EFFECT OF ROTOR LEADING-EDGE SWEEPBACK ON
PERFORMANCE OF A TRANSONIC TURBINE

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SUMMARY

An experimental investigation was conducted to determine the effect of rotor leading-edge sweepback on the aerodynamic performance of a transonic turbine. The sweepback was accomplished through modification of the rotor. Using an unmodified stator with this modified rotor resulted in large incidence angles at the rotor mean and tip sections. A drop in efficiency of only 1 point, from 0.85 for the unmodified unit to 0.84 for the sweptback unit, was obtained. This loss was attributed to the rotor incidence angles and corresponds to the predicted drop in efficiency of approximately $\frac{1}{2}$ points. Detailed surveys downstream of the turbine rotor at design point indicated that the decreased efficiency occurred in the form of increased losses in the region of the tip section.

INTRODUCTION

High specific weight flows in turbojet engines designed for supersonic flight depend to a great extent upon increased stresses within turbine-rotor blades. Specifically, reference 1 indicates that the rotor hub stress due to centrifugal force becomes the primary constraint in engine designs for operation at flight Mach numbers in excess of 2.0. This constraint occurs as a result of the last-stage turbine-rotor stress determining the exit annulus area and hence limiting the turbine specific weight flow.

It is well known that for a given stress limit an increase in turbine-rotor annulus area can be obtained by means of a blade taper (e.g., ref. 2), but it is also important that this taper be achieved in such a way that a minimum loss in efficiency would be expected.

In general, the throat region and hub section of high-velocity turbines (see ref. 3) are the critical regions from an aerodynamic standpoint. Thus, for a transonic turbine, rotor taper could be achieved by
means of a sweeping back of the less critical rotor leading edge. If the rotor is modified without modification of the stator blades, abnormally high rotor incidence angles occur that might have an adverse effect on turbine performance.

In order to evaluate quantitatively the effect of rotor sweepback on the efficiency of high-velocity turbines, the transonic turbine rotor of reference 3 was accordingly modified and experimentally investigated with the unmodified stator. The results of this investigation are presented herein and include a comparison of the over-all turbine performance of the unmodified (ref. 3) and modified units as well as detailed surveys downstream of the turbine rotor at design point. A comparison of the experimentally obtained loss due to the resultant rotor incidence angles with that theoretically obtained using the incidence loss assumption in reference 4 will also be included.

SYMBOLS

The following symbols are used in this report:

\[\begin{align*}
i & \quad \text{incidence angle, deg} \\
\Delta h' & \quad \text{specific work output, Btu/lb} \\
N & \quad \text{rotative speed, rpm} \\
p & \quad \text{absolute pressure, lb/sq ft} \\
p_2' & \quad \text{outlet total pressure, sum of static pressure plus pressure corresponding to absolute velocity, lb/sq ft} \\
r & \quad \text{radius} \\
V_{cr} & \quad \text{critical velocity, ft/sec} \\
w & \quad \text{weight flow, lb/sec} \\
\gamma & \quad \text{ratio of specific heats} \\
\delta & \quad \text{ratio of inlet-air total pressure to NACA standard sea-level pressure, } p'_0/p^* \end{align*}\]
\[ \varepsilon = \frac{y^*}{y} \left[ \frac{\left( \frac{y + 1}{2} \right)^{\frac{y}{y-1}}}{\left( \frac{y^* + 1}{2} \right)^{\frac{y^*}{y^*-1}}} \right] \]

\[ \eta_t \] total adiabatic efficiency, ratio of turbine work based on torque, weight flow, and speed measurements to ideal work based on inlet total temperature and inlet and outlet total pressure

\[ \eta_l \] local adiabatic efficiency, total state measurements from surveys downstream of rotor

\[ \theta_{cr} \] squared ratio of critical velocity at turbine inlet to critical velocity at NACA standard sea-level temperature, \( \left( \frac{V_{cr}}{\sqrt{\gamma^*}} \right)^2 \)

Subscripts:
- \( 0 \) station upstream of stator (all stations shown in fig. 3)
- \( 1 \) station at free-stream between stator and rotor
- \( 2 \) station downstream from turbine
- \( cr \) conditions at Mach number of 1
- \( t \) tip

Superscripts:
- \( * \) NACA standard conditions
- \( ' \) total state

DESCRIPTION OF TURBINE MODIFICATION

The turbine blading used in this investigation was obtained by sweeping back the leading edge of the turbine rotor blades investigated in reference 3. This taper is shown in figure 1 where the unmodified and modified rotor blades are shown projected in the radial-axial plane. In order to maintain the leading-edge radius within limits that were
considered practical, the centers of the new leading-edge circles were
placed on the mean camber line of the unmodified blade profile. The
suction and pressure surfaces were then faired so that there was no
sharp change in curvature. Shown in figure 2 are the unmodified and
modified blade profiles at the hub, mean, and tip sections. The co­
ordinates of the modified profiles are given in table I.

The unmodified stator (ref. 3) was used with the modified rotor.
Large positive angles of incidence were produced on the order of 130° and
35° at the mean and tip sections, respectively, when the turbine was oper­
ated at design point. It is therefore evident that the operation of the
modified rotor blades at such high incidence angles will increase the blade
losses (fig. 2). These values represent a considerable increase over the
4° used at all sections of the unmodified turbine rotor (see ref. 3). How­
ever, a loss in efficiency of only 1 2 points was predicted using the loss
assumption of reference 4. This assumption is that the velocity com­
ponent normal to the blade inlet angle represents a total-pressure loss. The
small reduction in efficiency as calculated was attributable to the high­
est incidence angles occurring in the region of lowest velocity. Also,
tending to counteract this increased loss is the effect of the reduced
mean and tip rotor chord on the profile losses. Thus, from these consid­
erations it is indicated that, theoretically, only small reduction in ef­
ficiency is expected as a result of the blade modification.

