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STALLED AND STALL-FREE PERFORMANCE OF AXIAL-FLOW COMPRESSOR STAGE WITH THREE INLET-GUIDE-VANE AND STATOR-BLADE SETTINGS

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16. Abstract

The performance of the first stage of a transonic, multistage compressor was mapped over a range of inlet-guide-vane and stator-blade settings. Both stall-free and deep-stall performance data were obtained. For the settings tested, as stall was encountered and flow was further reduced, a relatively sharp drop in pressure ratio occurred and was followed by a continuing but more gradual reduction in pressure ratio with reduced flow. The position of the stall line on the map of pressure ratio against equivalent weight flow was essentially unaffected over the range of inlet-guide-vane and stator-blade settings.

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STALLED AND STALL-FREE PERFORMANCE OF AXIAL-FLOW COMPRESSOR STAGE WITH THREE INLET-GUIDE-VANE AND STATOR-BLADE SETTINGS

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SUMMARY

The performance of the first stage of a transonic, multistage compressor, designed at the NASA Lewis Research Center, was mapped over a range of inlet-guide-vane and stator-blade settings. Both stalled and stall-free performance data were obtained to provide a better understanding of the performance of this stage in the multistage environment, where difficulties were encountered in matching the stages. Tests were conducted at 60, 80, and 100 percent of design speed.

For the three inlet-guide-vane and stator-blade settings tested, as stall was encountered and flow was further reduced, a relatively sharp drop in pressure ratio occurred and was followed by a continuing but more gradual reduction in pressure ratio with reduced flow. Even though the pressure-ratio gradient at the stall line was steep, a discontinuity was not noted. The position of the stall line on the map of the total-pressure ratio against equivalent weight flow was essentially unchanged for the three inlet-guide-vane and stator-blade settings. However, as the inlet guide vanes and stator blades were closed from their design settings, the stall points for the three speeds moved to lower flows and correspondingly lower pressure ratios. This partly explains the apparent ineffectiveness of inlet-guide-vane and stator-blade reset as a means of matching the stages of the five-stage compressor. Large changes in the inlet-guide-vane and stator-blade settings result in substantial reductions in stage efficiency.

INTRODUCTION

The NASA Lewis Research Center is engaged in a research program on axial-flow compressors for advanced airbreathing engines. The program is directed primarily towards providing the technology to permit reducing the size and weight of the compressor while maintaining a high level of performance. In support of this program, a 51-

centimeter-diameter, five-stage compressor designed for a weight flow of 29.7 kilograms per second and a pressure ratio of 9.27 was fabricated and tested.

Unpublished performance data obtained from initial tests of the five-stage compressor indicated that the first stage was not meeting its design performance. At part speed conditions, the first stage remained in or near stall. To map more completely the performance of the first stage, it was tested separately in the single-stage-compressor test facility at the Lewis Research Center. The stage was tested with inlet guide vanes. To facilitate matching the first stage to the downstream stages of the five-stage compressor at part speed, the inlet guide vanes and stator blades were made resettable. The initial tests were conducted with the inlet guide vanes and stator blades at design setting angles. The details of the performance of this stage with design blade angles and with a solid rotor casing are presented in reference 1, and the performance of this stage with several rotor-casing treatments is detailed in reference 2. To provide data for a better understanding of the stage matching difficulties encountered at part speed, the performance of the first stage alone, with a solid rotor casing, was mapped over a range of inlet-guide-vane and stator-blade setting angles. In addition to stall-free performance data, deep-stall data were also obtained to provide a better understanding of the performance of this stage in the five-stage environment.

Presented herein are both stalled and stall-free performance data for the first stage with the inlet guide vanes and the stator blades at design settings and at two off-design settings. The two off-design settings were selected to match the first stage to the downstream stages of the five-stage compressor at 60 and 80 percent of design speed. An off-design-analysis program (ref. 3) was utilized to predict the setting angles required. Data are presented for the stage over the stable (stall-free) operating flow range at rotative speeds of 60, 80, and 100 percent of design speed and in deep stall at 60 and 80 percent of design speed.

