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# A Study of Casing Treatment Stall Margin Improvement Phenomena[1]

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The results of a program of experimental and analytical research in casing treatments over axial compressor rotor blade tips are presented. Circumferential groove, axial-skewed slot, and blade angle slot treatments were tested at low speeds. With the circumferential groove treatment the stalling flow was reduced 5.8 percent at negligible efficiency sacrifice. The axial-skewed slot treatment improved the stalling flow by 15.3 percent; 1.8 points in peak efficiency were sacrificed. The blade angle slot treatment improved the stalling flow by 15.0 percent; 1.4 points in peak efficiency were sacrificed. These values are consistent with previous experience at transonic speeds. The favorable stalling flow situations correlated well with observations of higher-than-normal surface pressures on the rotor blade pressure surfaces in the tip region, and with increased maximum diffusions on the suction surfaces. Annulus wall pressure gradients, especially in the 50 to 75 percent chord region, are also increased and blade surface pressure loadings are shifted toward the trailing edge for treated configurations. Rotor blade wakes may be somewhat thinner in the presence of good treatments, particularly under operating conditions close to the baseline stall. Annulus wall boundary layer profiles are only slightly influenced by casing treatment.

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## INTRODUCTION

Recent applied research (References 1 to 7)[2] had shown that compressor casing treatment can substantially improve the stall characteristics of fan and compressor stages. Different casing treatment configurations had been identified which provide either significant improvements in extending the stall line with some penalties. The effectiveness of the treatment is judged primarily by its ability to maintain or increase the pressure ratio while decreasing the weight flow below that obtained for a reference solid casing at the stall limit point. This stall limit point is defined as the point of onset of rotating stall. The program described in Reference (1), for example, showed 7 percent improvement in stall margin for 2 points sacrifice in efficiency, Reference (2) described tests on a number of different treatment types. Significant stall margin increases were obtained with several of the treatments. The skewed slot configuration gave 20.7 percent increase in stall margin with a 7 point loss in efficiency. The blade angle slot and the circumferential groove configurations gave a 17.5 and 13.5 percent increase in stall margin, respectively, with efficiencies as high or slightly higher than those obtained with the reference solid casing.

The state-of-the-art with respect to casing treatment at the beginning of the present program could best be expressed by a series of empirical observations. The following list is a digest of information contained in References (1) to (7).

- Most of the rotors on which casing treatment seemed beneficial encountered instability in the form of a rotating stall initiated at a critically loaded rotor tip.
- All of the stages on which attractive casing treatment results had been found were transonic. Transonic stages tend to be designed with little or no camber in the tip region. They tend to have heavy leading edge loadings just prior to stall as compared with subsonic designs.
- The most successful casing treatments have 65 to 75 percent open area in the nominal casing surface.
- Treatment over the 20 percent of the meridionally projected rotor chord from either the leading or the trailing edge is ineffective. Most, if not all, of the benefits come from treating the center 60 percent of the chord projection.
- Some tip treatments have been observed which lead to increased blade tip loading and pressure rise as compared with a solid casing, as if the diffusion process were improved. The overall pressure rise of the stage may still appear to remain constant during throttling of a stage in which the tip region picks up load, if the strengthened tip results in transferring the throttle response to a hub region with a drooping characteristic.
- Recirculation in grooves, slots, or plenums may serve to stabilize or delay rotating stall. Some of the early casing treatment tests indicated that large recirculation gives a substantial efficiency sacrifice as compared with solid casings.

The various experimental programs (References (1) - (5)) had shown that the geometric parameters associated with the configuration designs could be quite critical. Only a few configurations of each type, chosen somewhat arbitrarily, had been investigated. It seemed likely that a detailed investigation into the mechanisms and principles behind the beneficial influences of casing treatment would lead to a

[2] Numbers in parentheses designate References at end of paper.

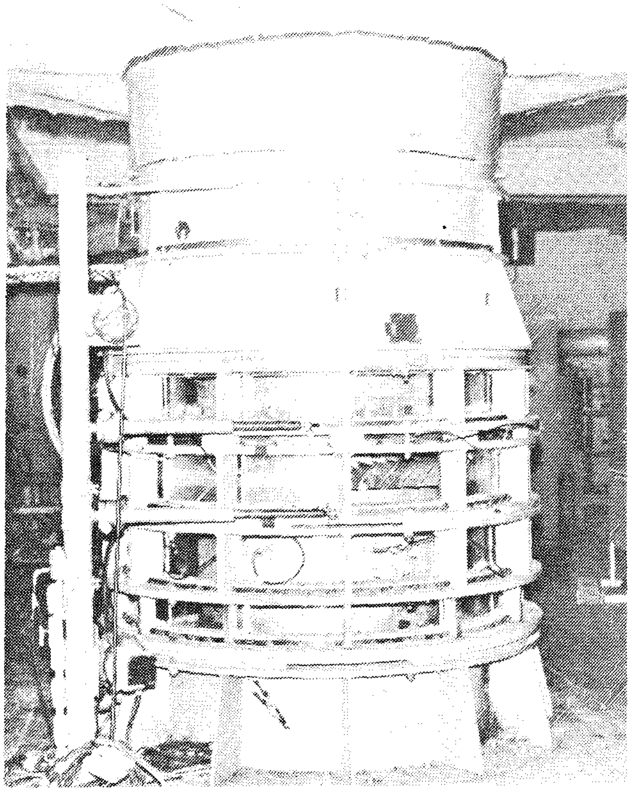

Fig. 1 General Electric Co. low speed research compressor with circumferential groove casing treatment windows partially installed

substantial further improvement in the observed performance. The present program (Reference (8)) was undertaken to make such a detailed investigation. Analytical modeling of the flow patterns in the casing treatment cavities was carried out in conjunction with the experimental program.

