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RESEARCH MEMORANDUM

MULTIPLE OVER-ALL PERFORMANCE AND ROTATING-STALL CHARACTERISTICS OF A 15-STAGE EXPERIMENTAL AXIAL-FLOW COMPRESSOR AT AN INTERMEDIATE SPEED

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

The 15-stage experimental axial-flow compressor was investigated at 78.5 percent of design speed, which falls in the region of the surge-limit line discontinuity. In this region indications of multiple characteristic curves of compressor operation had been found. On the basis of previous stage-matching analyses, these multiple performance characteristics appear to be the result of multiple-valued stage performance characteristics. At this speed of 78.5 percent, at least six separate characteristic performance curves were found, associated with five different numbers of rotating-stall configurations, from zero to four stall zones. It was difficult in many cases to repeat a given performance curve by approaching the test speed in a similar manner, and many of the curves were not stable, the no-stall curve being the only definitely repeatable one. In some cases a jump from one curve to another took place at the surge point, while in others the change occurred within the usual limits of a conventional performance curve and without any sudden obvious changes in observed data. In general, as the number of zones in the rotating-stall pattern decreased, the maximum weight flow, maximum efficiency, and maximum pressure ratio of the resultant curves were increased.

It appears, therefore, that multiple performance characteristics at a given speed are encountered in the region of the discontinuity of the surge line.

INTRODUCTION

The 15-stage experimental axial-flow compressor was tested at the NACA Lewis laboratory to determine its over-all performance characteristics. The results of these tests indicate that multiple-valued performance characteristic curves existed over the range of 70 to 81 percent of design speed, which is approximately the speed range of the surge-limit line discontinuity. Such results had been anticipated by the stage-stacking analysis of reference 1, which assumed that the inlet

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stages had characteristic curves of the discontinuous or double-branched type. This analysis, which also assumed an interaction effect causing several inlet stages to stall when any one of them stalled, clearly showed that at least two over-all characteristic curves could be obtained at a given compressor speed in the range where the inlet stages operate near the peak of their characteristic curves. In addition, in this same speed range the axial depth of penetration of the stall effects (the number of stages affected by interactions) could vary, depending upon the stall conditions. This variation of interaction effects could result in a multiplicity of compressor performance characteristic curves at any given speed in this intermediate-speed range. The potential of multiple-valued performance curves at a given speed is proved experimentally in reference 2, which shows three separate performance characteristics for a three-stage compressor operated at a single speed.

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In order to study this problem, the 15-stage experimental axial-flow compressor was investigated at a speed of 78.5 percent of design by using several modes of approach to this speed. The over-all performance and rotating-stall characteristics that could be obtained at this speed were evaluated. The results are presented herein.

APPARATUS AND PROCEDURE

The apparatus and instrumentation are the same as outlined in reference 3.

The normal test procedure of approaching a test speed from a lower speed with wide-open discharge throttle and then closing the throttle at constant speed was not followed in the present tests. The data reported herein were obtained by approaching the test speed from both the high- and low-speed ranges, and along various lines of constant discharge-throttle opening. These lines will be referred to as "throttle lines."

All points marked "approximate observed data" were obtained with only a single total-pressure tube at the compressor discharge. Other points marked "actual data" were obtained and calculated by the method presented in reference 4.

RESULTS AND DISCUSSION

Compressor Over-All Performance

The over-all performance characteristics of the present compressor are presented in figure 1 as over-all total-pressure ratio and adiabatic temperature-rise efficiency plotted as functions of equivalent weight flow at equivalent speeds from 30 to 100 percent of design.

Over-All Performance at 78.5-Percent Design Speed

In order to verify the results of reference 1, tests were run showing conclusively that any speed in the range from about 70 to about 81 percent of design would exhibit at least two characteristic curves of stable operation. A speed of 78.5 percent of design was chosen for the present investigation after preliminary tests had shown evidences of several characteristic curves obtainable at this speed. The investigation was conducted at this speed by approaching it from both the high- and low-speed sides and along several different throttle lines, since it was anticipated that the mode of approach to the operating speed, and the compressor operating and stall conditions present at the time the approach was started, would determine the operating and stall conditions at the test speed. Although the rate of approach would probably have some effect on which characteristic curve was reached during a certain approach, the very high inertia of the test rig prevented any investigation of such transient effects as might be encountered in engine operation.

The over-all performance of the compressor indicated at 78.5-percent speed is presented in figures 2 and 3 as plots of over-all total-pressure ratio and adiabatic efficiency against equivalent weight flow.

