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RESEARCH MEMORANDUM

EFFECT OF INLET-ANNULUS AREA BLOCKAGE ON OVER-ALL PERFORMANCE AND STALL CHARACTERISTICS OF AN EXPERIMENTAL 15-STAGE AXIAL-FLOW COMPRESSOR

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

As part of a general investigation of means of alleviating the general problems of blade vibration and poor off-design performance associated with compressor rotating stall at low and intermediate engine speeds, an experimental 15-stage axial-flow compressor was used to determine the effect of inlet-annulus area blockage on disrupting the rotating stall and altering the over-all performance and stall characteristics of the compressor. Although this compressor had not indicated any part-speed blade-vibration problems, it was felt that valuable information on the determination of means of disrupting the periodicity of rotating stall could be obtained.

The effects of blocking annular area in the tip region of the flow annulus and also of blocking the hub regions were investigated. The tip blockage reduced the compressor efficiency, did not affect the location of the stall-limit line, and was ineffective in removing the periodicity of the stall patterns. The hub blockage, however, appeared to be beneficial from two considerations: (1) In the form of an adjustable configuration, hub blockage seems to provide an improved acceleration potential for the engine up to 75 percent of design speed because of increased stall-limit margin; and (2) hub blockage also disrupts the periodic nature of the flow pulsations of the stall patterns by causing them to be erratic and unstable. It appears, therefore, that hub blockage would be an effective means of reducing or eliminating blade vibrations associated with rotating stall for the type of compressor design considered herein.

INTRODUCTION

As part of a general investigation conducted to alleviate the problems of compressor blade vibrations at the low and intermediate engine speeds, the NACA Lewis laboratory is studying various means of altering or disrupting the rotating-stall characteristics which have been encountered in this speed range. It has been previously pointed out (ref. 1) that blade vibrations in single-stage compressors can often be attributed to the periodic flow fluctuations associated with rotating stall. As is indicated in reference 2, such rotating stalls are encountered in the multistage compressor at low and intermediate compressor speeds where the front stages of the compressor are operating under stall angles of attack. Stall of the front stages at speeds below design can be attributed to the fact that the design ratio of compressor-inlet to discharge-annulus flow area is too great to permit efficient angle-of-attack operation of all stages of the unit. It has, therefore, been suggested that the inlet-annulus area might be effectively adjusted at speeds below design by blocking part of the annulus ahead of the inlet guide vanes by deliberately creating a thick boundary layer at either the inner or outer regions of the annulus. Such a boundary layer could be created by blocking part of the area ahead of the inlet guide vanes and might persist far enough through the compressor to improve the performance of the compressor as well as alter or disrupt the periodic rotating-stall flow fluctuations. Removing the periodicity of the stall would also eliminate the possibility of the occurrence of resonant blade vibrations induced by the stall flow fluctuations.

The effectiveness of blocking the flow in this manner can only be determined by experiment; and because of its availability, an experimental 15-stage axial-flow compressor was selected for the initial experiments. Previous investigations of this compressor indicated that a very noticeable rotating stall exists in the compressor at part speed; the frequency of the stall is sufficiently lower than the natural frequency of the blades to preclude resonant blade vibrations, however.

The present report discusses the effects on over-all performance and stall characteristics of introducing an annular blockage in the form of a ramp at the tip section upstream of the inlet guide vanes. Two blockages of approximately 12 and 28 percent of the inlet-annulus area were investigated at the tip section. Also presented is the effect of an annular blockage of approximately 21 percent of the annulus area at the hub section at the leading edge of the inlet guide vanes in the form of an axially symmetrical baffle plate. Although fixed-position blockages were investigated, it was felt that the effectiveness of the principle of retractable blockage could be determined. The results presented herein are preliminary, and further investigations would be required to determine optimum blockage areas and configurations.

APPARATUS AND PROCEDURE

Driving Power

Drive motor . . . . 15,000-hp synchrouous
Speed control . . . . Variable frequency
Gearbox . . . . 2.101-ratio single helical speed increaser
Compressor power required at design point with sea-level inlet
conditions, hp 32,900

