69-GT-103

an ASME publication

$1.50 per copy – $.75 to ASME Members

SOME MEASUREMENT PROBLEMS ENCOUNTERED WHEN DETERMINING THE PERFORMANCE OF CERTAIN TURBINE STATOR BLADES FROM TOTAL PRESSURE SURVEYS

by Thomas P. Moffitt, Herman W. Prust, Jr., and Harold J. Schum

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

ABSTRACT

This paper presents some of the problems encountered in determining turbine stator blade performance from total pressure surveys downstream of the blade row. The stator blades were suitable for turbine cooling and incorprated thick trailing edges having a large included wedge angle between the suction and pressure surfaces. Blade performance was rated in terms of kinetic energy loss coefficients, which relate the frictional and mixing losses to the ideal kinetic energy that could be developed at a given overall pressure ratio. The loss coefficients were calculated from the results of total pressure surveys and flow conditions as determined by measurements at the inlet and outlet of the blade row. For the type of blading involved, it was determined that these loss coefficients were sensitive to the size of support stem of the total pressure probe used and the size and axial location of the probe sensing element. The effect of these variables on the results obtained are presented and desirable manners of taking survey data for this type of blading are discussed.

Contributed by the Gas Turbine Division of The American Society of Mechanical Engineers for presentation at the International Gas Turbine Conference & Products Show, Cleveland, Ohio – March 10-13, 1969.

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS, UNITED ENGINEERING CENTER, 345 EAST 47th STREET, NEW YORK, N.Y. 10017

SOME MEASUREMENT PROBLEMS ENCOUNTERED WHEN DETERMINING THE PERFORMANCE OF CERTAIN TURBINE STATOR BLADES FROM TOTAL PRESSURE SURVEYS

INTRODUCTION

The NASA has recently conducted an experimental investigation to determine the detailed losses of turbine stator rows having blade features suited for cooling (ref. 1 to 3). These features were thick sections, blunt leading and trailing edges, and relatively large angle differences between the suction and pressure surfaces at the exit of the blading. The measurement problems encountered and the solutions found in obtaining accurate pressure loss and other data for establishing the detailed losses of these stators are presented in this paper. These matters are considered of interest since considerable effort is continuously being spent on similar investigations both at the NASA and elsewhere.

The findings presented in this paper are from an investigation of three different stators. These stators had the same shape of blading but different blade angle settings. These blade angle settings corresponded to design stator area setting and 70 and 130 percent of design area setting.

It was found that both the shape of the blading and the geometry of the first total pressure probe used in the investigation caused large flow variations at the exit measuring station. As a result accurate values of total pressure loss and representative values of exit static pressure conditions on which to base the loss quantities were difficult to determine. This being so, means were examined in the course of the investigation to both reduce the flow variations caused by the total pressure probe and to circumvent the flow variations caused by the blade geometry.

In this paper, the apparatus, instrumentation, and test procedure pertinent to the investigation are briefly described. Examples of the variations in exit flow conditions resulting from the blade shape are presented. It is shown that, for this shape of blading, loss values can be affected by the size and location of the sensing element of the total pressure survey probe. In addition, variations in exit static pressure conditions resulting from the use of two different design total pressure survey probes are shown, and the effect of these variations on loss quantities is considered. Finally, advantages of the different type probes and different locations for loss measurement are considered.

The loss quantities reported herein are in terms of kinetic energy loss coefficients. These coefficients express the loss in kinetic energy as a decimal part of the ideal kinetic energy of the actual flow at the pressure ratio being considered. The calculation methods used for computing these coefficients from experimental data are summarized in the appendices of reference 1.

APPARATUS, INSTRUMENTATION, AND TEST PROCEDURE

The apparatus used for the investigations consisted of a test section, a test stator, and the necessary pipes and valves to control the air flow. A schematic drawing of the test rig and a cross section of the stator blading and flow passages of the stator at one of the angle settings investigated is shown in figure 1. Some dimensions of the stator and blading significant to the investigation are:

Tip diameter, in.	30
Hub diameter, in.	22
Mean radius pitch (see fig. 1), in.	1.63
Mean radius chord (see fig. 1), in.	2.26
Wedge angle, approx. (see fig. 1), deg	16
Trailing edge radius, in.	0.035

Also shown on figure 1 is the axial and circumferential location of the instrumentation required for determining the stator performance. Inlet total pressure was measured at station 0 using Kiel type pressure probes; static pressure measurements were made with conventional 20 mil taps; and angle measurements were made with two-tube angle-seeking probes of the type shown in the photograph of figure 2. The inlet measuring station (station 0) shown in figure 1 was located one blade chord upstream of the blade leading edge; the wall static pressure taps at blade exit (station 2) were located about 0.10 in. downstream of the blade trailing edge, and the downstream setpoint station (station d) was located about 2-1/2 blade chords downstream of the blade trailing edge. All pressure measurements were made with calibrated transducers.