APPARATUS, INSTRUMENTATION, AND METHODS

The apparatus, instrumentation, and methods of calculating the per­
formance parameters are the same as those described in reference 3. A
diagrammatic sketch of the cold-air turbine test setup is shown in fig­
ure 3, and a photograph of the modified turbine rotor assembly is shown
in figure 4. Test runs were made at constant speeds in even increments
of 10 percent of design speed over a range from 30 to 130 percent of
design speed. For each speed, the turbine total-pressure ratio was varied
from approximately 1.4 to limiting-loading pressure ratio. Turbine inlet
temperature and pressure were maintained constant at nominal values of
145° F and 32 inches of mercury absolute, respectively. Detailed radial
and circumferential surveys of total pressure and total temperature were
made downstream of the rotor (fig. 3, station 2) at approximately design
speed and design work output.

RESULTS AND DISCUSSION

A performance map of the swept leading-edge turbine is presented in
figure 5(a). The equivalent specific work output $\Delta h'/\theta_{cr}$ is shown as a
function of the equivalent-weight-flow-speed parameter $\varepsilon wN/\theta$ with
contours of percentage of design speed, actual total-pressure ratio, and total efficiency superimposed. Rating total-pressure ratio is not used in this figure because the investigation is concerned with the effect of the rotor-blade modification on the turbine aerodynamic losses.

Inspection of figure 5(a) indicates that design point occurs 2 percent below limiting loading and at an efficiency approaching 0.84. Comparison of these results with those obtained for the unmodified turbine can readily be made by using figure 5(b), which is a reprint of the overall performance map presented in reference 3. For the unmodified unit, design point occurred 3 percent below limiting loading and at an efficiency approaching 0.85. Thus, it is indicated that sweeping back the leading edge of the rotor resulted in a 1-point loss in efficiency and an operation slightly closer to limiting loading. The reduction in efficiency is slightly less than the $1\frac{1}{2}$ points predicted as a result of the high rotor incidence angles. The difference might be attributed to the effect of the reduced mean and tip chords on the profile loss. However, little significance is attached to the difference, as it is on the order of the accuracy of the turbine efficiency. It might also be mentioned that the change in turbine exit flow angle was sufficiently small that the rating efficiency was also reduced by 1 point (0.84 to 0.83).

Figure 5 also indicates that the modified turbine had a peak efficiency of slightly over 0.86 which is approximately 1 point greater than that of the unmodified turbine (0.85). This improvement in peak efficiency can probably be attributed to the shift in the region of zero average incidence angle from design speed to speeds above design where the peak efficiency region occurs.

In order to study the performance of the turbine rotor at design point, detailed circumferential and radial surveys were taken downstream of the rotor and converted into local efficiencies. The peak local efficiency was then selected from circumferential surveys at a given radius as most representative of the rotor performance and is presented in figure 6. These peak values of local efficiency are considered to be most representative of rotor performance because they represent flow along streamlines which emanate from the regions of flow between the stator-blade wakes. Also included for comparative purposes is the curve obtained for the unmodified turbine. (This curve is taken from fig. 8 of ref. 5 and extended with known data to the wall region.) Over the lower two-thirds of the annulus (radius ratio from 0.7 to 0.9), the efficiency curves are approximately the same. In the region of the tip, however, the efficiency of the swept leading-edge turbine drops off from that of the unmodified unit. This condition might be expected as the low momentum fluids occurring as a result of the rotor incidence losses would tend to be forced out to the tip by centrifugal force showing up at the turbine exit as the tip loss.
CONCLUDING REMARKS

The results of this investigation indicate that for the particular turbine investigated, only a small reduction in efficiency was obtained as a result of the sweepback taper. It must be pointed out, however, that the unmodified turbine unit had a moderate efficiency of 0.85 and that the loading of the rotor was not too great. Thus, the effect of the swept leading edge on the performance of a more efficient or more highly loaded turbine is still unknown. It might also be pointed out that if the stator had been modified also so that no incidence loss would have been incurred at design point, the modified turbine may very well have had an efficiency at least equal to that of the unmodified turbine. Thus, the results indicate that this form of rotor-blade taper may offer a potential of rotor-hub stress reduction without serious penalty in efficiency.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 7, 1955

REFERENCES


### TABLE I. - MODIFIED ROTOR-BLADE COORDINATES

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<th>Mean</th>
<th>Tip</th>
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<td>0.30</td>
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<td>(\Phi), deg</td>
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Figure 1. - Projection of unmodified and modified blades in radial-axial plane.
Figure 2. - Unmodified and modified blade profiles at hub, mean, and tip.
Figure 3. - Diagrammatic sketch of cold-air turbine test section.
Figure 4. Modified transonic turbine rotor.
Figure 5. - Turbine performance maps.
Figure 5. - Concluded. Turbine performance maps.

(b) Unmodified rotor (ref. 3).
Figure 6. - Comparison of rotor-exit survey results obtained for unmodified and modified turbines at design point.