TEST STAGE

The design of the first stage of the five-stage compressor is discussed in detail in reference 1. The inlet guide vanes and stator blades are shown in figure 1, and the rotor is shown in figure 2. Originally, the compressor was designed without inlet guide vanes; these were designed later and were installed just prior to the testing of the stage. The profile coordinates of the inlet guide vane are shown in figure 3. Each vane was hinged (see fig. 1) at approximately 30 percent of its chord to enable the rear portion of the vane to be resetable. The vanes had multiple-circular-arc profiles. Twenty-six vanes having a tip solidity of 1.0 and an aspect ratio of 2.4 were used.

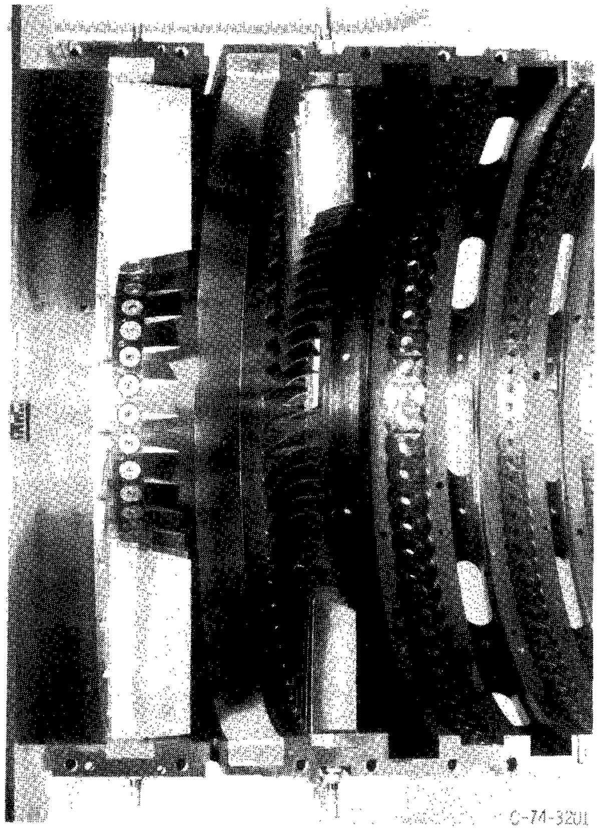


Figure 1. - Inlet guide vanes and stator blades.

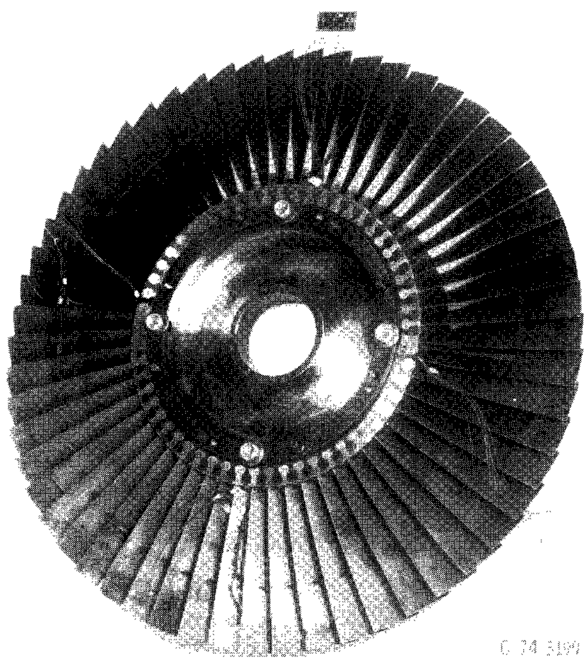
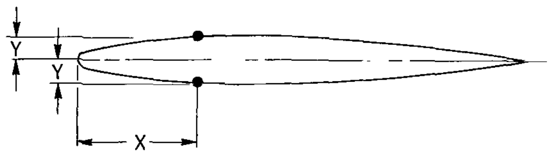


Figure 2. - Rotor.