Two different design total pressure probe assemblies, termed the orininal and modified designs, were used for total pressure loss survey measurements downstream of the blade row. A photograph of the original survey equipment is shown in figure 3, and a photograph of an original design probe installed in the test section is shown in figure 4. The actuator of figure 3 provided for radial movement of the probe, and the motor driven outer saddle assembly provided for circumferential motion. As indicated in figure 3, the probe was supported by a stem held in the outer wall saddle assembly. The location of this stem, which was nominally 1-1/4 in. from the blade in the direction of flow, was arbitrarily chosen as a compromise location in consideration of probe stem blockage effects and what was considered a reasonable length from a mechanical viewpoint between the probe stem and probe sensing element end. At the support point the stem was 0.25 in. in diameter as determined by strength considerations. From the support point to its end, the stem was tapered radially to about 1/16 in. in an effort to lessen flow blockage by reducing the area perpendicular to the flow.

The probe is shown to have two tubes for sensing elements. These were required in order to obtain measurements at the inner and outer walls without wall interference. For this probe the sensing element tubing was of 0.012 in. outside diameter and 0.006 in. inside diameter.

In figure 5, a photograph is shown of a modified design survey probe installed in the test section. The principal differences between this probe assembly and the original probe assembly were a smaller diameter probe support stem, a larger diameter probe sensing element, and an inner wall support (not shown) which was required to strengthen the smaller diameter support stem. The support stem for this probe design was of constant 0.100 in. outside diameter tubing, and the sensing elements were of 0.020 in. outside diameter and 0.015 in. inside diameter tubing. The actuator, outer wall saddle assembly, and outer wall probe stem support was the same for this probe as for the original probe. The inner wall probe stem support for this design was provided by an inner wall saddle assembly. The inner wall saddle assembly was supported and driven by a 1/2 in. diameter pin which was connected to the outer wall saddle assembly. This pin was located as far from the survey area as the dimensions of the saddle would permit in an effort to avoid flow disturbances in the survey area resulting from blockage of the pin.

All total pressure probes were calibrated before and after testing. The calibration corrections of the probes were essentially zero at flow angles up to about 10^{0} from the axis of the sensing element.

Particular set points were selected for the tests to cover the desired range of stator outlet critical velocity ratios from about 0.5 to 0.9. During testing, these set points were established by maintaining a fixed pressure ratio between the inlet total pressure at station 0 and the downstream hub static pressure at station d. At each setpoint, circumferential surveys of total pressure loss were conducted at a sufficient number of radii to adequately cover a complete annular sector. The number of circumferential surveys required to cover a sector was about 30 with the majority being made near the end walls where the radial gradient of total pressure loss was large. When conducting these surveys, the total pressure probe was fixed at an average fluid flow angle as determined by measurements with an angle probe of the type previously shown.

SURVEY PROBE STUDY RESULTS AS RELATED TO PRESSURE LOSS MEASUREMENTS

Initial Evidence of Measurement Discrepancies

Early in the investigation, evidence was found that the losses determined from measurements at different axial stations with the original type total pressure probe were not in agreement. The evidence consisted of the following. The probe was located at the mean radius of the passage and in a plane about 0.01 in. axially from the blade trailing edge. It was found that the total pressure loss measurements obtained when the probe angle was varied only a degree or so from the average flow angle of the fluid resulted in significantly different mean-section after-mix loss coefficients. An example of the different pressure loss traces obtained with different probe angles is shown in figure 6. And the different mean-section after-mix loss coefficients resulting from using loss data of the traces is shown in figure 7. In figure 7, the differences in loss coefficients for a setting of 27.5 degrees is shown to be about one third greater than the loss for a setting of 26 degrees. Decreasing loss is shown to occur with decreasing probe angle, the decrease in probe angle corresponding to an increased distance of about 0.03 in. between the blade trailing edge and sensing element end. The measured loss, which was expected to be very nearly constant for this change in measurement location, therefore, significantly decreased as the location of the measuring station was in effect moved downstream from the trailing edge.

Possible Reasons for Measurement Discrepancy and Means Considered for Avoiding Discrepancy

Causes for the differences in loss values determined from pressure loss measurements at different axial stations were considered and several explanations appeared reasonable. The discrepancy could have resulted from: (1) the radial movement of low energy fluids with axial position, (2) the presence of large static pressure gradients at blade exit or, (3) the presence of variations in fluid flow angles in the wake region which were larger than the permissible off-angle tolerance of the total pressure probe. Considering the large wedge angle and thick trailing edge of the blading, the latter explanation appeared most probable, so further attention was directed to determining the variations in fluid flow angles.

In an effort to determine fluid flow angles in the wake region at the blade trailing edge, circumferential surveys of flow angles were conducted at an average distance of about 1/8 in. downstream of the trailing edge. An example of the measured circumferential variation in flow angle at the blade mean section is presented in figure 8. The flow angle variation shown of about $\pm 7^{0}$ from average, while large, is still within the angle tolerance of about $\pm 10^{0}$ required to obtain accurate total pressure loss measurements with the fixed angle total pressure probes used. However, flow angle variations, larger than those measured, very probably occurred nearer the blade trailing edge. In addition, it was believed that angle variations larger than measured might have been present even at the location of measurement since the width of the sensing end of the angle measuring probe, which was 0.060 in., was somewhat large relative to the trailing edge thickness of 0.070 in.