Installation and Instrumentation

Air supply . . . . . Refrigerated air at pressure of 50 in. Hg abs, or atmospheric air
Exhaust . . . . Altitude exhaust at 10 in. Hg abs
Air control . . . . . Butterfly throttles in inlet and outlet ducting
Air metering . . . . Thin-plate orifice of 18.394-in. diam. in pipe of 41.25-in. I.D.
Compressor inlet . . . Depression tank 6 ft in diam. and approx. 10 ft long; bellmouth nozzle fitted directly to inlet of compressor
Compressor-inlet pressure . . Two wall static-pressure taps 180° apart and six total-pressure tubes located at area centers of equal area in depression tank
Compressor-inlet temperature . . . Five bare-wire thermocouples located at area centers of equal areas in depression tank
Compressor-discharge pressure . . Eight wall static taps spaced around circumference
Compressor-discharge temperature . . . Four radial rakes spaced around circumference each with five spike-type thermocouples equally spaced across passage and located 1 in. downstream of discharge guide vanes
Pressure measurement . . . . Mercury manometers
Temperature measurement . . . . .Calibrated self-balancing Brown potentiometer
Motor-speed measurement . . . . Electric chronometric tachometer
Compressor insulation . . . . 1-in. glass wool

The configurations considered for the inlet flow blockages are indicated in the diagrammatic sketch of figure 1. As has been pointed out in the INTRODUCTION, two tip-ramp configurations were investigated. The blockage area for the ramp was adjusted by moving the free end of the ramp radially to block arbitrarily 12 and 28 percent of the annulus area. Although a ramp-type blockage at the hub was desirable, inasmuch as this type would probably be advantageous in a production version, it was considered expedient to use a flat annular baffle plate for the preliminary tests. Only one area blockage (21 percent) was considered for the hub baffle, and again this was an arbitrary value. The flow fluctuations of rotating stall were detected and measured with hot-wire anemometers. Two hot-wire-anemometer probes were installed in radially traversing probe actuators in the first-stage stator blade row. The circumferential angle between the two probes was 112°. A third hot wire was installed in the fourth-stage stator-blade row. The frequency of the rotating-stall patterns was determined by the use of a variable-frequency oscillator and a dual-beam cathode-ray oscilloscope. The number of stalls was calculated by the procedure outlined in reference 3.

The over-all performance of the compressor was determined without the area blockage at speeds from 30 to 100 percent of design. The effect of the blockage on the over-all performance and rotating-stall characteristics was determined at speeds of 50, 65, and 75 percent of design speed. The hub baffle was also investigated at 80 percent of design speed.

The total-pressure ratio at each data point was determined by the method recommended in reference 4, whereby the discharge velocity pressure computed from the continuity equation is added to the average of the measured discharge static pressures to obtain the discharge total pressure.

RESULTS AND DISCUSSION

The results of the present investigation are divided into three principal parts, consisting of the discussion of the compressor performance with no flow-area blockage at the inlet, the performance with the tip-ramp blockage, and the performance with the hub-baffle blockage. Stall characteristics for all these configurations are also discussed.

Compressor Performance without Inlet-Area Blockage

Over-all performance characteristics. - The over-all performance of the compressor is presented in figure 2 as curves of pressure ratio and efficiency against equivalent weight flow for various percentages of design speed from 30 to 100 percent. Multivalued speed curves along with multiple stall-limit lines were encountered in the intermediate-speed range, making it impossible to draw a stall-limit line at these speeds.

Stall characteristics. - The stall characteristics (number and frequency) were determined by use of the hot-wire equipment previously mentioned. Typical stall patterns indicated by the hot wires in the first stator row are presented in figure 3. It is apparent that the stall regions are of the periodic rotating type. The data of figure 3 were obtained at 50 percent of the design speed. At speeds up to approximately 65 percent of design, four or five stall regions could be obtained over the entire flow range. For instance, at 65 percent of design speed, five stall regions could be found to persist at all flow conditions up to surge. Once the compressor surged, the stall pattern could alter so that only four stall regions were obtained. Subsequent surging of the compressor at this speed could then cause the stall pattern to revert to the five-stall configuration. Over-all performance, however, was apparently unaffected by the number of stall regions. At 75 percent of design speed, only four stall regions were indicated over the entire flow range. For all speeds investigated (up to 75 percent of design), the rotating rate was approximately 57 percent of the rotor speed. The stall appeared to be essentially a tip stall of rather large radial depth for the speeds investigated. For example, at 50 percent of design speed, preliminary data indicate that the stall region extended over approximately 75 percent of the radial blade height from the tip section. This radial extent remained the same regardless of whether the four- or five-stall condition was prevalent. The hot-wire measurements in the fourth-stage stator blade row indicated that the stall patterns passed axially through the compressor.

Compressor Performance with Tip-Ramp Blockage

Because the stall characteristics of the compressor appeared to indicate a tip-stall condition, disruption of the stall might be possible by blocking off this section of the inlet annulus. It was realized, however, that the effect of such a blockage, if it were greater than the effective area blockage of the stall zones, might be to force air flow down toward the hub section of the inlet-stage blades, thus unloading this section. Some detrimental effect on pressure ratio might be anticipated from such a condition in view of the fact that the hub section is generally operating at much more favorable angles of attack than is the tip section for the type of velocity-diagram design used in the present compressor. Inasmuch as the effect of the baffles on performance cannot be divorced from the effect of the baffles in altering stall patterns, both the performance and the stall characteristics of the compressor will be discussed in order to evaluate the effectiveness of the tip-blockage configurations investigated.