Approach from low-speed side. - The first approach to the test speed was made by increasing speed along the approximate throttle line marked T_1 on figure 2. Operation at 78.5-percent speed after this approach was on curve A at the data point indicated as A_0, and at this condition there were four rotating-stall zones present. The discharge throttle was opened with resulting operation down curve A to lower pressure ratios and higher flows with four rotating-stall zones present at all points.

When the throttle was closed from the maximum flow point indicated on curve A, compressor operation moved to point A_1, possibly discontinuously, and there were still four stall zones present, although as viewed on the oscilloscope, there was a very low-frequency rotating expansion and contraction cycle that periodically varied the circumferential width of the rotating-stall zones. Further closing of the discharge throttle resulted in operation at an essentially constant pressure ratio with a reduction in weight flow. A data point on this constant-pressure-ratio characteristic was arbitrarily taken at point A_2, with three stall regions present. When the throttle was closed very slightly more, the compressor surged, indicating that point A_2 was very close to a surge point. Operation after the compressor was brought out of surge by opening the throttle somewhat appeared to be along curve A. Although the number of zones in the stall pattern at point A_2 was different from that of curve A, it was thought that the surge point of curve A, as obtained by closing the throttle at 78.5-percent speed from the point obtained after approaching along the original throttle line T_1, would be at about point A_2 with four stall zones present. However, this assumption was not checked.

In an attempt to reach point A_1 again, for the purpose of determining its operating curve, the original throttle line T_1 was followed closely in approaching 78.5-percent speed and the throttle was then opened. Instead of remaining on curve A as had previously been the case, the compressor operation moved to curve B, probably discontinuously, although the path of operation was not definitely established. As the throttle was closed, the compressor operation moved up curve B 3264
with two rotating-stall zones present, although most of the points observed along this curve had associated with them stall zones spaced asymmetrically around the circumference. For example, the two stall zones might have been displaced by 90° or 120° rather than 180°. At a point just above the maximum pressure ratio limit of curve B, surge occurred, and after a slight opening of the throttle the compressor was found to be operating on curve A. Whether surge caused the shift in operation or the shift occurred immediately before surge could not be ascertained.

At another date the test speed was again approached approximately along the throttle line T_2 with resultant operation at about the center of curve C with three rotating-stall zones present. As the throttle was opened, the three circumferentially asymmetric stall zones changed to two circumferentially asymmetric stall zones and the weight flow increased about 4 pounds per second, possibly discontinuously, with resultant operation on curve D. The two stall zones persisted as the throttle was opened and then closed along curve D until just before surge occurred, at which point there was only one stall zone present. This single-stall-zone pattern remained after surge, and curve D was then found to be repeatable over its full range.

In addition to the curves just discussed, several others were found. Curve C, which was previously mentioned, has three rotating-stall zones with all points displaying either circumferential asymmetry or the expansion-contraction effect already described. Curve E is a locus of some points which, in addition to those of curve A, exhibit four rotating-stall zones. The two sections of the curve were determined separately and are shown joined by a dashed line, since they may in reality not be parts of a single continuous curve. An indication had been found of another curve at the same speed but with a considerably lower weight-flow range than that of curve A. However, this curve has not been presented because of lack of accurate point determinations and because no rotating-stall data were taken at the time.

The majority of the stall zones measured extended about 1/2 to 3/4 of the radial depth of the annulus from the tip.

It probably would be possible to obtain other characteristic curves, perhaps many of them, at the test speed by using still different modes of approach from the low-speed side. However, their value would probably be small in evaluating any further general effects of multiple characteristic curves than those already given here. Similarly, there are many more speeds in the intermediate range which could have been investigated but which would probably show effectively the same results.

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A general trend can be observed of maximum weight flow as related to number of rotating-stall zones for each of the curves of figure 2. With the exception of the slight discrepancy found in comparing the two- and one-stall-zone curves (B and D), it is quite evident that, as the number of rotating-stall zones is decreased, the maximum weight flow of the resulting characteristic curve is increased. With the increase in maximum weight flow of the speed curve, the peak pressure ratio is also increased, as would be expected, since the inlet stages operate at lower angles of attack and therefore closer to the peaks of their individual pressure-ratio curves. This increase in weight flow and peak pressure ratio indicates an improvement in stage matching that may result from a decrease in the number of stages affected by interaction due to rotating stall or a decrease in the deterioration of stage performance as a result of rotating stall instigated by an inlet stage.