Blade chord, cm 6.0494
Maximum thickness, cm. 0.5968
Leading edge radius, cm 0.0596
Trailing edge radius, cm. 0.0298
Number of blades 26
Blade tip solidity 1.0

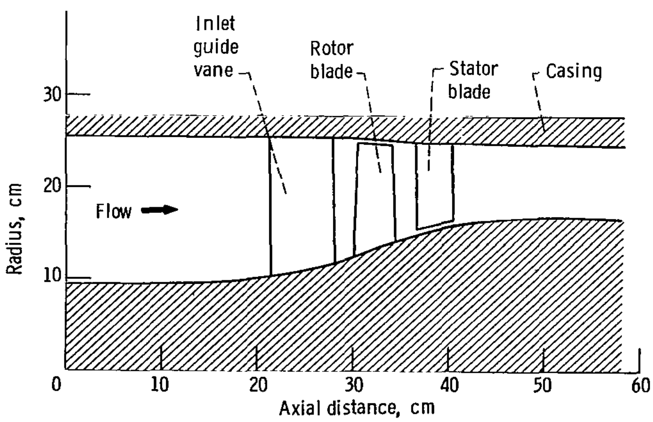
X	Y
0.0000	0.0000
.0596	.0597
.3136	.1092
.5676	.1532
.8216	.1910
1.0756	.2230
1.3296	.2494
1.5836	.2703
1.8376	.2852
2.0916	.2946
2.3456	.2984
2.5996	.2974
2.8536	.2939
3.1076	.2875
3.3616	.2784
3.6156	.2667
3.8696	.2520
4.1236	.2347
4.3776	.2146
4.6316	.1918
4.8856	.1661
5.1396	.1377
5.3936	.1064
5.6476	.0724
5.9016	.0356
6.0196	.0299
6.0494	.0000

Figure 3. - Inlet-guide-vane profile coordinates.

The overall design parameters for the rotor and stage are listed in table I, and the flow path is shown in figure 4. This stage was designed for an overall pressure ratio of 1.61 at a weight flow of 29.7 kilograms per second (197 (kg/sec)/m^2 of annulus area). The design tip speed was 425 meters per second. The rotor had 57 blades with an aspect ratio of 3.1, and the stator had 64 blades with an aspect ratio of 2.7. The rotor blades had vibration dampers located at about 40 percent span from the rotor tip. The maximum thickness of the damper was 0.180 centimeter. The rotating radial tip clearance of the rotor was estimated to be a nominal 0.05 centimeter at design speed.

TABLE I. - OVERALL DESIGN PARAMETERS FOR TEST STAGE

Rotor total-pressure ratio	1.621
Stage total-pressure ratio	1.606
Rotor total-temperature ratio	1.168
Stage total-temperature ratio	1.168
Rotor adiabatic efficiency	0.881
Stage adiabatic efficiency	0.863
Rotor polytropic efficiency	0.888
Stage polytropic efficiency	0.871
Rotor head-rise coefficient	0.237
Stage head-rise coefficient	0.232
Flow coefficient	0.464
Weight flow per unit annulus area, (kg/sec)/m^2	197.021
Weight flow, kg/sec	29.710
Rotative speed, rpm	16042.300
Tip speed, m/sec	425.426



Flow path coordinates		
Axial distance, cm	Radius, cm	
	Inner	Outer
0.000	9.595	25.654
2.588	9.550	
5.128	9.571	
7.668	9.601	
10.208	9.624	
12.748	9.652	
15.288	9.728	
17.828	9.914	
20.063	10.163	
22.860	10.584	
25.400	11.110	25.616
27.940	11.808	25.527
29.207	12.220	25.474
30.480	12.700	25.400
33.020	13.536	25.217
35.265	14.275	25.044
38.100	15.077	24.877
41.214	15.847	24.788
43.180	16.314	24.750
45.720	16.500	24.712
50.800	16.500	24.666
58.420	16.500	24.666

Figure 4. - Flow-path geometry of test stage.