It may seem that the pressure measurement problem caused by flow angle variations at the blade trailing edge could easily have been avoided by conducting surveys farther downstream, say 1/2 in., from the trailing edge. However, in addition to the overall loss, it was desired to determine the separate loss characteristics of the suction and pressure surfaces of the blading and of the end walls. If pressure loss measurements are made downstream, the wake patterns from the trailing edge which define the separate losses, are either altered or destroyed by mixing and radial and circumferential secondary flows as indicated in figure 6.

If loss was to be measured at the blade trailing edge where large angle gradients are present, it was felt that a total pressure probe having larger diameter sensing elements than the original probe might give better results. The reason for this belief is indicated in the scale drawing of figure 9. The figure represents the ends of two different probes having sensing elements of 0.010 and 0.020 in. outside diameter in the type of flow pattern believed present around the trailing edge of this blading. The probe ends are shown with axes located in the same circumferential position and with the same axial clearance relative to the blade trailing edge. In this position the center of the sensing element of the probe having the larger diameter is seen to be located farther downstream (dimension "a") where the angle differences between the probe and flow are reduced. In addition, as reported in reference 4, when a total pressure probe is used in a flow regime having total pressure gradients, the probe weights the larger pressures too heavily. This effect is presented in the inset of figure 9. As a result, as indicated by the inset, the average total pressure in a linear gradient is measured when the center of the sensing element is displaced about 1/3 the diameter of the sensing element in the direction of lower pressure away from the location of the average total pressure. As shown by a comparison of dimension "b" on figure 9 for the two probes, this probe characteristic results in the measuring center of the probe having larger diameter sensing element being moved farther downstream than the measuring center of the probe having smaller diameter sensing element. For these reasons, the outside diameter of the sensing element of the modified probe was increased from the 0.012 in. tubing used for the original probe to 0.020 in. tubing.

Comparison of Losses Obtained from Data Measured Near Trailing Edge with Two Survey Probes Having Different Diameter Sensing Elements

In order that a comparison could be made between results obtained with the original and modified design probes, probes of both designs were used in the second phase of the investigation in which the stator loss was determined at 130 percent of design area setting. For this testing, the ends of the sensing elements of both probes were located in a plane roughly 0.01 in. axially downstream of the blade trailing edge. However, since the test deflection of the two probe designs was probably different, it was not known whether the axial location of the sensing elements of the two probes was the same when testing. Since the loss obtained with the two probes at a given radius but different axial locations might be different because of radial movement of loss fluids, the compared results are based on full annular surveys, which are not effected by radial movement of the fluid.

Figure 10 presents a comparison of the annular sector after-mix kinetic energy loss coefficients computed from data measured with the two probes. Values of these coefficients represent the total loss of the stator and include blade surface loss, end wall loss, trailing edge loss, and loss due to complete mixing of the free stream and loss fluids. As expected, in the flow field near the trailing edge where large angle gradients are present, the pressure recovery of the modified probe was indicated to be better than the original. Consequently, the loss obtained using the modified probe with larger diameter sensing element was lower than that obtained using the original probe.

Confirmation That Loss Values Measured Near The Trailing Edge With The Modified Probe Were Actual Loss Values of The Stator

It remained to be determined, if overall results obtained with the modified probe close to the trailing edge would be consistent with overall results obtained from loss measurements downstream of the blading where the flow angle variations were small. It is assumed that the loss measurements obtained at downstream stations represented the actual loss of the stator. Such a study was made during the last phase of the investigation which involved the stator set at 70 percent of design stator setting. At different setpoints corresponding to different stator velocity levels, annular surveys of total pressure loss were conducted at different downstream measuring stations using either an original or a modified design total pressure probe. All surveys were conducted with the total pressure probe alined at the same experimentally predetermined average flow angle.

The results of this study are shown in figure 11. The loss coefficients obtained with the modified probe show good agreement for all distances from the trailing edge where data were taken, and the loss coefficient obtained with the original probe agreed well with the modified probe when pressure loss was measured away from the blade trailing edge. However, when the original probe was used to measure loss near the trailing edge, the obtained loss coefficient was again larger as it was for the second stator angle setting investigated.

The larger losses that have been shown, obtained when using the original type probe very near the trailing edge, are in the upper range of the stator flow velocities investigated. To determine if similar error resulted at lower velocity levels, tests were made with both type probes over a range of velocity levels. Figure 12 shows the results of these tests. As shown by the figure, the larger loss obtained using the original type probe close to the trailing edge also occurred at lower velocity levels, so the error was apparently independent of velocity level for the range of velocities investigated.

From these results it was concluded that for this type blading, (1) the losses obtained using a probe with too small a diameter sensing element and with the end of the sensing element too close to the blading are higher than actual (2) consistent losses can be measured using probes with different diameter sensing elements if measurements are made away from the trailing edge and (3) the losses obtained using the probe with a larger diameter sensing element close to the blading were the actual loss of the blading since they were consistent with the losses obtained from downstream measurements.

Although for this investigation, actual loss values were apparently obtained when using a probe with larger diameter sensing element very close to the blading, it is considered unlikely that a general relationship can be found between the blade geometry and the size and location of probe sensing element required for accurate measurements near the trailing edge. Loss values based on such measurements are believed highly subject to error, and it is suggested that such values be confirmed by other values based on downstream measurements.