A specific objective of the present Casing Treatment program was to explore the relevance of a series of possible mechanisms which had been suggested as possible explanations for the manner in which casing treatment works to extend stable operating ranges. The mechanisms which seemed worthy of exploration fell into a number of groups:

1 Suppression of incipient separation - inherently two-dimensional cascade effects. This mechanism about the influence of a casing treatment on the stability of a compressor rotor is based on the premise that stalling starts with an instability in the two-dimensional or quasi-two-dimensional flow around the blade tip airfoils. Thus if a critical corner boundary layer develops on the suction surface near the blade tip, flow out of a cavity may impinge on the boundary layer, energizing it and delaying separation. Flow into a cavity may serve as a bleed, removing low energy fluid from a critical corner boundary layer between a blade suction surface and the annulus wall, delaying separation. Flow into or out of a cavity may also dissipate an incipient vortex generation.

Casing treatments may increase the effective turbulence for flow close to the annulus wall, leading to energized boundary layers and increased flow stability. It should be noted that airfoils with extreme leading edge loading may be particularly susceptible to boundary layer instability in the mid-chord region, and therefore are special candidates to respond to artificial stabilizing devices.

2 Meridional boundary layer control. The meridional boundary layer control mechanisms, in contrast to the incipient two-dimensional boundary layer separation mechanisms, disregard considerations of stability of the two-dimensional flow around a blade. Attention is given instead to the pressure difference across a flow barrier which produces a force component in the axial direction. The cavities may serve to damp the fluctuation of the moving rotor pressure field in a way to stabilize the annulus wall boundary layer. The flow barriers between casing treatment cavities may even interfere with a tendency toward flow reversal in the annulus wall boundary layer.

3 Compliant wall absorption of pressure disturbances. It is clear that a small "blob" of high pressure fluid impinging on a solid wall will have its velocity component perpendicular to that wall brought suddenly to rest, resulting in an amplification of the high pressure. The same high pressure blob impinging on the separation surface between the freestream and a stagnant cavity will find that the contents of the cavity give way. The high pressure disturbance is then reflected as a low pressure disturbance. Thus the separation surface between an essentially stagnant cavity and the free-stream flow is compliant to local disturbances, serving as a damper on them where a solid wall would act as an amplifier.

The resources available for the present program promised to permit detailed examination of many blade surface, annulus wall, and cavity flow characteristics. A suitably planned program could yield much new information on the correlation between these detailed characteristics and the overall performance.

Table 1 Blade Geometry for Low Speed Research Compressor Casing Treatment Phenomena Investigation

| | Inlet Guide Vanes | | Rotor | | Stator | |
|---|---|---|---|---|---|---|
| Number of Blades | 40 | | 54 | | 53 | |
| Radius Ratio | 0.7 | 1.0 | 0.7 | 1.0 | 0.7 | 1.0 |
| Camber (deg.) | 21.5 | 34.5 | 41.7 | 23.1 | 32.6 | 31.6 |
| Stagger (deg.) | 13.2 | 21.9 | 16.4 | 43.4 | 29.9 | 41.5 |
| Solidity | 1.5 | 1.5 | 1.88 | 1.31 | 1.85 | 1.30 |
| Thickness/Chord | 0.1 | 0.1 | 0.13 | 0.045 | 0.04 | 0.12 |
| Aspect Ratio: $\frac{\text{Span}}{\text{Chord}}$ | 1.5 | | 1.96 | | 1.94 | |
| Tip Clearance/Chord | | | 0.016 | | | |
| Mean Line | A4K6* | | Circular Arc | | Circular Arc | |
| Profile | 63 Series | | 65 Series | | 65 Series | |

*Dunavant, J.C.; Cascade Investigations of a Related Series of 6-Percent-Thick-Guide-Vane Profiles and Design Charts, NACA TN3959, May 1957.

## EXPERIMENTAL RESOURCES

### Low Speed Research Compressor Facility

The General Electric Low Speed Research Compressor (LSRC) is designed to provide quantitative and qualitative aerodynamic data on axial flow compressor stages. It is ideally suited for the exploration of phenomena in which viscous effects, characterized by Reynolds number, play a predominant role but where compressibility effects, characterized by Mach number or density ratio, are relatively unimportant. Even though the blade tip speed employed is low (80 meters per second maximum), the large tip diameter (152.5 cm) allows testing with blade chord Reynolds numbers of about 500,000. This is sufficiently high to be above any critical value known for compressor stages and, in fact, is higher than many smaller engines encounter during altitude operation. The large diameter also makes possible the study of small scale phenomena, such as secondary flows, without the need for extreme miniaturization of instrumentation. A photograph of the LSRC is shown in Fig. 1. The details of the facility and its operation are presented in Reference (8).

### Test Compressor

The test compressor selected for the Casing Treatment program was a 0.7 radius ratio single-stage compressor which had been tested as a four-stage assembly. The four-stage assembly had been tested extensively, including various perturbations on stagger, solidity, and clearance; some of these results are reported in Reference (9). Tuft explorations and performance measurements had shown that the design was subject to stalling of the rotor tip. It was, therefore, expected to be a good showcase for the stabilizing influence of casing treatments on the rotor tip flow. The stage consisted of inlet guide vanes, rotor and stator. Blade design geometry is given in Table 1.

### Casing Treatment

Transparent removable casing windows were used over the rotor for the various casing treatment configurations. Testing with plain casing windows provided a baseline for comparison. Three casing treatment configurations included circumferential grooves, axial-skewed slots, and blade angle slots. All three configurations were centered over the rotor tip and covered approximately 70 percent of the axial projection of the rotor tip section. A photograph of the various treatment configurations is shown in Fig. 2. More information about the treatment geometry is given in Table 2.