APPARATUS AND PROCEDURE

Test Facility

The compressor stage was tested in the single-stage-compressor test facility at the Lewis Research Center. Figure 5 is a schematic diagram of the facility. Atmospheric air enters the test facility through an inlet located on the roof of the building, flows through the flow-measuring orifice and into the plenum chamber upstream of the test stage. The air then passes through the experimental compressor stage into the collector and is exhausted to the atmosphere. Weight flow is controlled with a sleeve valve in the collector.

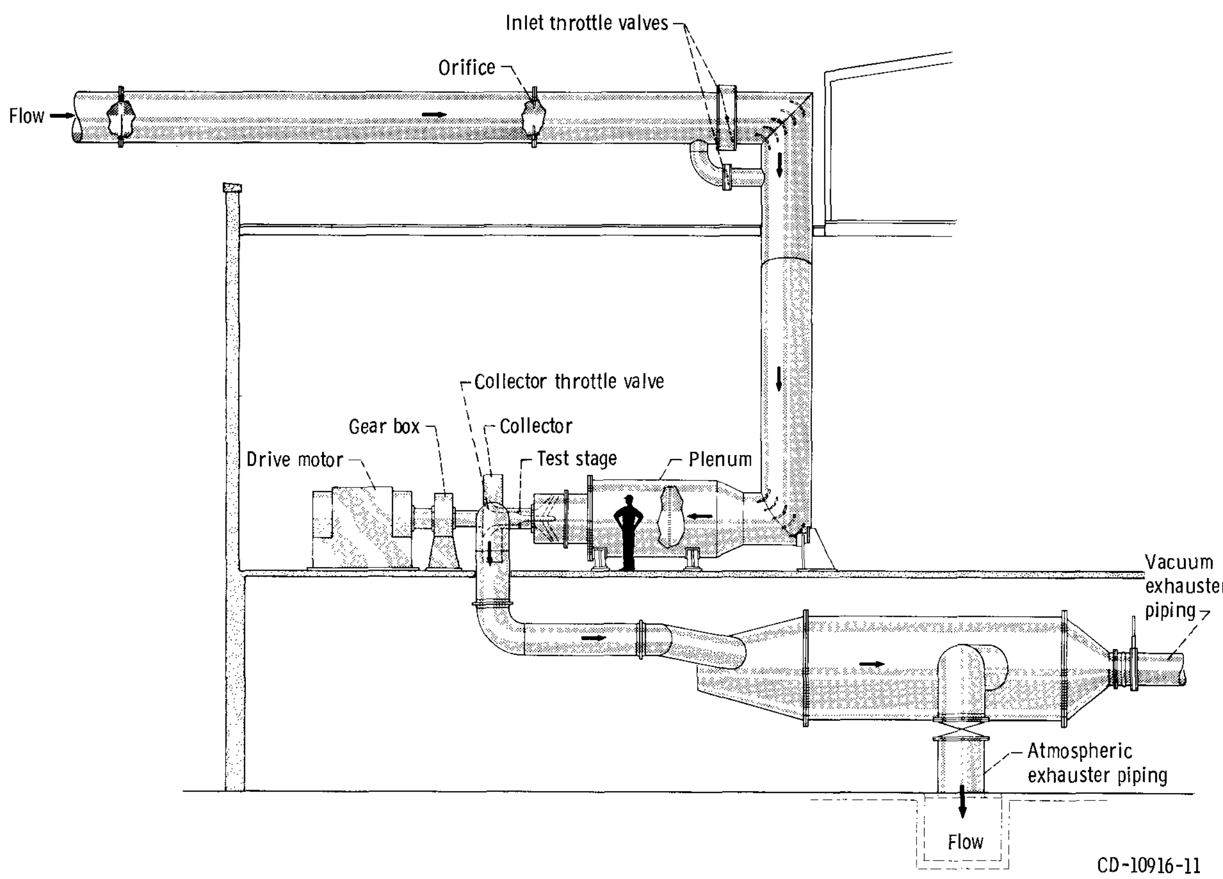


Figure 5. - Compressor test facility.

