations are tabulated in Table I. The velocity diagram information listed in the table shows that the flow velocities generally decreased in the rotor and increased in the stator as the rotor was first smoothed and then thinned. This agrees with the trends shown in Fig. 9. Also to be noted is that the change in flow angles was not very large. In particular the rotor incidence did not change very much as the rotor configuration was changed. This indicates that the change in rotor incidence among the three turbine configurations was not a major factor contributing to the change in stage performance.

As mentioned earlier the as-cast blade profile was thicker than the design profile and therefore would have more trailing edge drag and a larger mixing loss. It was suspected that the increased trailing edge losses of the as-cast blade could account for a large portion of the performance difference between it and the reworked blade. To test this hypothesis an estimate of the effect of the rotor trailing edge thickness on rotor performance was obtained by using the Stewart mixing model (6). To this model was added a trailing edge drag suggested by Prust (7). The blade surface-friction boundary layer parameters needed in the mixing equations were obtained from a boundary layer computer code (8), using the design mean static surface velocities. Rotor kinetic energy loss coefficients were calculated for three values of trailing edge thickness; design, as-cast and reworked. The trailing edge thicknesses of the as-cast and reworked blades were measured. The result of these calculations predicted an increase in rotor efficiency of 1.9 points due to the trail-
ing edge difference between the as-cast and reworked blades. This change in rotor efficiency was then used in a turbine performance computer code (9) to predict the effect on the stage performance. The results of the analysis indicated an increase in stage efficiency of 2.7 points by thinning the rotor blades. The difference in efficiency shown in Fig. 8 between the reduced roughness and reworked rotors was nominally three points. Therefore, it appears that the reduction in rotor trailing edge loss was the main reason for the performance gain.

An analysis procedure similar to that described above for the effect of blade trailing edge thickness was used to try to predict the effect of blade surface roughness. However, the results were inconclusive because of present limitations in the referenced boundary layer code to account for surface roughness changes.

A comparison was also made between the effect of blade surface roughness measured in this test program and the results reported in (1). According to the information in the reference a decrease in the surface roughness from 1.35 micrometers to 0.64 micrometers could result in an increase in stage efficiency of about 1.2 points. This predicted increase in efficiency is generally consistent with the increase measured during the test program. An increase of nominally one point was measured with the turbine operating at design equivalent speed and work.

CONCLUDING REMARKS

The results obtained in this experimental investigation showed that inaccuracies in the manufacture of small turbine blades can cause significant turbine performance penalties. Small dimensional deviations from design that may be acceptable in large machines must be critically examined to judge the impact in a small machine. Ultimately, analytical methods must be developed to predict these effects. For this turbine, obtaining an accurate blade profile and a smooth surface finish significantly improved its performance. Analytical predictions of these effects compared closely with the experimental results. Finally, the quality of the castings procured for this demonstrator engine program may not be indicative of what may be reasonably achieved given more time to further develop the manufacturing processes.

REFERENCES


<table>
<thead>
<tr>
<th>TABLE 1. - CALCULATED STAGE VELOCITY DIAGRAMS AT DESIGN WORK FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Percent span (hub is zero)</strong></td>
</tr>
<tr>
<td><strong>Stage 2</strong></td>
</tr>
<tr>
<td><strong>Absolute velocity ratio</strong></td>
</tr>
<tr>
<td><strong>Relative velocity ratio</strong></td>
</tr>
<tr>
<td><strong>Relative flow angle, deg</strong></td>
</tr>
<tr>
<td><strong>Rotor incidence, deg</strong></td>
</tr>
<tr>
<td><strong>Stage 3</strong></td>
</tr>
<tr>
<td><strong>Relative velocity ratio</strong></td>
</tr>
<tr>
<td><strong>Absolute flow angle, deg</strong></td>
</tr>
<tr>
<td>Percent span (hub is zero)</td>
</tr>
<tr>
<td>---------------------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Station 2</td>
</tr>
<tr>
<td>Absolute velocity ratio</td>
</tr>
<tr>
<td>Relative velocity ratio</td>
</tr>
<tr>
<td>Relative flow angle, deg</td>
</tr>
<tr>
<td>Rotor incidence, deg</td>
</tr>
<tr>
<td>Station 3</td>
</tr>
<tr>
<td>Absolute velocity ratio</td>
</tr>
<tr>
<td>Relative velocity ratio</td>
</tr>
<tr>
<td>Absolute flow angle, deg</td>
</tr>
</tbody>
</table>
Figure 1. - Cross-sectional schematic of turbine.

Figure 2. - Design mean section velocity diagram and blade surface velocity distributions.
Figure 2. - Concluded. Figure 3. - Comparison of design and as-cast rotor blade profiles.
Figure 4. - Radial variation in rotor throat dimension.

Figure 5. - Test installation schematic.
INSTRUMENTATION

- STATIC PRESSURE
  □ TOTAL PRESSURE
  ✗ TOTAL TEMPERATURE
  ✳ TOTAL PRESSURE - FLOW ANGLE

Figure 6. - Flow path instrumentation, viewed looking downstream.

Figure 7. - Variation of equivalent mass flow with pressure ratio at design speed.

Figure 8. - Variation of efficiency with pressure ratio at design speed.
Figure 9. Variation of static pressure with axial location at design speed and stage total pressure ratio.

Figure 10. Radial variation in efficiency at design speed and work.
The effect of rotor blade thickness and surface finish on the performance of a small axial flow turbine

Richard J. Roelke and Jeffrey E. Haas

NASA Lewis Research Center and AVRADCOM Research and Technology Laboratories, Cleveland, Ohio 44135

An experimental investigation was conducted to determine the effect of blade profile inaccuracies and surface finish on the aerodynamic performance of a 11.13 cm tip diameter turbine. The as-received cast rotor blades had a significantly thicker profile than the design intent and a fairly rough surface finish. Stage test results showed an increase of one point in efficiency by smoothing the surface finish and another three points by thinning the blade profiles to near the design profile. Most of the performance gain between the as-cast thick and the thinned rotor blades, both with the same surface finish, was attributed to reduced trailing edge losses of the recontoured blades.