An incidental point that was observed during this investigation bears reporting at this time. After the compressor was brought out of the surge that occurred on curve E by opening the discharge throttle somewhat, there were three stall zones in the first stage and two stall zones in the fourth stage. This lasted only a few seconds, after which the oscilloscope showed three stall zones in both stages, and operation appeared to be on curve C. Perhaps for these few seconds there was a three-stall-zone pattern at the inlet that was nearly expended and was replaced before the fourth stage by an unstable two-stall-zone pattern that eventually split into a three-stall-zone pattern.

<u>Approach from high-speed side.</u> - Curve F was determined by increasing the compressor speed until the unstalled condition was reached, then closing the discharge throttle and decreasing the speed along a constant throttle line until the speed of 78.5 percent was reached at point F_0. This curve is stable and repeatable after surge and exhibits no rotating-stall pattern at any time.

This no-stall curve is related to the curves previously discussed in the same manner that these curves are related to one another; that is, as the number of stall zones is decreased, the maximum weight flow and surge pressure ratio are increased.

Efficiency at 78.5-Percent Design Speed

From the three curves of figure 3, which are the efficiency plots corresponding to curves A, B, and F of figure 2, and which represent operation with four, two, and no rotating-stall zones, respectively, it can be seen that the peak efficiency of each curve becomes higher as the number of rotating-stall zones is decreased, or similarly, as the maximum weight flow is increased. The explanation for this is the same as for the increased peak pressure ratio; that is, the inlet stages are operating at lower angles of attack and therefore closer to their individual peak efficiencies. Although no efficiency data were taken for the 3264
observed points shown on figure 2, it was expected that the peak efficiencies for the three- and one-stall-zone curves would probably follow the same trend. Further evidence to support the observation that the higher maximum-weight-flow curves have higher peak efficiencies is shown in figure 3. Point A_1, which is on a higher weight-flow curve than curve A, although it has the same number of rotating stalls, has an efficiency higher than the peak efficiency measured on curve A.

SUMMARY OF RESULTS

The following results were obtained from an investigation at 78.5-percent design speed of the experimental 15-stage axial-flow compressor:

1. Six different characteristic curves of operation at a given intermediate speed of 78.5 percent were indicated. Each of these curves seems to be accompanied by a definite number of rotating-stall zones, although a given number of rotating-stall zones does not necessarily determine a single operation curve.

2. In general, as the number of rotating-stall zones is decreased, the resulting operation curve has a higher maximum weight flow, higher peak efficiency, and higher surge pressure ratio.

3. When the speed is decreased to the test speed from the unstalled conditions, a single operation curve is determined. However, when the speed is increased to the test speed from the stalled condition, the resulting operation could be on any one of several curves.