Instrumentation

Strain gages were mounted on several rotor and stator blades in order to observe the vibratory blade stresses, particularly in the stall region of operation. Accelerometers were used to determine the horizontal and vertical components of force on the journal-bearing housings.

Two Chromel-constantan thermocouples were located in the plenum tank for sensing plenum total temperature. Plenum total pressure was assumed equal to plenum static pressure and was measured with four manifolded wall static-pressure taps located approximately 90° apart on the plenum tank. The stage outlet conditions were determined from measurements obtained with four rakes located approximately 90° apart and approximately 40 centimeters downstream of the stator trailing edge. For all stator-blade settings, the orientation of the rakes was maintained in the axial direction. Each rake had five total-pressure elements and five Chromel-Alumel thermocouples located side by side at 10, 30, 50, 70, and 90 percent of the passage height from the outer casing (fig. 6). Static pressures at the five rake radial positions were determined by assuming a linear variation between the measured inner- and outer-wall static pressures. Rotor speed was determined by the use of a magnetic pickup in conjunction with a gear mounted

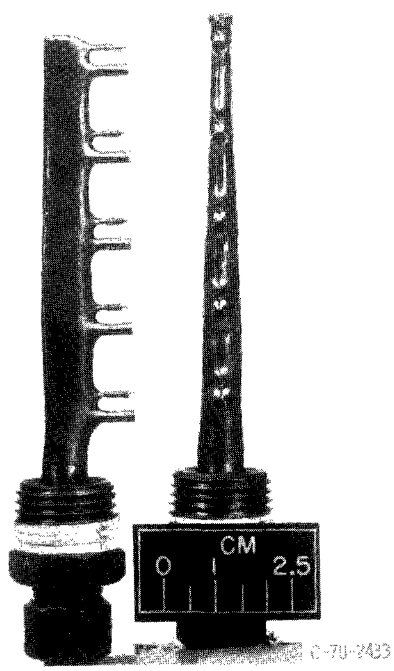


Figure 6. - Rake probe.

on the drive-motor shaft. A calibrated orifice plate in the inlet line was used to determine the compressor weight flow.

The estimated errors of the data due to the inherent inaccuracies of the instruments and recording systems are as follows:

Flow rate, kg/sec	±0.3
Temperature, K	±0.6
Inlet total pressure, N/cm^2	±0.01
Outlet total pressure, N/cm^2	±0.10
Outlet wall static pressure, N/cm^2	±0.10
Rotor speed, rpm	±30

Test Procedure

Data were recorded at 60, 80, and 100 percent of design speed. The data in the stall-free operating region of the compressor were taken over a range of weight flows from maximum flow to stall at atmospheric inlet pressure. These tests were conducted at three combinations of inlet-guide-vane and stator-blade settings: (1) design settings; (2) inlet guide vanes and stator blades closed 18° and 10°, respectively, from the design settings; and (3) inlet guide vanes and stator blades closed 45° and 25°, respectively, from the design settings.