### Instrumentation

The instrumentation used to obtain overall performance was common to all configurations and consisted of total pressure rakes, flow angle and stream static pressure traverse probes, casing and hub static pressure taps, B&K microphones for recording time varying static pressures, hot film anemometers, wet and dry bulb thermometer, barometer, strain gage torquemeter and an elec-

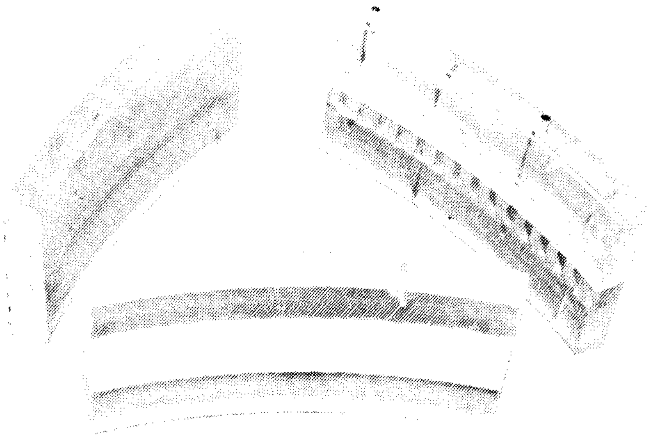

Fig. 2 Baseline, circumferential groove, and axial-skewed slot casing treatment windows

tronic tachometer. Two rotor blades were fitted with blade surface static pressure taps. Detailed quantitative measurements of the flow within the treatment cavities were made with steady-state and dynamic instrumentation.

## ANALYTICAL FLOW MODELING

Several analytical models for flow patterns in and around the casing treatment cavities were constructed and used. An incompressible, inviscid, two-dimensional flow model for the flow in a circumferential groove casing treatment cavity, with constant total pressure relative to a moving blade row and freestream static pressure distributed from blade to blade according to a cascade prediction, was synthesized using an analogy to the classical "wavy-wall problem." The results of this analysis showed that the blade-to-blade rotor tip static pressure gradients should induce significant radial flows in and out of the groove and could produce a radial outflow or suction effect over blade tip region. This analysis predicted influences of the groove depth on the radial flows which are roughly proportional to the stall line improvement found in Reference (5). A flow model was also developed for longitudinal flow in slots driven by an applied static pressure field using numerical finite difference field solutions for two-dimensional incompressible flow. The Navier Stokes equations with the assumptions of classical Poiseuille theory were used to predict a viscous flow pattern for the grooves; this model predicted that the freestream velocity would penetrate only a small fraction of the distance to the bottom of the groove. In another model, the results of an incompressible flow calculation with vorticity constant along streamlines suggested that the flow might move into the axial-skewed slot cavity along the down-rotation wall, acorss the cavity and outward along the up-rotation wall, with near-stagnant conditions at depths greater than 80 percent of the cavity width below the lip. The flow patterns of such predictions provided guidance in designing experiments to measure the flow patterns within the cavities.

## EXPERIMENTAL RESULTS

### Overall Performance

Many investigators had shown that wall treatments may improve stall margin, prior to this program. However, almost without exception, their experience had been gained on transonic stages. Thus a fundamental question needed to be answered:

> Could an influence of wall casing treatment on compressor performance, and especially on the limit to the stable operating range set by stall, be found in a vehicle where compressibility effects are insignificant?

This question was quickly answered affirmatively: the stable operating range of this test axial compressor stage is extended by casing treatment, at approximately Mach number 0.11. Additional testing at one-half of this nominal Mach number level showed almost the same effects. Thus compressibility effects, such as cavity resonance, are not required in order for casing treatment to be effective.

Overall performance of the various casing treatment configurations, based on casing static pressure rise, is compared with that of the baseline configuration in Fig. 3. Qualitative behaviors are similar to those reported previously, for example in References (2) and (4). A conventional circumferential groove treatment gave a 6 percent improvement in stalling flow with virtually no sacrifice in peak efficiency. An axial-skewed slot configuration gave a 15 percent improvement in stalling flow with 1.8 points sacrifice in peak efficiency. A blade angle slot configuration gave 15 percent improvement in stalling flow with 1.7 points sacrifice in peak efficiency.

An overall comparison of performance and stall characteristics of the various configurations emphasizing salient features is presented in Table 3. The baseline configuration and the circumferential groove configuration exhibited substantially the same work input. The blade-

Table 2 Casing Treatment Geometry

| | Circumferential Groove | Axial Skewed Slots | Blade Angle Slots |
|---|---|---|---|
| Axial Extent of Treatment/Axial Projected Chord | 0.706 | 0.706 | 0.706 |
| Cavity Depth/Cavity Width | 2.86 | 3.00 | 2.66 |
| Cavity Width/Land Width | 2.33 | 2.33 | 2.59 |
| Open Area/Total Area | 0.70 | 0.70 | 0.72 |
| Cavity Depth/Blade Spacing | 0.286 | 0.286 | 0.286 |
| Slot Angle (relative to rotor tip stagger angle) | N.A. | -43.4° | +10° |
| Slot Angle (relative to radial direction) | N.A. | 60° | 0° |

Table 3 Overall Performance and Stall Characteristic Comparisons Among the Casing Treatment Configurations

| | Baseline | Circumferential Grooves | Baffled Axial-Skewed Slots | Baffled Blade Angle Slots |
|---|---|---|---|---|
| Stalling Throttle Position (Counts) | 112.2 | 100.5 | 83.5 | 84.5 |
| % Change in Stalling Flow from Baseline | --- | -5.8 | -15.3 | -15.0 |
| % Change in Pressure Rise at Baseline Stall Throttle from Baseline | --- | +1.8 | +4.9 | +3.1 |
| % Change in Work Coefficient at Baseline Stall Throttle from Baseline | --- | 0 | +4.9 | +3.8 |
| Change in Peak Efficiency from Baseline | --- | 0 | -0.018 | -0.014 |
| % Change in Peak Pressure Rise from Baseline | --- | +3.7 | +7.8 | +5.7 |

angle slot configuration, and the baffled axial-skewed slot configuration showed progressively increasing work inputs.