Indirect Confirmation of Blade Row Losses from Other Measurements

In addition to overall blade row losses, the portion of blade row loss resulting from blade surface friction was also separately determined during the stator performance investigation. Besides providing additional information concerning the performance of the blading, these losses were also used as described in the following to further confirm the previous conclusions of this report.

The pressure loss data for calculating the blade surface friction loss was based on mean-section survey measurements just upstream of the blade trailing edge (see station 2a, fig. 1). At this station, measurement problems associated with flow angle gradients are avoided since the flow is attached and therefore follows the angle of the blade surfaces. Values of blade surface friction loss are of obvious interest in that they indicate the quality of the channel design. In addition, these experimental values of blade surface friction loss may be added to theoretical values of trailing edge loss to obtain predicted values of blade surface friction loss plus trailing edge loss. The predicted values of surface friction plus trailing edge loss can then be compared with corresponding experimental loss values based on pressure loss measurements just downstream of the trailing edge to obtain further check on the accuracy of the previously obtained results. In figure 13 values of blade surface friction loss are shown for the stator at two of the stator area settings investigated along with a comparison of predicted and experimental values of blade surface friction loss plus trailing edge loss. Excellent agreement is shown between the upper two curves of the figure which represent the predicted and experimental values of blade surface friction plus trailing edge loss. From these results, indirect confirmation was obtained that the experimental results based on downstream measurements were correct. These results also indicate that the quality of blade channel design can be determined by pressure loss measurements at a location inside the channel just before the trailing edge loss occurs.

SURVEY PROBE STUDY RESULTS AS RELATED TO EXIT STATIC PRESSURE DETERMINATION

At the start of the investigation it was not anticipated that the static pressures at blade exit (station 2) would be significantly influenced by survey probe obstruction, so only one of the inner and outer wall taps shown in figure 1 were provided in the survey area during the initial phase of investigation. These taps were located in the center of the right hand passage adjacent to the right hand blade in the survey area (see tap "C" fig. 1). (The other taps shown on fig. 1 in the survey area were added after the initial phase of investigation.) It was found that the original probe did seriously obstruct the flow since pressures at these locations were greatly affected by both the radial and circumferential position of the probe when steady state flow conditions were maintained at the inlet and downstream stations. An example of the influence of probe position on these wall tap static pressures for the stator with design area setting is shown in figure 14. Variations in pressure with circumferential location of the probe are shown for three different probe immersions, the largest variation occurring, of course, with the greatest immersion. In figure 15, an example is shown for all probe immersions of the variations in average values of the inner wall pressures and average values of the outer wall pressures occurring in the channel when the probe was in the wake region. In addition, these figures compare the pressures occurring with and without probe obstruction.

Since the stator losses determined for the investigation are dependent upon the static pressure conditions existing in the channel when the loss occurs, correct values of loss can be determined only if the actual static pressure conditions occurring in the passage at the time of measuring total pressure loss in the same channel are known. In figure 15, the average static pressures in the passage at the time of measuring loss are represented by the pressures with obstructed flow. Using static pressure data similar to that of figure 15, loss coefficients based on obstructed and unobstructed flows were computed for the first of the three stators investigated. The results are shown and compared on figure 16. (These annular sector results are based on linear radial distribution of exit static pressures and the assumption that flow conditions at the blade mean section were representative of the average flow conditions in the channel). These results show that up to a velocity ratio level of about 0.8, only small differences in loss coefficients would have resulted had the influence of the probe on flow conditions not been considered. However, at higher velocities, the difference in loss coefficients are large enough to cause concern, and the loss coefficients are considered unreliable.

The large blockage of the original probe, which varied with probe immersion, was of course highly undesirable since it made the selection of representative blade exit static pressures on which to base the stator loss difficult, if not impossible, to determine. Therefore, as previously described and as indicated in figures 4 and 5, this probe was designed to have less blockage than the original probe when the original probe was fully immersed and to have uniform blockage with immersion whereas the original probe had variable blockage with immersion. In figure 17, the measured effect of probe location on the mid channel blade-exit wall tap pressures of the surveyed passage are compared for the original and modified probes. The results shown are for the stator with 130 percent of design area setting and were obtained after installation of all the wall tap static pressure taps shown at station 2 in figure 1. These results show that the modified probe obstructed the flow as much as the original probe. However, for the original probe, the static pressures occurring in the passage when loss was being measured are shown to vary with both radial and circumferential probe position, whereas, for the modified probe the static pressures occurring when loss was being measured were little effected by the position of the probe. From these results it was concluded that the modified probe was better than the original since its use resulted in much more uniform exit static pressure conditions in the channel in which loss was being measured.