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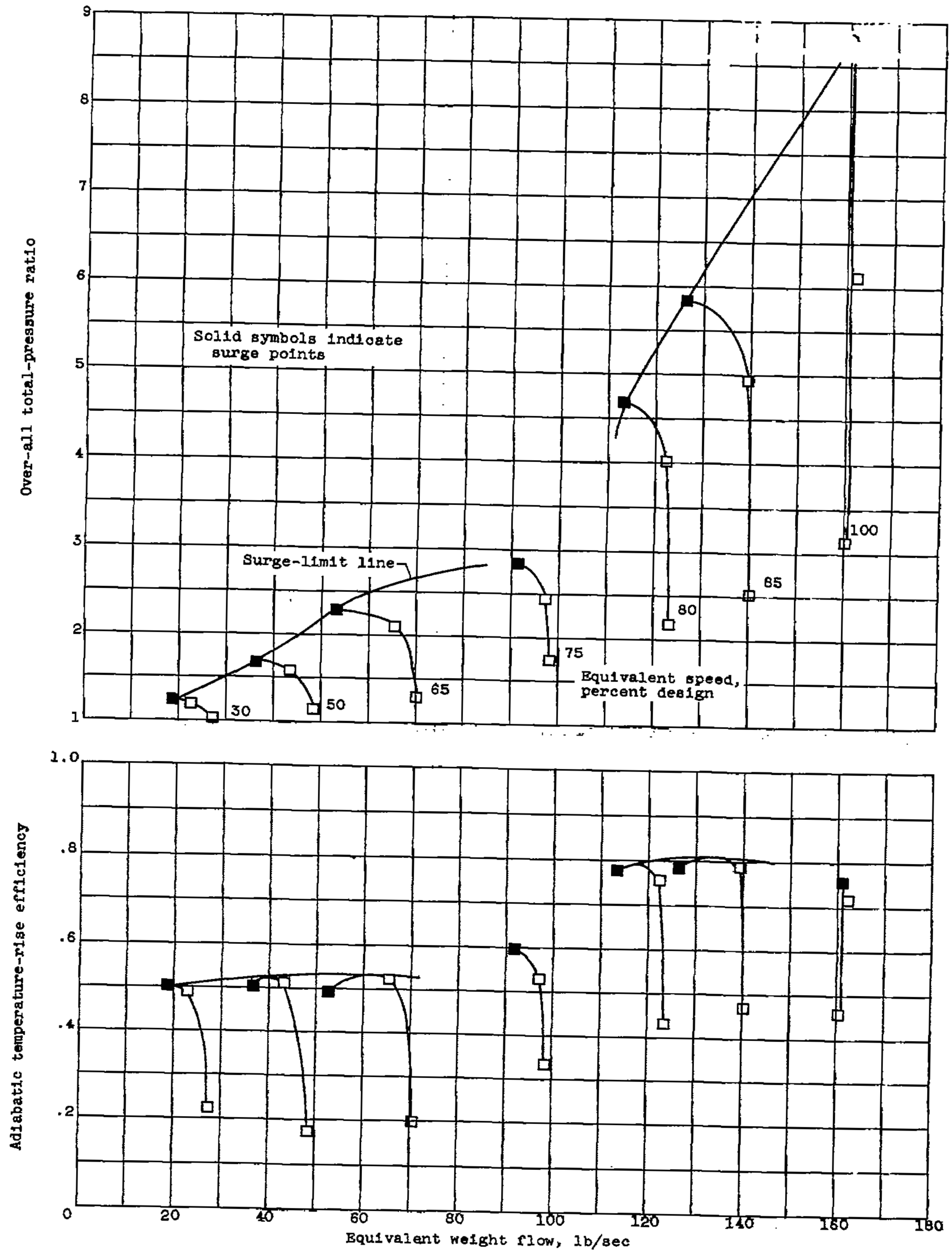

Figure 1. - Over-all compressor performance.

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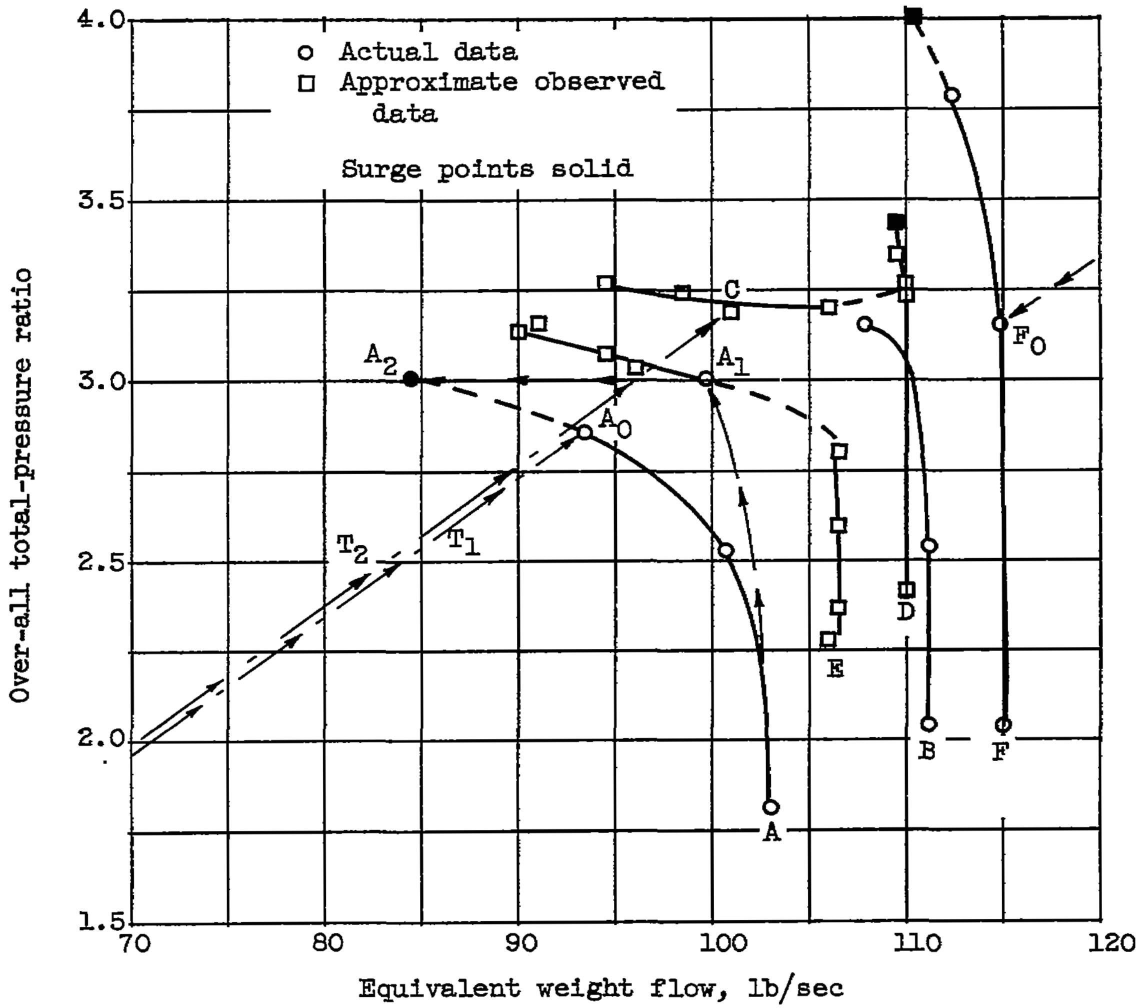