Over-all performance characteristics. - The over-all performance characteristics of the compressor with both the 12- and the 28-percent area-blockage tip ramps are presented in figure 4 as curves of pressure ratio and efficiency against weight flow for 50, 65, and 75 percent of the design speed. Also presented for comparison is the performance of the compressor without inlet blockage (fig. 2). It is immediately apparent that a reduction in flow was obtained at all speeds investigated. The maximum flow at 75-percent speed was reduced approximately 18 percent by the larger inlet tip ramp. The peak efficiency was also found to decrease noticeably. At 75 percent, the efficiency decrease was approximately 10 points from 60 to 50 percent. The position of the surge line appears to be unaltered for the speed range investigated, as a result of the decrease in pressure ratio associated with the decrease in weight flow. Because of the drop in the peak-efficiency level and because the surge line is relatively unchanged, the acceleration potential of an engine using these tip ramps at the compressor inlet would probably be worse than if the ramps were not used.

Stall characteristics. - The effect of the tip ramp on stall characteristics was found to be small. For 12-percent blockage, the stall propagation rate and the number of stalls encountered were essentially the same as those for the case without inlet-area blockage. The stall regions, however, were found to extend from the tip down to the hub section for the three speeds and the flows investigated.

For the 28-percent blockage ramp, four stall regions were obtained over the entire flow and speed range. The principal effect of increasing the blockage area appeared to be an effect on stall propagation rate. The ratio of stall frequency to rotor speed changed from a value of approximately 0.57 indicated for the compressor without blockage to approximately 0.45 for the large ramp.

In general, therefore, it appears that the tip ramp was ineffective in appreciably altering the stall pattern or disrupting the periodicity of the stall. Evidently, the attempt to augment the stalling at the tip did not interfere with the mechanism creating the rotating stall, even though the performance curve of the compressor was sensibly altered.

Compressor Performance with Hub-Baffle Blockage

Consideration of the effects of the tip blockage indicated that it might be advantageous to alter the stall configuration or to alleviate the off-design stall problems to some extent by the use of a hub blockage which would force flow out toward the first-stage tip section. Such a configuration would reduce the angles of attack at the tip of the first rotor at a given speed, thus increasing the stall-free operating range. In addition, reduction in the angle of attack at the tip section to low speeds would cause the pressure ratio across this section to be increased.

It was pointed out previously that, for reasons of expediency, the hub-section blockage was effected by inserting a flat annular ring or baffle at the leading edge of the inlet guide vanes. The effect of the hub baffle on the performance and stall characteristics of the compressor was investigated at speeds of 50, 65, 75, and 80 percent of the design speed. Although the baffle investigated occupied 21 percent of the annulus area, the effect of a streamline curvature or a vena contracta would probably cause a noticeably greater effective flow-area blockage near the leading edge of the first rotor. The actual effective flow-area blockage for the present investigation is unkown.

Over-all performance characteristics. - The over-all performance of the compressor with the hub baffle is compared with the performance of the compressor without inlet-area blockage in figure 5. It is immediately apparent that the flow range obtained at both 75 and 80 percent of the design speed is appreciably changed by application of the hub baffle. A large reduction in flow at any speed is indicated for the compressor with the hub baffle installed. At 80 percent of design speed, this decrease in flow is approximately 32 percent of the maximum flow obtained for the compressor without inlet-area blockage. At any given speed, the flow range with the baffle is greater than that without the baffle. The combined effects of the flow reduction and the increase in the stable flow range in the intermediate speed region causes a shift in the stall-limit-line position to lower flows at any given pressure ratio over the speed range investigated.

Stall characteristics. - The stall characteristics measured by the hot-wire probes in the first stator row for the compressor with the hub baffle installed indicate extremely irregular and erratic flow pulsations rather than periodic pulsations up to 80 percent of design speed. Thus, it appears that the hub baffle was extremely effective in disrupting the periodicity of the stall, so that any induced blade vibrations at low and intermediate speeds for a compressor of this design would be eliminated.

In addition, the use of a retractable hub baffle appears to have a beneficial effect on acceleration potential of the engine, so that a twofold gain can be anticipated from such an adjustable compressor configuration.