CONCLUDING REMARKS

This paper has presented some of the measurement problems encountered and the solutions found when determining the loss of certain stator blading from total pressure surveys and blade exit data. The characterizing features of the blading investigated were thick cross sections, blunt leading and trailing edges, and large angle differences between the suction and pressure surfaces of the blading at the trailing edge. The findings included the following:

1. Blading having this shape causes large flow angle gradients at blade exit near the trailing edge. As a consequence, local flow angles relative to a fixed angle total pressure probe, with sensing element close to the blading, may be larger than permissible for obtaining accurate measurements.
2. For the blading investigated, the use of two total pressure probes having different diameter sensing elements showed that the probe having smaller diameter sensing element quite close to the blading resulted in loss values that were higher than actual whereas the probe with larger diameter sensing element close to the blading resulted in actual loss values. The better results obtained with the probe having larger diameter sensing element, when used at about the same small axial clearance as the probe with smaller diameter sensing element, is apparently due to the measuring center of the probe with larger diameter sensing element being farther downstream of the blading.
3. When total pressure loss was measured downstream of the blading away from the flow angle gradients at the trailing edge, the validity of loss values were not affected by the diameter of the probe sensing element.
4. The two total pressure probes of different design used in the investigation both significantly affected the flow conditions at the stator exit. The findings show that these effects on flow conditions result in loss values that are, in some instances, substantially different than the loss values obtained if these flow effects are neglected. Of the two probe designs used, the one having constant diameter support stem was found preferable to the other having a tapered support stem since its use resulted in more uniform flow conditions.

While actual loss values were apparently obtained in this investigation using measurements quite close to the blade trailing edge, it is felt that loss values for this shape blading based on such measurements are suspect and should be confirmed by values based on more reliable downstream measurements.

NOMENCLATURE

$\overline{e}$	kinetic energy loss coefficient
p	pressure
V	absolute gas velocity
Subscripts:	
cr	conditions at Mach 1
d	station downstream used for setpoint
h	blade hub section

i	ideal coditions corresponding to isentropic process
m	blade mean section
o	inlet measuring station upstream of blading
t	blade tip section
2	measuring station at exit of blading
2a	measuring station just upstream of blade trailing edge
3	theoretical station after complete mixing occurs
3d	three dimensional or annular sector

Superscript.

(')	total state

REFERENCES

1. H. W. Prust, Jr., H. J. Schum, and F. P. Behning, "Cold-Air Investigation of a Turbine for High-Temperature Engine Application. II. Detailed Analytical and Experimental Investigation of Stator Performance," NASA TN D-4418, 1968.
2. T. P. Moffitt, H. W. Prust, Jr., and B. Bider, "Effect of a Variable Stator Area on Performance of a Single-Stage Turbine Suitable for Air-Cooling. II. Stator Detailed Losses With 130 Percent Design Area," NASA TM X-1635, 1968.
3. H. W. Prust, Jr., T. P. Moffitt, and B. Bider, "Effect of Variable Stator Area on Performance of a Single-Stage Turbine Suitable for Air Cooling. V. Stator Detailed Losses with 70-Percent Design Area," NASA TM X-1696, 1968.
4. C. C. Gettelman and L. N. Krause, "Considerations Entering into the Selection of Probes for Pressure Measurement in Jet Engines," ISA Proceedings, vol. 7, 1952, p. 134.

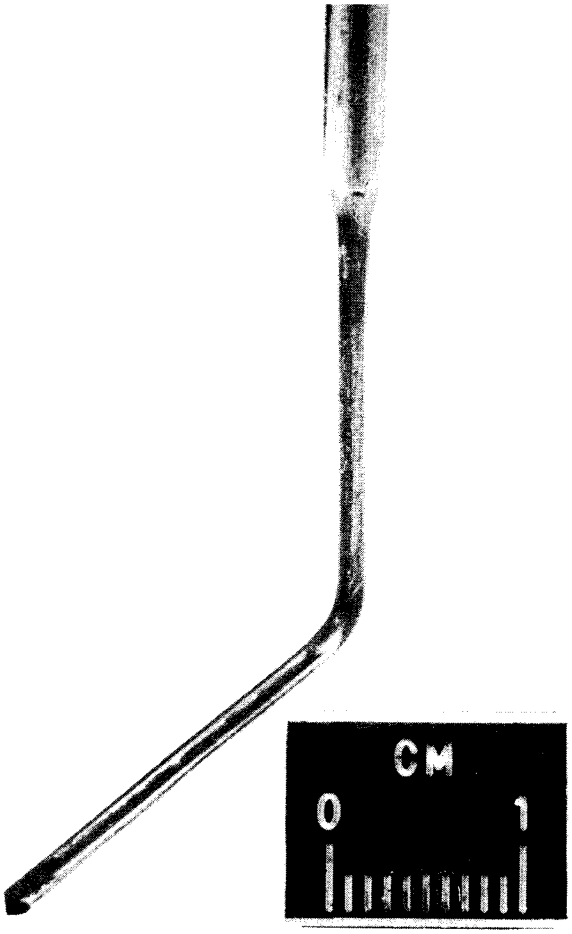


FIGURE 2. - PHOTOGRAPH OF ANGLE SEEKING PROBE.