Several variations in the circumferential groove treatment configurations were tested. Grooves over the entire center 73 percent of the blade axial projection contributed to the stalling flow improvement. Still more improvement could be achieved by inserting a few partitions to restrict the circumferential flow in the grooves. Removal of the mid-length baffles from the axial-skewed slots produced a small improvement in stalling flow with serious efficiency loss. A blade angle slot configuration with a cavity width substantially greater than the blade thickness gives more favorable performance than a cavity width which is less than the blade thickness.

Comparisons of the radial profiles of total and static pressure and of flow angle show that, except near stall, the various casing treatments have very little influence on the profiles. At the near-stall condition, however, the circumferential groove treatment shows a small tendency toward a higher total pressure than the baseline in the outer 30 percent of the annulus. Both slot configurations (the axial-skewed slots and the blade angle slots) show substantially higher total pressure than the baseline in this outer 30 percent of the annulus. This high total pressure represents a flow shift, such that total pressures in the hub region should be reduced.

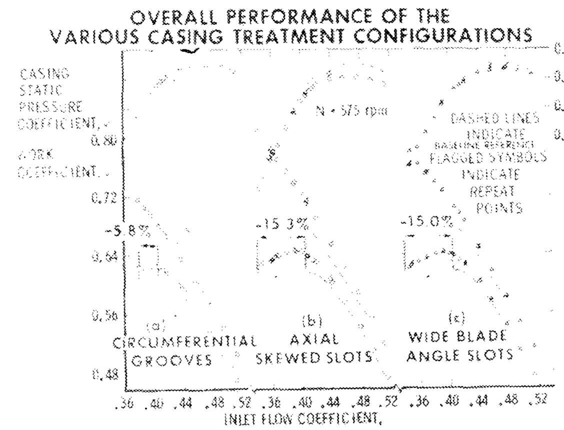


Fig. 3 Overall performance of the various casing treatment configurations. Dashed lines indicate baseline performance for comparison

Some reduction does appear in the hub region, but the mean dynamic pressure appears to increase, suggesting that the extra tip loading has come partly at the expense of increased rotor wake blockage.

<u>Flow Visualization By Knitting Yarn Tufts</u>

The Low Speed Research Compressor with its transparent casings over the rotor blading provided an opportunity to explore the flow patterns within the treatment cavities. If the flow patterns for each type of cavity are characteristic, these patterns may provide clues to the ways in which these cavities improve flow stability and stall margin. Tuft surveys were made within each type of cavity.

Two simple flow patterns in axial-skewed slot cavities seemed to be the most likely possibilities. The flow might be predominantly longitudinal, driven by the circumferential average pressure field of the compressor. Flow would enter the cavity at the downstream or high pressure end, progress counter to the freestream flow direction along the cavity bottom, and return to the free stream at the upstream or low pressure end. Or, the flow might be mostly circumferential, being scooped into the cavity by the tip of the partition between cavities and returned toward the free stream along the opposite wall, a sort of "roller-bearing" situation. The actual flow pattern was not simple. Time variations were on a scale too long to be related to blade passage, integral revolutions, or passage of rotating stall cells. Fig. 4 shows two typical photographs of the tuft behavior. Free stream flow is from top to bottom; rotor blade travel is from left to right. In the upper or upstream cavity the flow does seem to be in at the downstream end and out at the upstream end. In the lower cavity the flow near the bottom is from both ends toward the center. At mid-depth of this cavity some of the flow appears directed toward the end wall. Reference (8) gave a larger selection of photographs of these tufts, which made a regular pattern seem improbable.

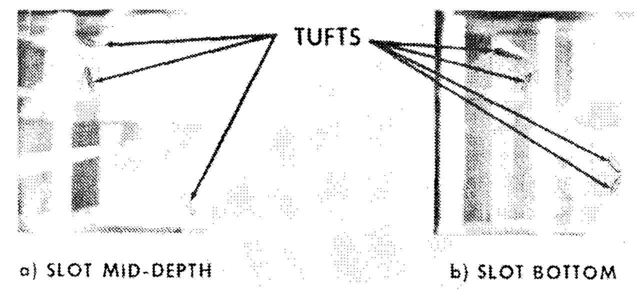


Fig. 4 Typical photographs of flow-visualization tufts in axial-skewed slots

The longitudinal flow pattern with flow in at the downstream end and out at the upstream end was also a pre-test favorite for the wide blade angle slots. Two representative photographs, with the tufts near the cavity face and near the cavity bottom, are shown in Fig. 5. Unfortunately it has not been possible to capture very much of the impression given by the tufts in a photograph. Live study of the tufts did show a predominant flow out of the upstream ends of both cavities (forward and aft of the baffle). Flow along the aft end of either cavity usually appeared in a direction counter to rotor rotation. Flow near the fore-and-aft center of the cavity was in almost all directions, forward, aft, or radial from the freestream into the cavity. The variations were clearly not related to blade passage. Observation of the tufts included a search for a regular pattern, such as would be expected in response to a rotating stall cell: no such pattern was identified.

Tuft observations of the flow in circumferential grooves showed a dominant flow along the grooves in the direction of rotation. There were suggestions of small transverse and radial components, but without a sufficiently clear definition to justify reporting.