An attempt to evaluate this general conclusion has been made by calculating an ideal operating line for this compressor when installed in the engine with a constant jet-nozzle area for the cases with the baffle installed and with the baffle removed. The calculation of the operating line assumes a constant turbine efficiency of 85 percent and that the turbine stators are choked under all compressor-flow conditions. A pressure ratio of 7.5 has been selected as the design or reference point. The flow margin between the operating line and the surge line gives an indication of acceleration potential for each of the configurations. The results of the calculation are presented in figure 6 as curves of the pressure ratio and flow for each of the compressor conditions along the operating line superimposed on the performance map of figure 5. The results of figure 6 indicate that application of the hub baffle would improve engine acceleration rate at speeds up to 75 percent because of the existence of a stable flow range between the equilibrium operating line and the surge line for this baffle configuration. The equilibrium operating line for the compressor without the baffle falls in the surge region.

Because only one fixed-position hub baffle has been investigated, the present results must be considered preliminary. These results should be applied in a full-scale engine to determine optimum modes of adjusting blocked area by retracting the baffle so as to realize the desired improvements in stall and blade-vibration characteristics and acceleration potential at low speeds and still obtain continuous, stable operation to the design conditions. Although preliminary, the results also indicate new and interesting possibilities for control of engine thrust at any speed including design by adjustable inlet-area control. The performance map of figure 6 indicates the sensitivity of compressor air flow, and thus engine thrust, to inlet-area blockage. Evaluation of such a thrust-control device requires additional compressor component and engine investigations.

SUMMARY OF RESULTS

The analysis of the data of the present investigation indicates the following results:

1. Application of the tip-ramp blockage reduced the peak compressor efficiency up to 75 percent speed, caused no change in the position of the surge line, and had only minor effects on the compressor stall

characteristics. A periodic rotating stall existed with this baffle, and the nature of the stall was not greatly different from that observed without the baffle.

2. Application of the hub-baffle blockage appears to be extremely effective in improving the low- and intermediate-speed stall characteristics. With the hub baffle installed, the stall pattern was of a nonperiodic type, thus indicating that blade vibrations associated with low- or intermediate-speed conventional rotating-stall characteristics could be eliminated with an adjustable compressor configuration incorporating the hub-baffle concept.

3. It appears that application of the hub baffle blockage would improve the acceleration potential of an engine using this compressor up to 75 percent of design speed.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland Ohio, Dec. 10, 1953

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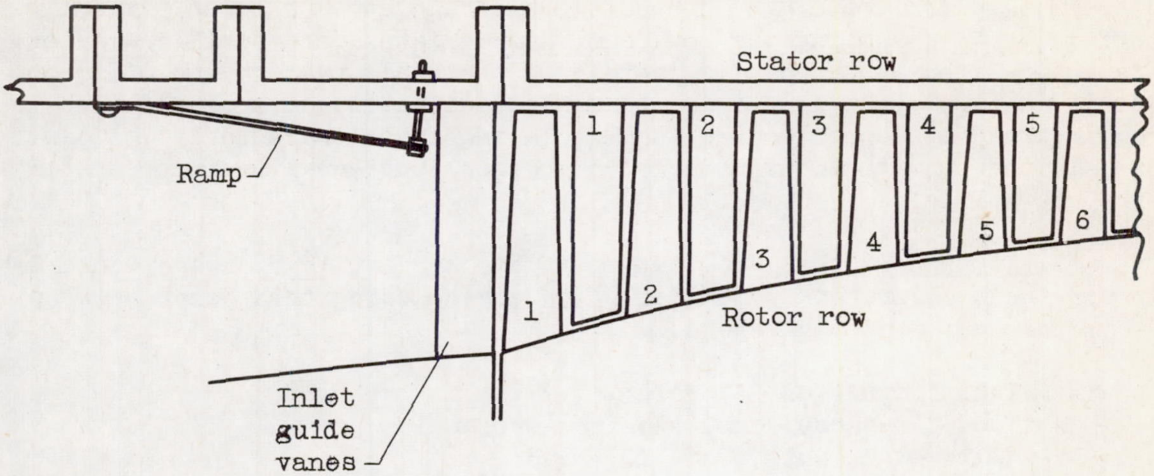
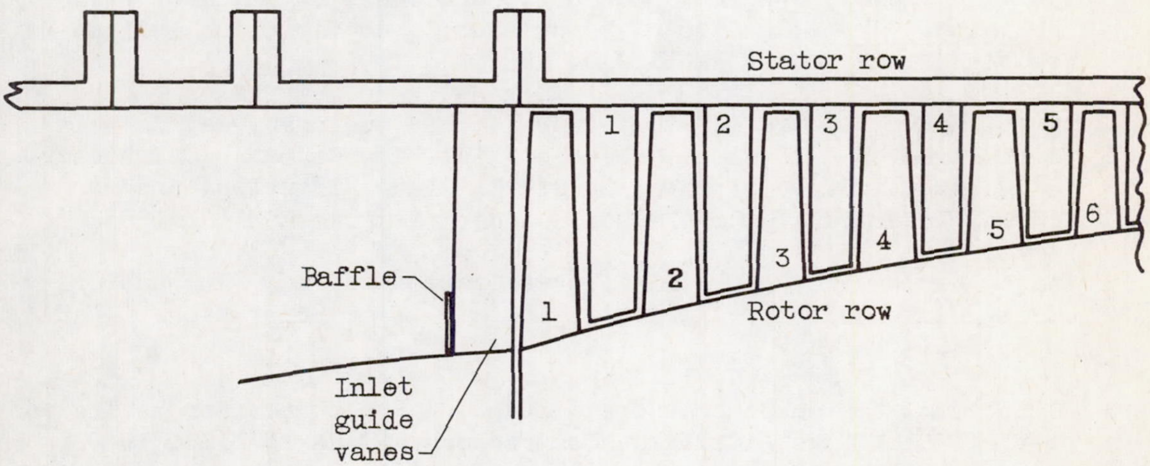