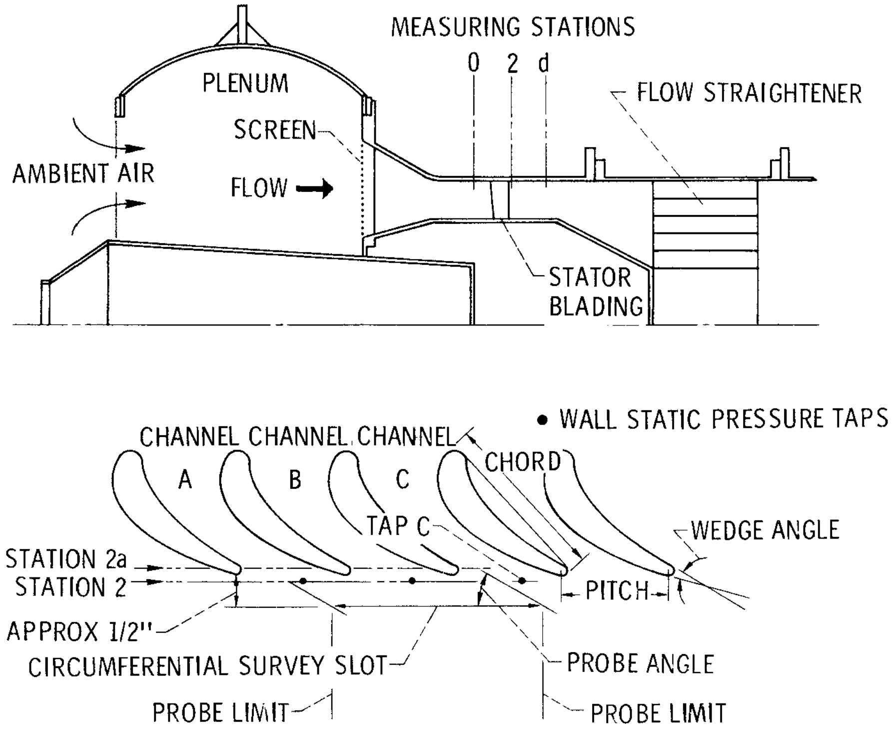


FIGURE 1. - SCHEMATIC OF TEST RIG CROSS SECTION AND FLOW PATH OF BLADING, AND LOCATION OF INSTRUMENTATION.

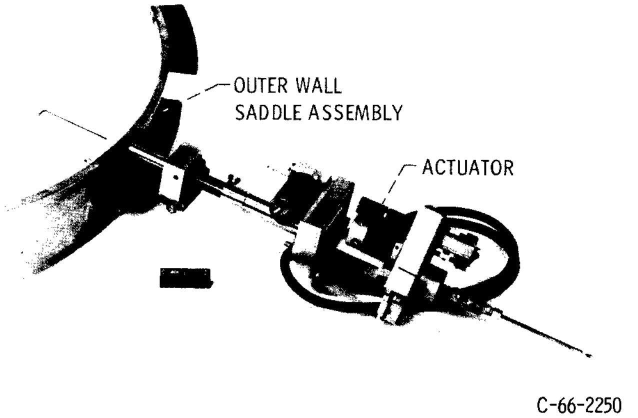


FIGURE 3. - PHOTOGRAPH OF ORIGINAL DESIGN TOTAL PRESSURE SURVEY EQUIPMENT.

FIGURE 4. - PHOTOGRAPH OF AN ORIGINAL DESIGN PROBE INSTALLED IN TEST FACILITY.

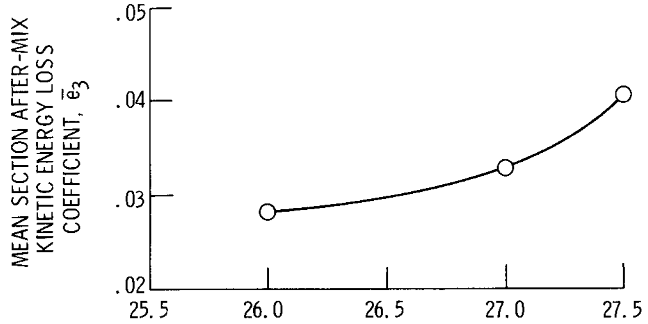


FIGURE 7. - MEAN-SECTION LOSS COEFFICIENTS OBTAINED FROM TRACES AT DIFFERENT PROBE ANGLE SETTINGS.

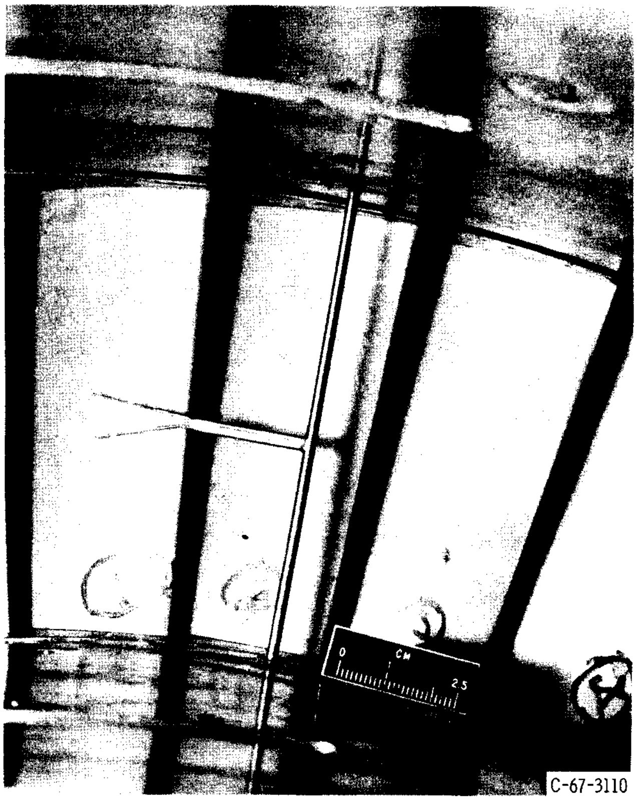


FIGURE 5. - PHOTOGRAPH OF A MODIFIED DESIGN PROBE INSTALLED IN TEST FACILITY.