Much of the appearance of random timing of flow directions in the wide blade angle slots was suppressed in the narrow version. The flow did appear to be generally from the freestream into the cavity over the downstream half and from

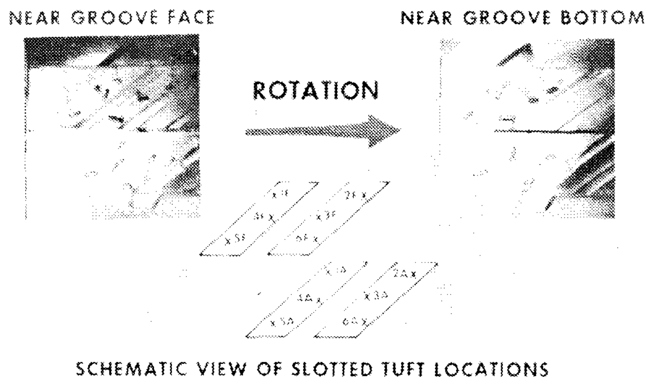


Fig. 5 Typical photographs of flow-visualization tufts in wide blade angle slots

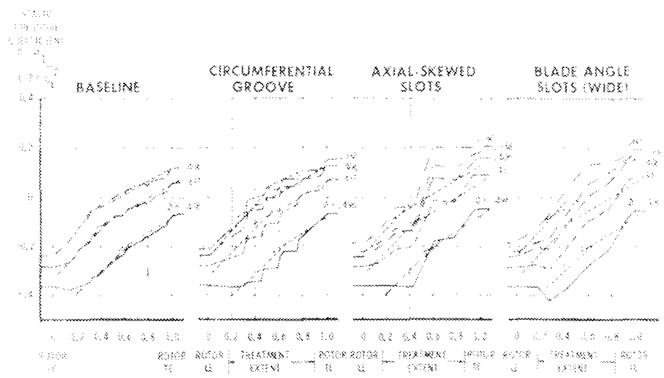


Fig. 6 Casing treatment influence on annulus wall static pressure distribution

the cavity to the mainstream at the upstream end. The pattern was clear enough to encourage an effort to measure a dynamic pressure of the velocity along the cavity. Neither orientation of a total pressure probe showed a pressure significantly different from the static pressure at the bottom of the cavity.

Annulus Wall Static Pressure Distribution

The time average static pressure distribution along the annulus wall over the rotor tips seemed to change when casing treatments were used. Fig. 6 summarizes the measurement of static pressure on or near the nominal casing radius. Data were taken upstream and downstream of all cavities. Data for the circumferential grooves were taken on the freestream surfaces of the lands between the grooves and on the side walls of the grooves near the groove faces. Data for the blade angle slots were taken on the freestream surfaces of the lands between the slots. Pressures were measured at various locations around the axial-skewed slots; those presented on Fig. 6 were taken on the portion of the slant wall of the cavity open to the freestream, close to the freestream surface.

Approximately half of the static pressure rise along the annulus wall of the baseline configuration at the critical near-stall condition occurs in the first one-third of the rotor axial projection. The distribution of this pressure rise at all flow levels is in the form of two nearly linear rises separated by a slope discontinuity, as if a wall-stall situation terminates the rapid leading edge rise and limits subsequent rise to a lower level. At the more open throttle settings a lightly loaded leading edge region contributes little to this pressure rise history. Idealization of the wall pressures as two constant slope regions provides a convenient reference for the treatment configurations. The first slope, in the steeper pressure gradient region, increases with increasing back pressure. The terminal slope decreases with increasing back pressure, as if increasing severity of the wall-stall damages the ability of the boundary layer farther downstream to sustain a gradient, but without completely preventing further pressure rise.

As has been discussed previously, the introduction of the circumferential groove casing treatment makes little difference to the overall pressure rise of the stage at any flow level. Rotor pressure rise in this treatment configuration is also close to the baseline observations. Most of the grooves show little transverse pressure difference. The pressure rise is concentrated in jumps across the thickness of the lands between grooves. Terminal pressure gradients at each flow level are similar to those demonstrated during the baseline test. In the steep pressure gradient region, however, the land surface pressure corresponds to the pressure at similar axial positions in the baseline case, while the average pressure over the groove faces is substantially below the baseline pressure at the groove centerline. It seems as if the surface pressure on the downstream groove wall, which is lower than the freestream pressure at the same axial position, calls for a boundary layer bleed flow into the cavity. Then the wall boundary layer may start fresh on each land. The circumferential groove configuration, tested at the stall limit flow level of the baseline configuration, shows a substantially lower initial gradient than the baseline, and a later transition point between gradients. Both gradients at the circumferential groove near-stall point are similar to the gradients of the baseline configuration at its near-

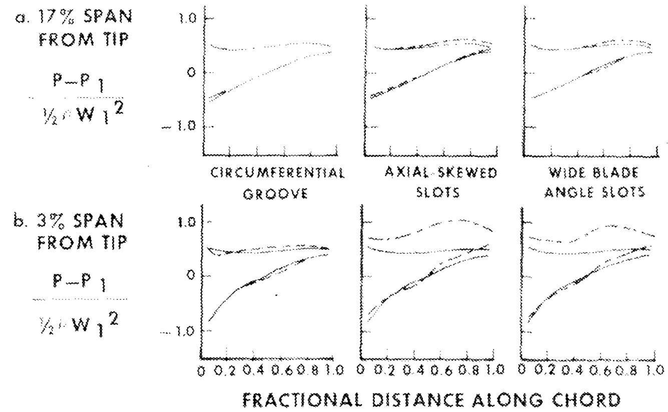


Fig. 7 Casing treatment influence on blade surface pressure distribution. Data at baseline stall throttle setting. Solid curves give baseline reference