(a) Tip-ramp area blockage.



(b) Hub-baffle area blockage.

Figure 1. - Schematic diagrams of inlet-area blockage methods.

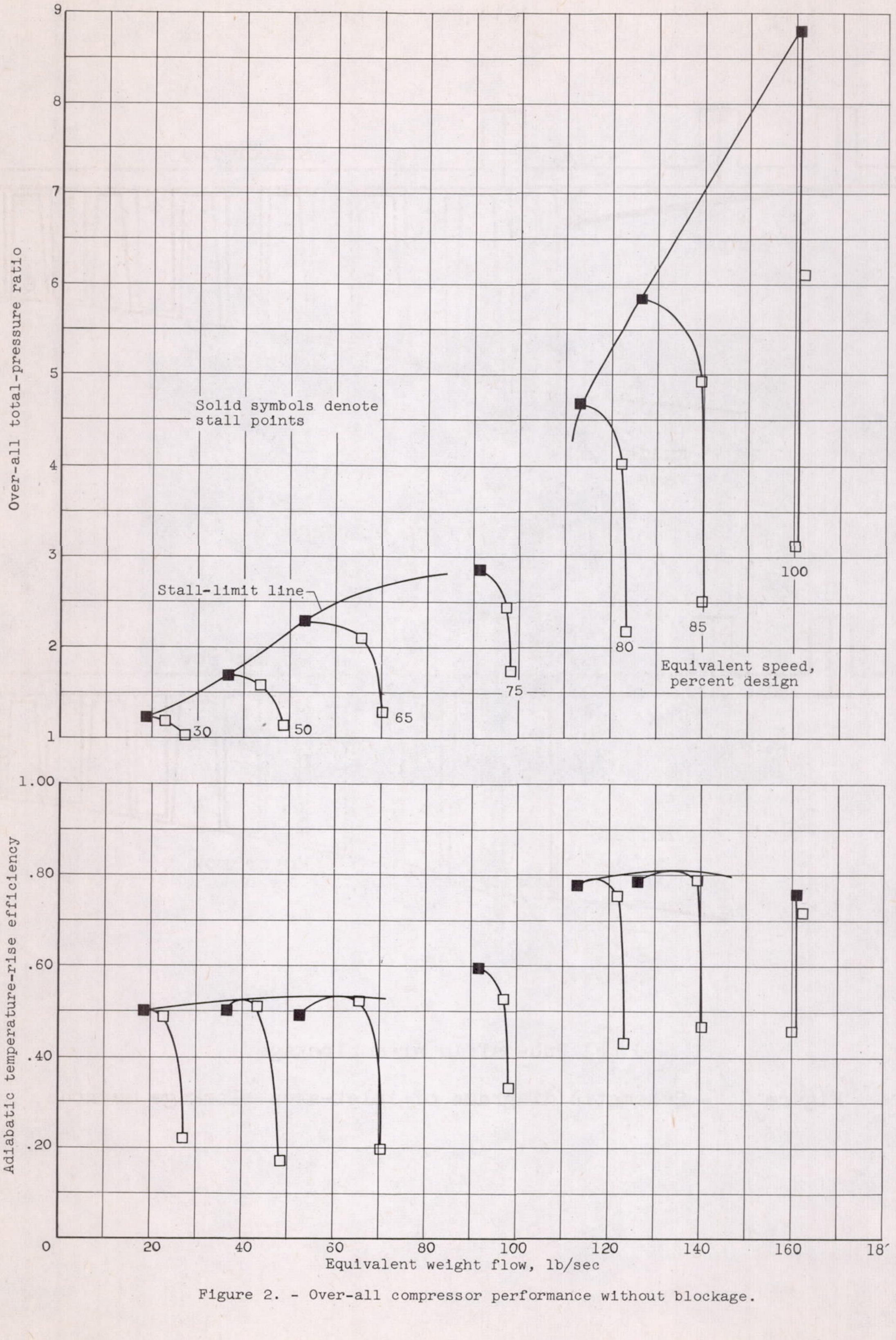
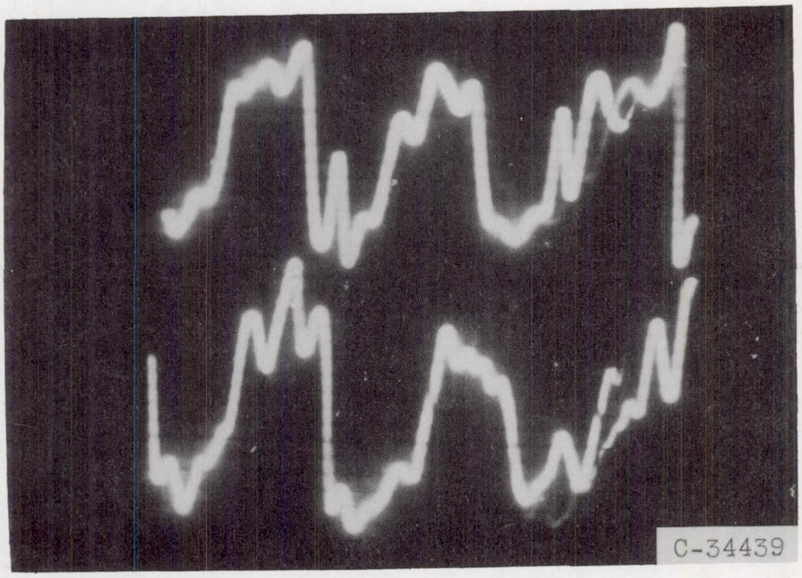