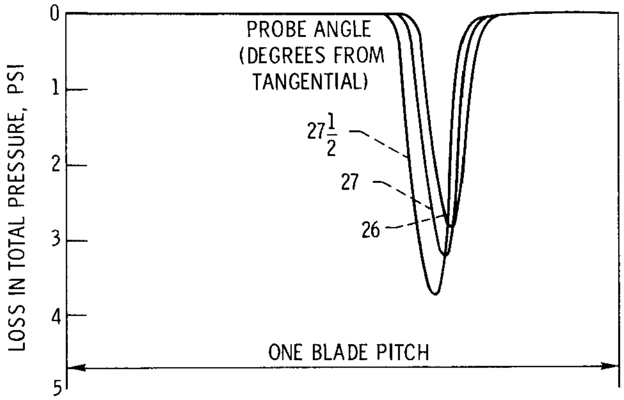


FIGURE 6. - EXAMPLE OF DIFFERENT PRESSURE LOSS TRACES OBTAINED USING ORIGINAL DESIGN PROBE AT DIFFERENT ANGLE SETTINGS. $(V/V_{cr})_{i,m,3} = 0.825$.

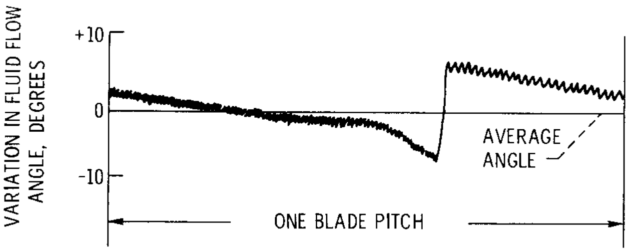


FIGURE 8. - EXAMPLE OF MEASURED CIRCUMFERENTIAL VARIATION IN FLUID FLOW ANGLE NEAR BLADE TRAILING EDGE AT MEAN SECTION.

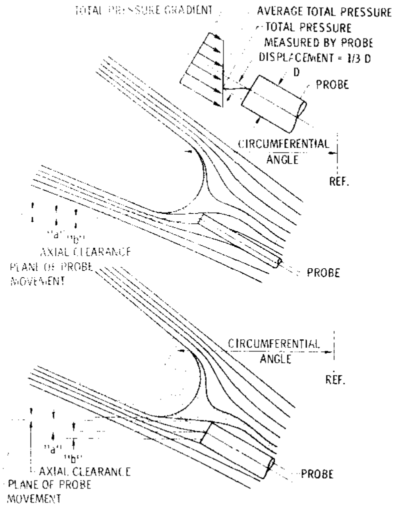


FIGURE 9. - COMPARISON OF ORIENTATION OF TWO PROBES OF DIFFERENT DIAMETER IN AN ASSUMED DOWNSTREAM FLOW PATTERN.

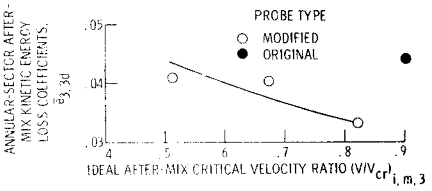


FIGURE 10. - COMPARISON OF LOSS COEFFICIENTS COMPUTED FROM DATA MEASURED NEAR BLADE TRAILING EDGE WITH DIFFERENT TYPE PROBES. DATA SHOWN IS FOR STATOR WITH 130 PERCENT OF DESIGN AREA SETTING.

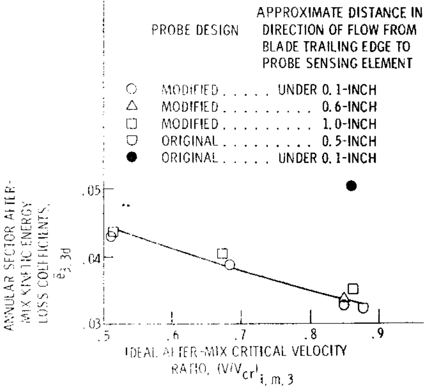


FIGURE 11. - COMPARISON OF LOSS COEFFICIENTS OBTAINED FROM MEASUREMENTS WITH DIFFERENT DESIGN TOTAL PRESSURE PROBES AT DIFFERENT DOWNSTREAM STATIONS. DATA SHOWN IS FOR STATOR WITH 70 PERCENT OF DESIGN AREA SETTING.