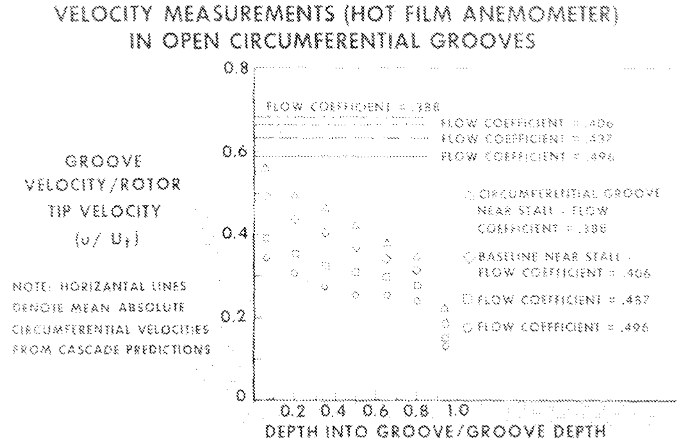


Fig. 8 Velocity measurements (hot film anemometer) in open circumferential grooves. Dashed lines denote mean absolute circumferential velocities from cascade predictions

stall point.

Overall pressure rise of the blade angle slot configuration at the baseline near-stall point was 2 percent of the reference dynamic pressure (based on tip speed) greater than the baseline configuration (Fig. 3). The rotor pressure rise was 3 percent greater at all comparable test points, open throttle as well as near stall. This apparently represents a slight loss in pressure recovery in the stator; the loss may be within the data resolution. The concept of a steep initial gradient and a discontinuous slope change to a terminal gradient seems applicable to this configuration. The terminal gradient, however, remains considerably steeper than the corresponding levels for baseline and circumferential groove configurations, until throttling pushes the flow below the baseline stall limit. Under open throttle conditions the extent of the lightly loaded leading edge region is substantially greater than for either the baseline or the circumferential groove configuration.

Data from the axial-skewed slots close to the freestream have been included on Fig. 6. The rotor pressure rise in the axial-skewed slot configuration is also higher than the baseline rotor pressure rise at the same flow level. The overall pressure rise increases a smaller amount. Static pressures in the downstream or aft cavity are higher than those at similar axial positions for the baseline case. Pressures deeper into the cavity are somewhat lower, and are comparable to the baseline values. The average over the cavity-freestream interface appears to be above the baseline level. Thus the cavity flow pattern may be "pumping up" the effective pressure near mid-rotor-chord to a level close to the rotor exit pressure, such that wall stall does not limit the pressure rise. In the upstream or forward cavity the data presented are higher than those farther down in the cavity for open throttle conditions. Near stall the situation reverses and the pressures deeper in the cavity are much higher than those close to the free stream. On the average, the forward cavities also appear to be pumping the interface pressures up to a high level. Reference (8) contains a more detailed presentation of these results.

All of the casing treatments appear to improve the ability of the trailing edge region to support adverse annulus wall pressure gradients. Wall pressure rises are delayed in the presence of treatment and the leading edge region is unloaded. There may be a correlation between the process of throttling until the unloaded leading edge region disappears and the leading edge pressure gradient reaches a limiting level, and the location of the stage stall point.

Blade Surface Pressures

Some effects of the casing treatments on the detailed aerodynamic performance of the rotor blading were also found in pressures measured on the blade surfaces. Provisions were made for measuring these surface pressures at 3, 8, and 17 percent span from the casing wall. Since the nominal clearance was set at 0.8 percent of the span, the 3 percent span surface pressures may be influenced by tip leakage flows. Two objectives in studying blade surface pressures were fundamental: to see whether casing treatments would affect the spanwise distribution of blade loading and to see whether the pressure distributions might reflect changes in boundary layer characteristics.

Representative surface pressure distributions are presented in Fig. 7. Only minimal spanwise variations were found with the solid and circumferential groove casings. These two configurations seemed to show nearly identical pressure distributions within the experimental resolution. Close to the tip, in the trailing edge region, the circumferential groove configuration exhibits slightly higher pressure difference across the blade, by virtue of a little more pressure surface diffusion. This observation is presumably related to the correspondingly increased annulus wall pressure gradient.

Both the axial-skewed slot configuration and the wide blade angle slot configuration showed conspicuously high pressure surface pressures close to the blade tip. Some of the local pressures are higher than the relative total pressure; therefore they are incompatible with conventional two-dimensional cascade aerodynamics. Subsequent investigation revealed no reason, such as damage to the measurement system, to discredit the high level of the pressure readings. The high pressures could be explained as the effect of flow coming out of the cavity with zero absolute swirl (blade angle slots) or swirl opposite to rotor rotation (axial-skewed slots). This type of flow could have a higher total pressure relative to the rotor than the free-stream flow which has acquired pre-swirl in passing through the inlet guide vanes. If the high pressure region on the pressure surface serves as a source of energizing fluid for the blade wakes, a subsequent upstream interaction may stabilize the suction surface boundary layer. Unfortunately the measurement of rotor blade wakes, carried out for the baseline and circumferential groove configurations, was not repeated for the slot configurations.

Cavity Velocity Measurements

Since the tuft observations gave only qualitative indications of the flows in the various cavities, efforts were made to measure the flow with both steady-state and transient instruments. The tuft observations provided guidance on what to look for. Consideration was also given to searching for flow patterns predicted by the analytical flow modeling, even when the tuft observations failed to show these patterns.