Figure 2. - Over-all compressor performance without blockage.

Mass-flow rate



Time

Figure 3. - Rotating-stall flow fluctuations indicated by hot-wire anemometers at 50 percent of design speed for compressor without blockage.

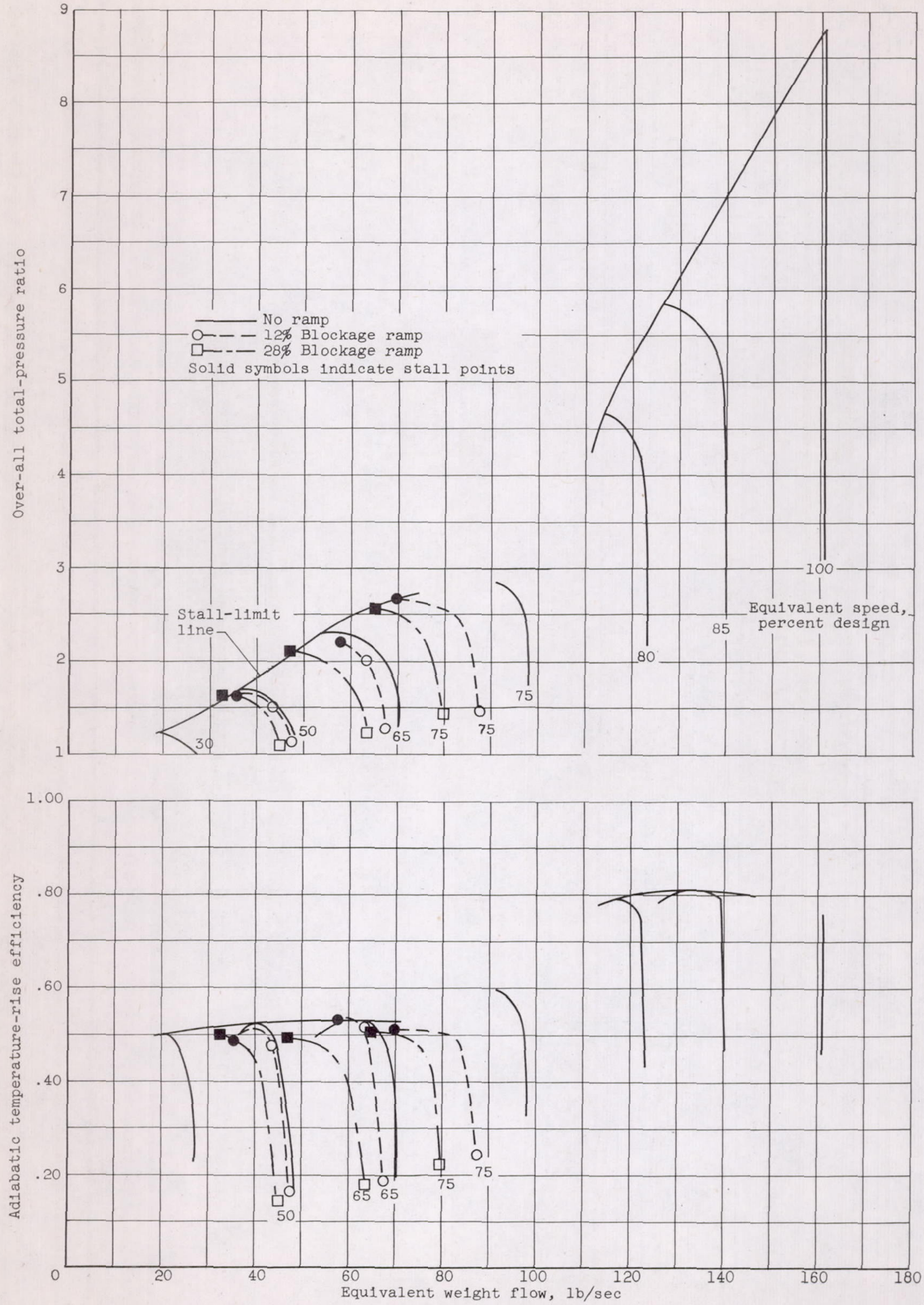


Figure 4. - Over-all performance with and without tip ramps.