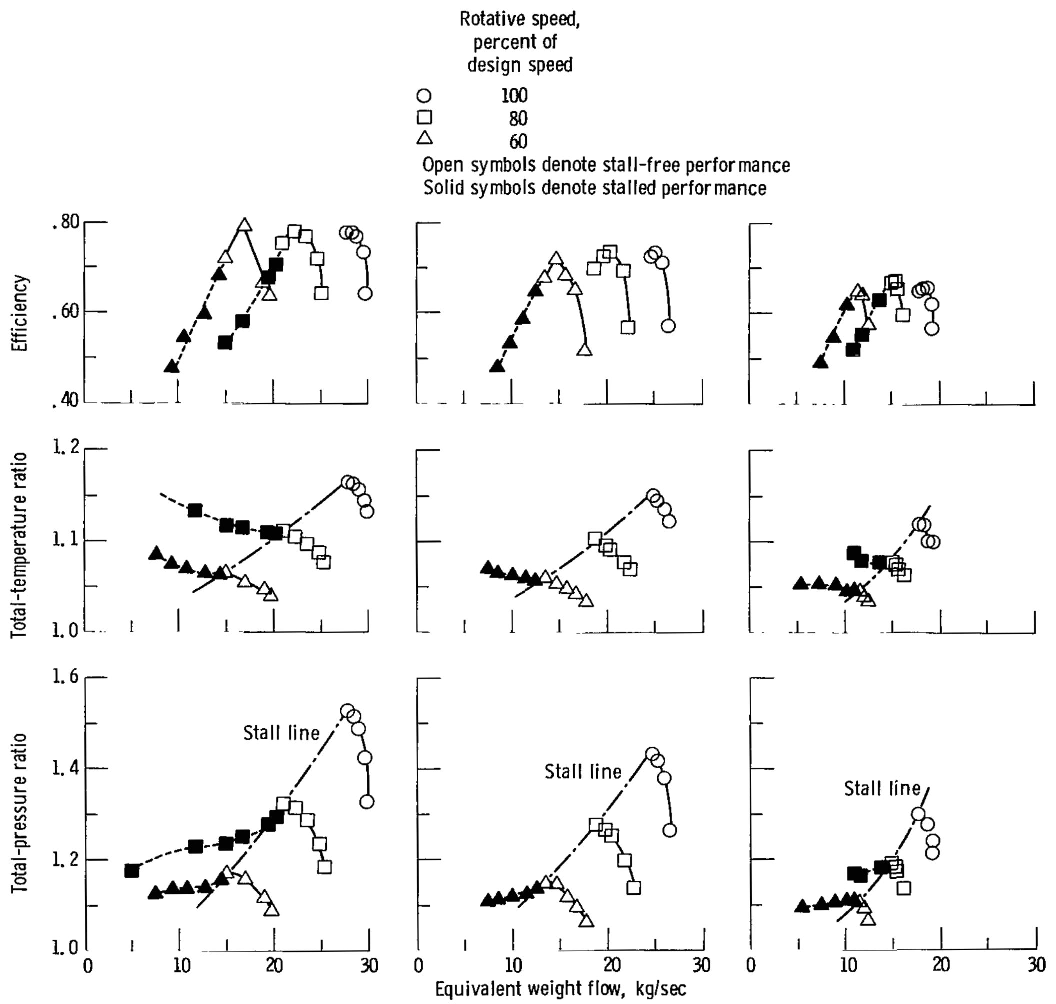
At 60 and 80 percent of design speed, data were taken in the deep-stall region of the compressor operation. The stall data were taken at 0.25 atmospheric inlet pressure to reduce blade stresses. The lowest flow point for each speed line in the stall region was limited by excessively high bearing-housing vibrations.

Performance Calculation Procedure

The overall stage performance calculation was based on averaged conditions in the plenum tank and mass-averaged values of temperature and pressure at the stage outlet as determined by the outlet rake instrumentation. Outlet temperature measurements were corrected for Mach number. Orifice weight flow was corrected to sea-level conditions based on the plenum conditions.

RESULTS AND DISCUSSION

The overall performance of the first stage of a five-stage compressor was mapped. Data were obtained at three combinations of inlet-guide-vane and stator-blade settings. The results are presented in figure 7.



(a) Design settings.

(b) Inlet guide vanes and stator blades closed 18° and 10°, respectively, from design settings.

(c) Inlet guide vanes and stator blades closed 45° and 25°, respectively, from design settings.

Figure 7. - Stage overall performance with three inlet-guide-vane and stator-blade settings.