Figure 2. - Over-all total-pressure ratio at 78.5-percent design speed.

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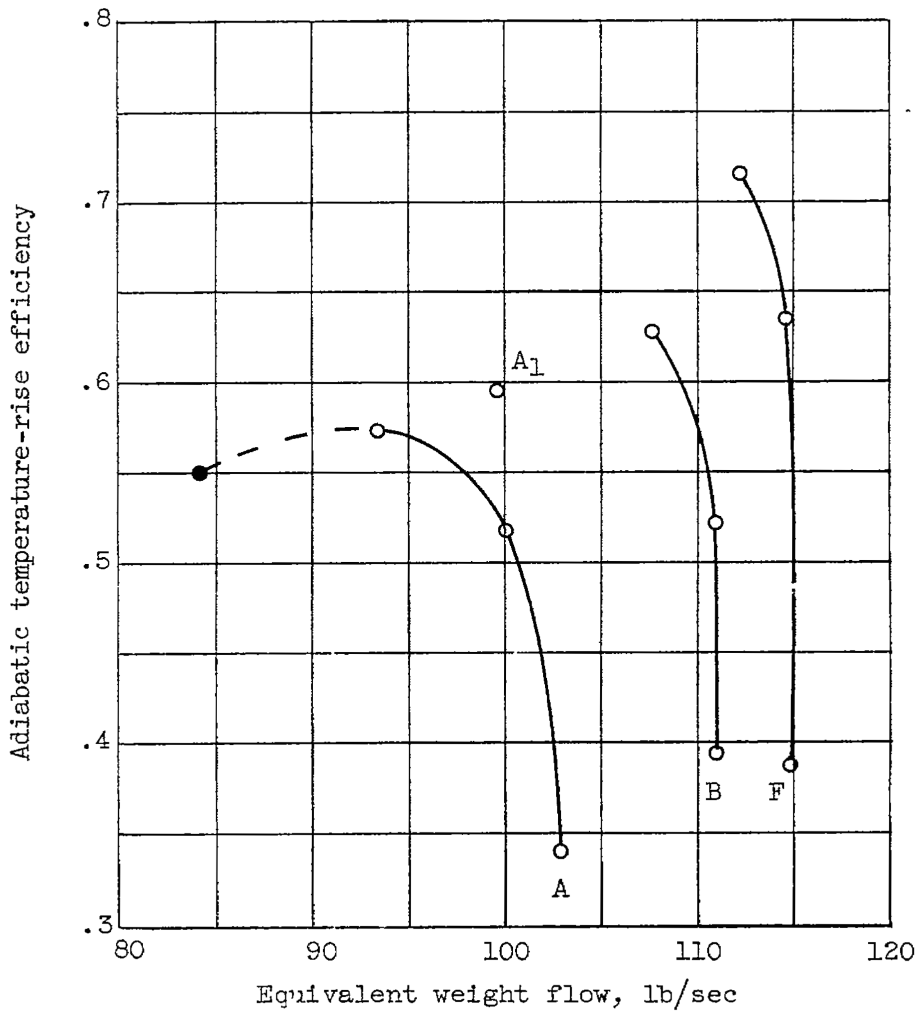

Figure 3. - Over-all compressor efficiency at 78.5-percent design speed.

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