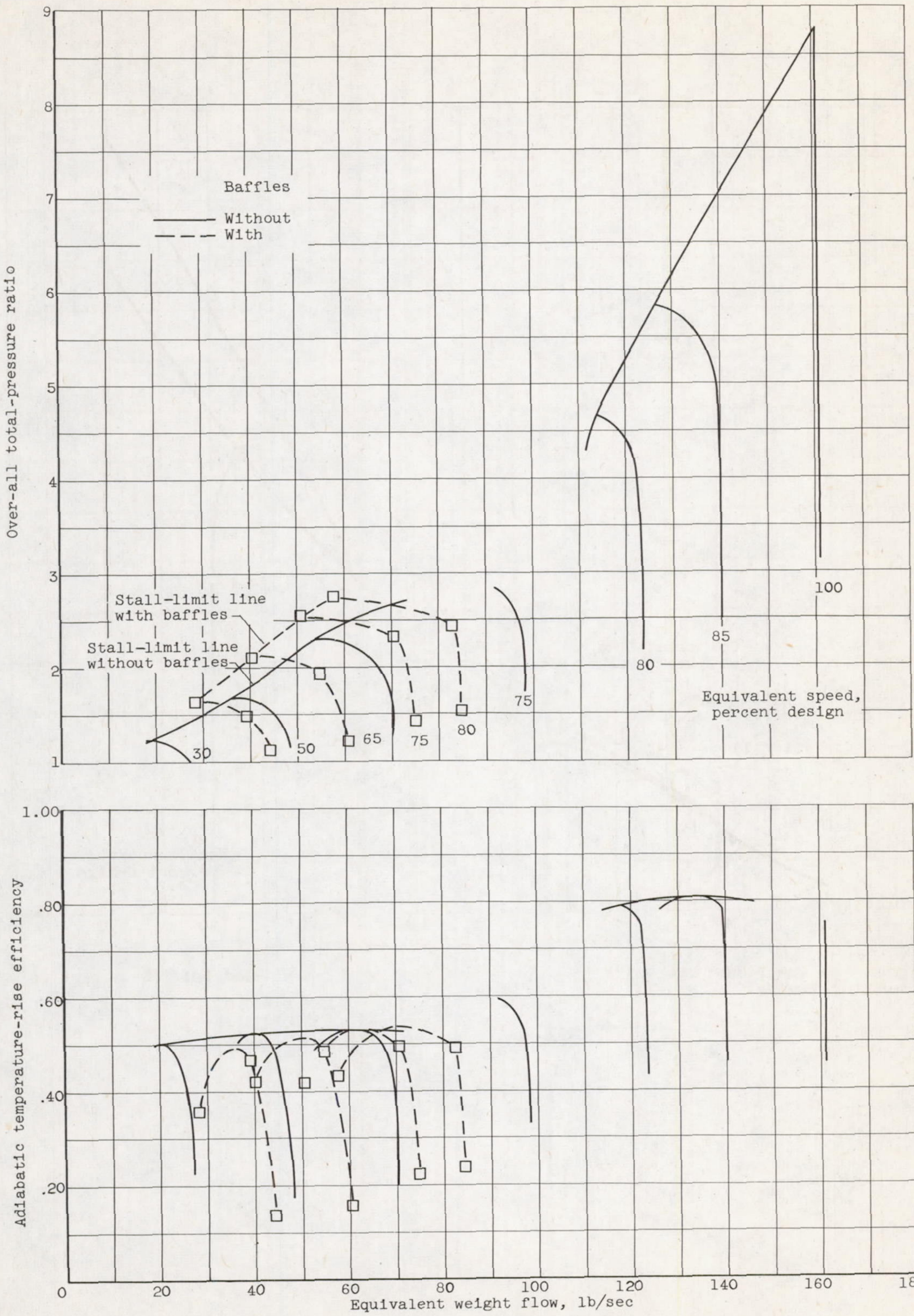


Figure 5. - Over-all performance with and without hub baffle.

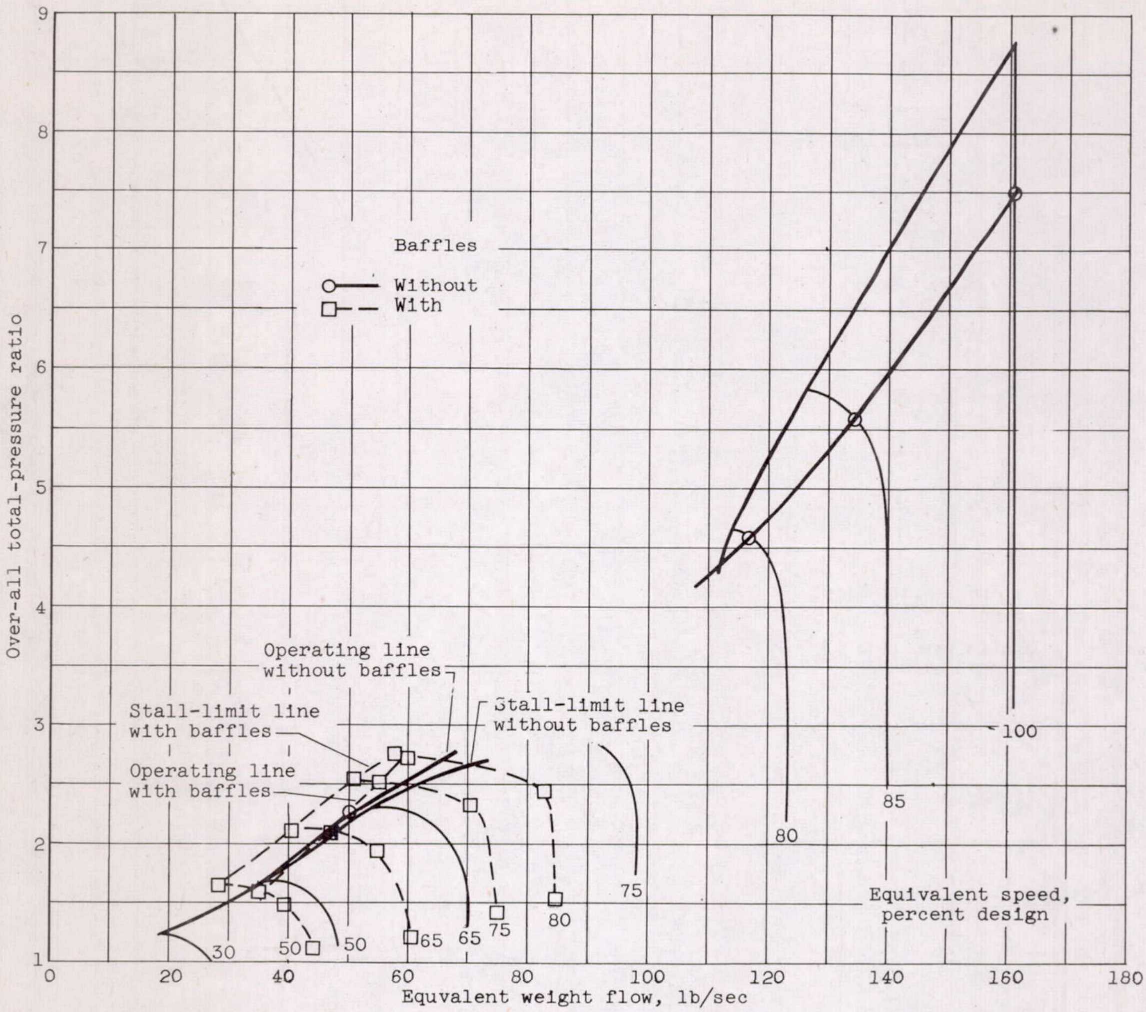


Figure 6. - Compressor operating line characteristics with and without baffles as part of a turbojet engine.