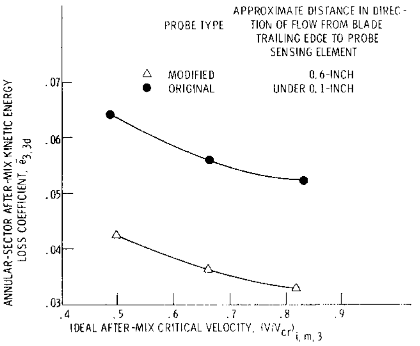


FIGURE 12. - COMPARISON OF LOSS COEFFICIENT AT DIFFERENT VELOCITY LEVELS OBTAINED USING DIFFERENT DESIGN PROBES AT DIFFERENT DOWNSTREAM STATIONS. DATA SHOWN IS FOR STATOR WITH DESIGN AREA SETTING.

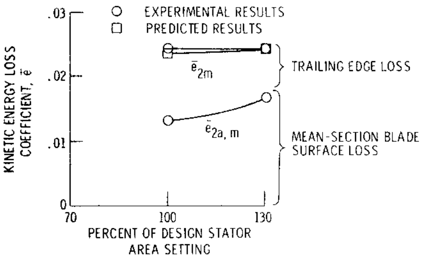


FIGURE 13. - EXPERIMENTAL VALUES OF BLADE SURFACE FRICTION LOSS AND COMPARISON OF EXPERIMENTAL AND PREDICTED BLADE SURFACE FRICTION PLUS TRAILING EDGE LOSS AT $(V/V_{cr})_{i,m,3}$ = 0.790.

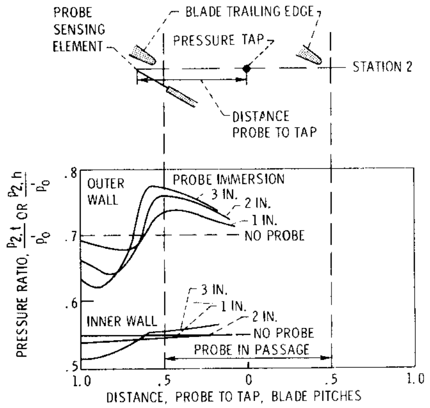


FIGURE 14. - EFFECT OF POSITION OF ORIGINAL DESIGN PROBE ON MIDCHANNEL WALL TAP EXIT PRESSURES OF SURVEYED PASSAGE. DATA SHOWN IS FOR STATOR WITH DESIGN AREA SETTING.

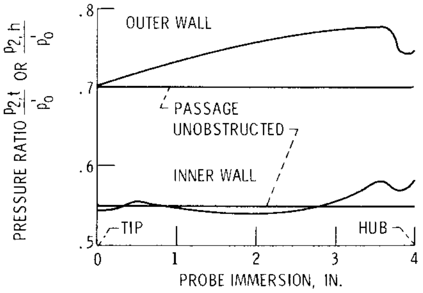


FIGURE 15. - EFFECT OF IMMERSION OF ORIGINAL DESIGN SURVEY PROBE ON AVERAGE MIDCHANNEL WALL-TAP EXIT STATIC PRESSURES OF SURVEYED CHANNEL.

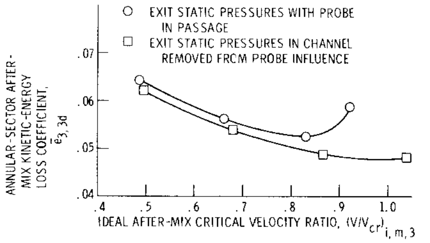
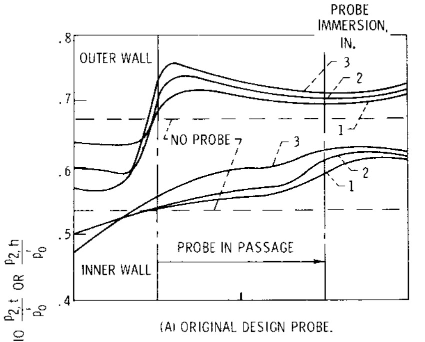
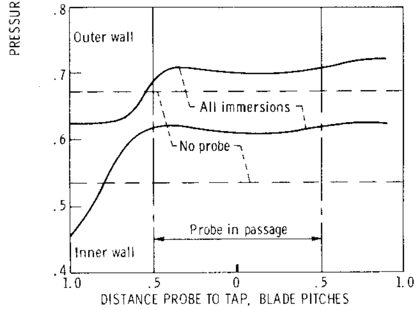


FIGURE 16. - COMPARISON OF LOSS COEFFICIENTS BASED ON EXIT STATIC PRESSURES WITH THE FLOW OBSTRUCTED AND UNOBSTRUCTED BY THE ORIGINAL SURVEY PROBE.



(A) ORIGINAL DESIGN PROBE.



(B) MODIFIED PROBE.

FIGURE 17. - COMPARISON OF EFFECT OF ORIGINAL AND MODIFIED DESIGN SURVEY PROBES ON WALL-TAP MIDCHANNEL BLADE-EXIT PRESSURES IN SURVEYED PASSAGE. DATA SHOWN IS FOR THE STATOR WITH 130 PERCENT OF DESIGN AREA SETTING.