Inlet Guide Vanes and Stator Blades at Design Settings

With the inlet guide vanes and stator blades at the design settings, the overall performance of the stage (fig. 7(a)) was essentially the same as that presented in table VI of reference 1. However, small differences, particularly lower efficiency, are noted in this report. For a true comparison of overall performance, the cumulative values of the tabular data of reference 1 must be used. (In ref. 1, the cumulative values accounted for inlet-guide-vane losses, whereas the plotted data did not.) The lower overall peak efficiency value of 0.77 at design speed, down three percentage points from that of reference 1, is attributed to differences in the method of instrumentation and calculation procedure. The data presented in reference 1 are more precise, in that the pressures and temperatures were based on mass-averaged surveys (both radially and circumferentially) at 11 streamlines as opposed to the mass-averaged (radially only) fixed-rake instrumentation at five streamlines reported herein. The data presented in this report provide a comparison in trends of overall performance for the three inlet-guide-vane and stator-blade settings, in both the stall-free and deep-stall regions.

At design speed, the stage peak efficiency of 0.77 occurred at a flow rate of 28.5 kilograms per second. Corresponding values of total-pressure ratio and total-temperature ratio were 1.52 and 1.16, respectively. Stall at design speed occurred at a weight flow of 27.8 kilograms per second. At 80 and 60 percent of design speed, stall occurred at 21.0 kilograms per second and 15.0 kilograms per second, respectively. The stall-free flow range at design speed was approximately 2.5 kilograms per second, and at 80 and 60 percent of design speed, it was approximately 5 kilograms per second.

Data in the stall region of the compressor were taken at 80 and 60 percent of design speed. In general, as stall was encountered and flow was further reduced, a relatively sharp drop in pressure ratio occurred and was followed by a continuing but more gradual reduction in pressure ratio with reduced flow. Even though the pressure-ratio gradient at the stall line was steep, a discontinuity was not noted. The energy addition, as reflected in the total-temperature ratio, increased as the flow was reduced in the stall-free region. However, as stall was encountered, the total-temperature ratio dipped. Then, as the flow was further reduced, the total-temperature ratio increased again. A sizeable flow range, in stall, was obtained at both 80 and 60 percent of design speed. The lowest flow point for each speed line in the stall region was limited by excessively high bearing-housing vibrations.

Inlet Guide Vanes Closed 18° and Stator Blades Closed 10° from Design Settings

To match the first stage of the compressor to the downstream stages at 80 percent of design speed, the inlet guide vanes were set to provide 18° of prewhirl into the rotor.

The stator blades were closed 10° to maintain their design suction-surface incidence angle. With these settings (fig. 7(b)), stage peak efficiency at design speed deteriorated to 0.73, four percentage points below that achieved with the design settings. Peak-efficiency weight flow was 25.2 kilograms per second. Corresponding values of total-pressure ratio and total-temperature ratio, at peak efficiency, were 1.42 and 1.145, respectively. Stall at design speed occurred at a weight flow of 24.5 kilograms per second. At 80 and 60 percent of design speed, stall occurred at 18.7 and 13.5 kilograms per second, respectively. The stall-free flow range at all three speed lines did not significantly change with these inlet-guide-vane and stator-blade settings. The flow at design speed remained approximately 2.5 kilograms per second, and at 80 and 60 percent of design speed, approximately 5 kilograms per second. At 80 percent of design speed, stage peak efficiency deteriorated to 0.73, four percentage points below that obtained with the design settings.

In general, for a given speed, closing the inlet guide vanes and the stator blades lowered the total-pressure ratio, the total-temperature ratio, and the weight flow, as expected. The lower efficiencies are most likely attributable to a radial redistribution of flow, which could result in some of the blade elements operating at off-design incidence angles and thus higher losses. The position of the stall line on the curve of total-pressure ratio against equivalent weight flow remained essentially unchanged when the inlet guide vanes and stator blades were reset. However, as the speed was decreased from the design speed, the stall points shifted to lower flows and correspondingly lower pressure ratios. In the stall region, data were obtained only at 60 percent of design speed, because of mechanical considerations. In the stall region, the total-pressure ratio and total-temperature ratio showed the same trends with weight flow as when the inlet guide vanes and stator blades were at design settings.