The velocity measurements for the circumferential grooves were the most successful. Hot film anemometers were used effectively to measure both time average velocities and transient fluctuations. Measurements of total pressure in the grooves and static pressures on the side walls and bottom of the groove implied similar time average velocities. The analytical modeling investigations had related the flow in the grooves to the mean absolute swirl velocity of the freestream flow outside of the grooves. This mean swirl velocity was predicted to rise from 40 percent of rotor tip velocity in the plane of the upstream groove to 60 percent of rotor tip velocity opposite the downstream groove. The mean velocities were expected to increase slightly with throttling. Fig. 8 shows a comparison of the velocities measured in the center groove with this prediction. The measured velocities are approximately two-thirds of the freestream prediction close to the groove face and vary linearly with depth into the groove, dropping to a level that is roughly half the freestream level at 80 percent depth. Beyond 80 percent depth a boundary layer profile may be found. A fully laminar analysis had predicted that effective penetration of the freestream velocity into the cavity should stop at a depth approximately two-thirds of the groove width. A fully turbulent analysis had predicted that the velocity level should remain above 90 percent of the free stream velocity for at least 85 percent of the groove depth. Neither the fully laminar nor the fully turbulent hypothesis predicts the experimental influence of groove depth on the effectiveness of treatments.

Some typical time variations of the groove velocities in the middle groove are shown on Fig. 9. Measurements were taken with a "diagonal X array" instrument, having two perpendicular sensing elements at 45 deg to the longitudinal axis of the groove. Outputs of the two elements were coupled electronically so that one signal would display the velocity component along the groove, and the second signal, the depthwise component. Two such instruments were used, one near the groove wall on the upstream side, the other near the downstream wall, expecting that the depthwise components would show the presence of helical flow. The oscillograms of Fig. 9 show traces for five different rotor revolutions, at arbitrary time intervals. The longitudinal components exhibit the general character of the predictions with constant total pressure in a frame moving with the rotor. The velocity increases steadily during the time period between blade passages and drops sharply as the blade goes by. The fluctuation amplitudes, however, are only about one-half the predictions. Measured depthwise velocity components are rather small. They seem too small to account for altered blade element characteristics. No evidence was seen at any throttle setting in the stable operating re-

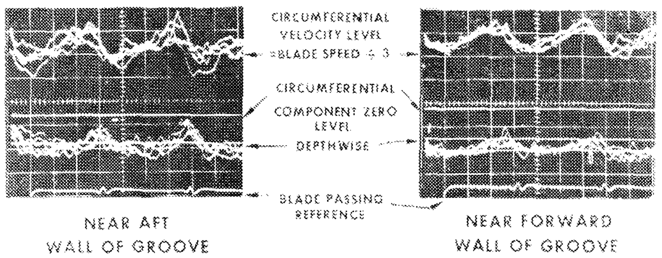


Fig. 9 Hot film anemometer measurements of two-dimensional flow in circumferential grooves at 6 percent depth into cavity from face

gion, of any systematic velocity fluctuations to indicate the passage of rotating stall cells. Time varying velocities measured in the groove nearest the leading edge were similar in character to those in the middle groove. In the groove nearest the trailing edge the velocities were somewhat erratic without evidence of response to the passage of blades. Both of these grooves appeared to be important to the compressor flow stability.

Hot film anemometers were also used to measure flow velocities in the axial-skewed slots. The instruments were chosen to search primarily for circulation in the longitudinal plane of the slot. Velocity fluctuations were conspicuously random and there was no evidence of correlation with either blade passing frequency or passage of rotating stall cells. Many velocities were measured in the range 40 to 50 percent of the rotor tip velocity, comparable to the absolute free stream velocity. Velocities in the neighborhood of 20 percent of rotor tip velocity were also measured a significant proportion of the time. Flow directions were as widely scattered as in the tuft observations.

Total pressure probes were inserted in the narrow blade angle slots, where tuft observations indicated a dominant longitudinal velocity, and the measurements were compared with the static pressure measured on the cavity bottom. Total pressure was close to static pressure for probe orientation in either direction.

## Measurement of Rotor Blade Wakes and Annulus Wall Boundary Layer Profiles

Under the hypothesis that casing treatments delay the onset of stall by energizing suction surface boundary layers and inhibiting separation, it seemed desirable to measure rotor blade wakes. "Perpendicular X-array" hot film anemometers with the sensing elements located in a

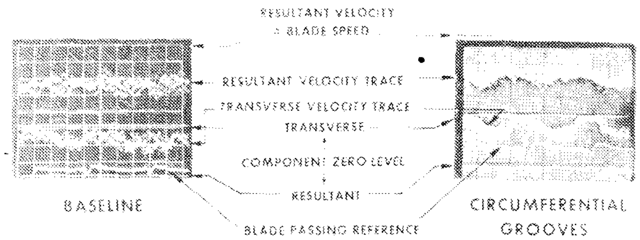


Fig. 10 Influence of casing treatment on rotor blade wakes

plane perpendicular to the radial stem of the traversing probe, provided a means for measuring rotor blade wakes and annulus wall boundary layers at the same time. Fig. 10 shows typical results of the attempt to measure blade wakes. With the sensing elements located at the same spanwise position as the tip blade surface pressure taps, the anemometer signal for the baseline configuration indicated a highly turbulent flow condition, masking the passage of the rotor blades. Some of the turbulence intensity seemed to be suppressed by the circumferential groove treatment, so that a velocity fluctuation at blade passing frequency appears clearly in the signal. More comparisons of anemometer output from the two configurations signals may be found in Reference (8). In some of these comparisons, the casing treatments appear to have destabilized the flow patterns.

Unfortunately, the turbulent nature of the anemometer output signals from the first two configurations was allowed to discourage the investigation. These measurements were not repeated for any of the slot configurations. After conclusion of the experimental program it became apparent that measurement of the wakes for these configurations would have been a valuable companion to the measurement of the high blade surface pressures.

The annulus wall boundary layers were measured with the same apparatus as the rotor blade wakes. The RMS anemometer outputs are displayed on a digital voltmeter and the probe is rotated for null output of the transverse component. The mean flow angle may then be read mechanically. Through the normal operating range of the stage, as demonstrated in the baseline configuration, little variation was found in the profiles. All profiles compare closely with a 1/7th power model using 7 percent span as the profile-free-stream match point. One exception to the generality of this profile was found. Close to the actual stall points of the slotted configurations the wall boundary layer at rotor exit was much thinner than in the normal operating range. Annulus wall boundary layers were also measured upstream of the rotor and found comparable to a 1/7th power model with 10 percent span as the match point to freestream.

## DISCUSSION

The effort to choose among two-dimensional cascade flow characteristics, meridional or annulus wall boundary layer characteristics, interaction of cavity flow with freestream flow, or compliant wall absorption of pressure disturbances as the most important feature of the casing treatment effect provides a convenient basis for discussion. Some aspects of the experimental results favor each of these features: some aspects do not seem to correlate with any one of these features. One may, of course, conclude that different features are critical to the success of the different types of treatment.

The quasi-two-dimensional cascade characteristic clearly can be modified by the presence of treatment. Fig. 3 shows that the stage pressure rise at given flow levels near baseline stall is increased. Under normal operating line conditions the pressure rises for all the configurations are identical. The blading behaves, therefore, as if increasing angles of attack normally lead to gradually increasing flow separation, such that the pressure rise component of blade force fails to rise as rapidly as the work input component. In the presence of casing treatments, especially the slot types, the separation is suppressed and the pressure rise component increases in proportion to the work input component, to a substantially higher angle of attack. The concept of separation inhibition also plausibly describes delay of a catastrophic flow breakdown, or stall, to higher angles of attack. Data in Reference (8) indicate 1.5 to 2 deg increase in stalling angle of attack for the circumferential groove configuration, 4 to 5 deg increase for the axial-skewed slot configuration. It was hoped that rotor blade wake measurements would confirm the change in two-dimensional separation characteristics. These measurements showed some evidence of change, but not in a form to encourage a definite conclusion.

Positive evidence of the role of annulus wall boundary layer characteristics may be found in the distribution of wall static pressures. Adverse wall static pressure gradients are larger in the trailing edge region with treated casings. The treatment configurations do not, however, seem to produce significant changes in the wall boundary layer profiles.

The test results from the circumferential groove configuration suggest that interactions between cavity flows and freestream flows are not very important. Inserting partitions which inhibit circumferential flow made the treatment system slightly more effective at delaying the onset of stall but required noticeably more work input to produce the same flow and pressure rise than the open groove configuration. The trailing edge grooves showed no evidence of flow exchange with the freestream. Averaging the peak transverse velocities measured near the groove faces on the forward and aft sides of the groove (Fig. 9) showed the maximum velocity in or out of the groove is about 5 percent of blade speed, or 10 to 12 percent of the mean circumferential flow velocity. Since the effort to correlate stall margin improvements with flows in and out of the circumferential grooves was not successful, the chief alternative hypothesis, concerning compliant interface absorption of pressure disturbances, seems to hold a favored position. The observations about the effect of partitions on efficiency suggest that the fluid in the grooves may act like a moving belt, reducing effective tip clearance.

Substantial velocities (up to 40 percent of blade speed) were measured in the axial-skewed slots. These influence freestream flow patterns, at least with respect to blade surface pressures. The cavity velocities were erratic in magnitude and direction and do not encourage use of a steady-state flow model to describe the treatment influence. There was no evidence of correlation between the cavity velocities and any rotating stall patterns.

The high blade surface pressures also appeared in the blade angle slot configuration. However, since the tuft observations showed highly erratic flow directions in the cavities, no attempt was made to measure their magnitude.

The evidence of this investigation confirmed previous deductions that downstream-upstream recirculation has an important bearing on the stage efficiency. In this respect, testing with an increased number of cavity baffles, and with shallower slots, would have improved understanding of the contribution of the recirculation to flow stability as well as energy dissipation. While observers have found that shallow circumferential grooves are inferior to grooves with substantial depth, there have been no similar investigations published comparing efficacies of either axial-skewed or blade angle slots having depths comparable to the width, rather than three times depth or greater as in this investigation and that of Reference (2). Additional useful data on all the configurations might be obtained by running comparative tests at different inlet guide vane flow deflections so as to alter the mean absolute freestream swirl levels driving the cavity flows.

## CONCLUDING REMARKS

The most significant results of this investigation may be summed up in a few concluding remarks:

1 The beneficial effects of casing treatments as stall inhibitors are not dependent on high Mach numbers or cavity resonances.

2 Casing treatments often increase rotor and stage pressure rises near stall as if incipient separations are being suppressed.

3 Casing treatments increase annulus wall pressure gradients in the trailing edge region, as if wall stall effects are being suppressed.

4 Velocity components in circumferential grooves are primarily longitudinal, at a level close to the mean circumferential velocity in the freestream. These velocities may contribute to an effective moving wall and a reduced effective clearance. Velocity components into and out of the grooves seem insufficient to interact with the freestream flow.

5 Pressure surface pressures on the rotor blades close to the tips are substantially higher in the presence of axial-skewed slot or blade angle slot treatments than in the baseline configuration, and may be higher than the freestream relative total pressure. This situation may explain the improved flow stability.

6 Velocity components in axial-skewed and blade angle slots are highly random, and do not seem to correlate with systematic effects such as the blade surface pressures and the operating range extensions.

7 Further investigations are needed to refine understanding of casing treatment behavior. For example, the influences of reducing the depth of slot-type cavities, and of adding more baffles, do deserve investigation.

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