Inlet Guide Vanes Closed 45° and Stator Blades Closed 25° from Design Settings

To match the first stage of the compressor to the downstream stages at 60 percent of design speed, the inlet guide vanes and stator blades were closed 45° and 25°, respectively, from their design settings. With these settings (fig. 7(c)), stage peak efficiency at design speed deteriorated to 0.65, which is 12 percentage points below that achieved with the design vane and blade settings. Peak-efficiency weight flow was 18.7 kilograms per second. Stall at design speed occurred at a weight flow of 17.7 kilograms per second. At 80 and 60 percent of design speed, stall occurred at 15.0 and 11.5 kilograms per second, respectively. At 60 percent of design speed, peak efficiency deteriorated to 0.65, which is 14 percentage points lower than that obtained with the vanes and blades at the design settings. At both 80 and 60 percent of design speed, the flow range was substantially reduced, but the position of the stall line remained unchanged. However, as the speed was reduced, the stall points moved to lower flows and correspondingly lower pressure ratios. Again, the trends in the stall region, at both 60 and 80 percent of design speed, are consistent with the trends observed with the other inlet-guide-vane and stator-blade settings.

CONCLUDING REMARKS

It is apparent from the performance obtained in these tests that the effectiveness of variable geometry for matching this stage to the downstream stages of the five-stage compressor was limited. The fact that the stall line remained essentially unchanged over the wide range of inlet-guide-vane and stator-blade settings negates the benefit from the reduction in flow capacity of the front stage. The relatively fixed position of the stall line is, in part, due to the rapid deterioration in efficiency along with a corresponding drop in pressure ratio with closure of the inlet-guide-vane and stator-blade settings.

When the stall line reported herein was superimposed on the unpublished performance curve (total-pressure ratio against equivalent weight flow) of this stage in the five-stage environment, it became apparent that the first stage was stalled through 80 percent of design speed. At design speed, the maximum flow achieved in the five-stage environment indicated that the first stage should have been stalled. However, the total-pressure ratio in the five-stage environment indicated that the stage had recovered from stall, which suggests that the stall line of the first stage at design speed shifted to somewhat lower flow in the multistage environment.

SUMMARY OF RESULTS

The first stage of a transonic multistage compressor, designed at the Lewis Research Center, was tested at three combinations of inlet-guide-vane and stator-blade settings: (1) design settings; (2) inlet guide vanes and stator blades closed 18° and 10°, respectively, from the design settings; and (3) inlet guide vanes and stator blades closed 45° and 25°, respectively, from the design settings. The two off-design settings were selected for matching the first stage to the downstream stages of the five-stage compressor at part-speed conditions. The overall performance results for the three settings were recorded for both stalled and stall-free flow conditions. Tests were conducted at 60, 80, and 100 percent of design speed. The stalled performance data were obtained only at 60 and 80 percent of design speed. The following are the principal results of the investigation:

1. With all three inlet-guide-vane and stator-blade settings, as stall was encountered and flow was further reduced, a relatively sharp drop in pressure ratio occurred

and was followed by a continuing but more gradual reduction in pressure ratio with reduced flow. Even though the pressure-ratio gradient at the stall line was steep, a discontinuity was not noted. The energy addition, as reflected in the total-temperature ratio, increased as the flow was reduced in the stall-free region. However, as stall was encountered, the total-temperature ratio dipped. Then, as the flow was reduced further, the total-temperature ratio increased again.

2. Off-design settings of the inlet guide vanes and stator blades tended to lower the stage efficiency. The greatest loss in efficiency (14 percentage points) occurred with the inlet guide vanes and stator blades closed 45° and 25°, respectively, from the design settings, at 60 percent of design speed.

3. At part-speed conditions, the position of the stall line on the curve of total-pressure ratio against equivalent weight flow was essentially unchanged for the three inlet-guide-vane and stator-blade settings. However, for each of the three speeds tested, the stall points moved to lower flows as the inlet guide vanes and stator blades were closed from their design settings.

Lewis Research Center,
National Aeronautics and Space Administration
Cleveland, Ohio, December 3, 1976,
505-04.

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