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Enhanced Design of Turbo-Jet LPT by Separation Control Using Phased Plasma Actuators

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April 2003

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Summary

This work deals with the documentation and control of flow separation that occurs over turbine blades in the low-pressure turbine stage at low Reynolds numbers that exist at high altitude cruise. We utilize a specially constructed linear cascade that is designed to study the flow field over a generic LPT cascade consisting of Pratt & Whitney "Pak B" shaped blades. This facility was constructed under a previous one-year NASA Glenn RC initiative (NRA-99-GRC-2). The center blade in the cascade is instrumented to measure the surface pressure coefficient distribution. Optical access allows two-component LDV measurement for boundary layer profiles. Experimental conditions have been chosen to give a range of chord Reynolds numbers from 10K to 100K, and a range of free-stream turbulence levels from u'/U_∞ =0.08% to 3%. The surface pressure measurements were used to define a region of separation and reattachment that depend on the free-stream conditions. The location of separation was found to be relatively insensitive to the experimental conditions. However, reattachment location was very sensitive to the turbulence level and Reynolds number. Excellent agreement was found between the measured pressure distributions and predictions from Euler and RANS simulations. Two-component LDV measurements are presently underway to document the mean and fluctuating velocity components in the boundary layer over the center blade for the range of experimental conditions. The fabrication of the plasma actuator is underway. These are designed to produce either streamwise vortices, or a downstream-directed wall jet. A precursor experiment for the former approach was performed with an array of vortex generators placed just upstream of the separation line. These led to reattachment except at the lowest Reynolds number. Progress has also been made on the proposed concept for a laterally moving wake. This involved constructing a smaller wind tunnel and

molding an array of symmetric airfoils to form an array. Following its development, it will be scaled up and used to introduce lateral moving wakes upstream up the Pak-B cascade.

Background:

The general objective of this work is to develop advanced designs of the low pressure turbine stage of turbo-jet engines to allow higher blade loading through the use of active separation control. For this we have

1. designed and built a large-scale, low disturbance wind tunnel that provides good spatial resolution and easy access for hot-wire and LDV measurements,

2. designed turbulence generators that produce a large range of turbulence intensity levels with isotropic scales,

3. documented details of the separation and reattachment with changes in chord Reynolds number and turbulence level.

The separation control is based on the use of phased plasma actuators. These actuators consist of electrodes that are located on the surface of the blades. A high-voltage a.c. supplied to the electrodes causes the air in their vicinity to ionize. The ionized air (plasma) in the presence of an electric field gradient produces a body force that can induce steady or unsteady velocity components. Numerical simulations of the electric field, body force and induced velocities have led to optimized designs. We intend to use two designs:

1. to produce streamwise vortices which are similar to those produce by surface "bumps" in the experiments by Bons *et al*, 1999; and

2. a downstream-oriented wall jet, which we have been found to be effective in attaching leading-edge flow separation on airfoils at post-stall angles of attack (Post, 2002).

Accomplishments:

The work during this period has been divided into five areas:

1. the documentation of the separation and reattachent locations on the instrumented blade as a function of chord Reynolds number in the low ($u'/U_\infty = 0.08\%$) free-stream turbulence wind tunnel condition, and comparison to numerical simulations;

2. the design and documenting of turbulence generators to produce a range of turbulence conditions, and the documenting of its effect on the separation and reattachent locations;

3. preliminary reattachment study using vortex generators;

4. the completion of a smaller wind tunnel for the development of a proposed moving wake concept; and

5. the measurement of velocity profiles over the instrumented blade using a 2-component LDV.

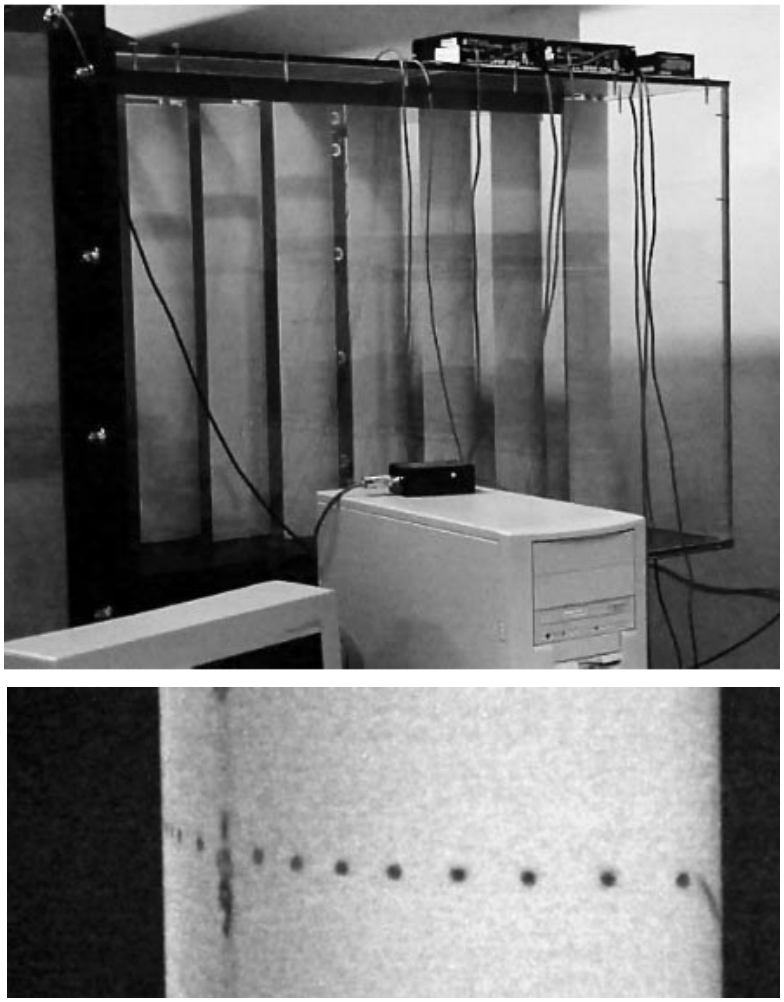


Figure 1: Photograph of Pak-B cascade and enlarged view of upper surface pressure ports.

Low-disturbance Separation and Reattachment Locations

The documenting of the separation region was done by measuring the surface pressure coefficient distribution on the middle blade in the cascade. A photograph of the cascade is shown in Figure 1. The suction surface pressure ports are shown in the enlarged view. The locations of all of the pressure ports are shown in Figure 2.

Figure 3 shows the C_p distribution on the blade for the Reynolds number range, $10,000 \leq Re_c 100,000$, and the lowest free-stream turbulence level of $u'/U_{infty} = 0.08\%$. Also shown is the computed pressure distribution based on an Euler (inviscid) code. The computations are equivalent to an infinite Reynolds number. Therefore they should indicate the distribution without flow separations. Comparing the measured distribution to the calculated distribution therefore indicates the region of separation.

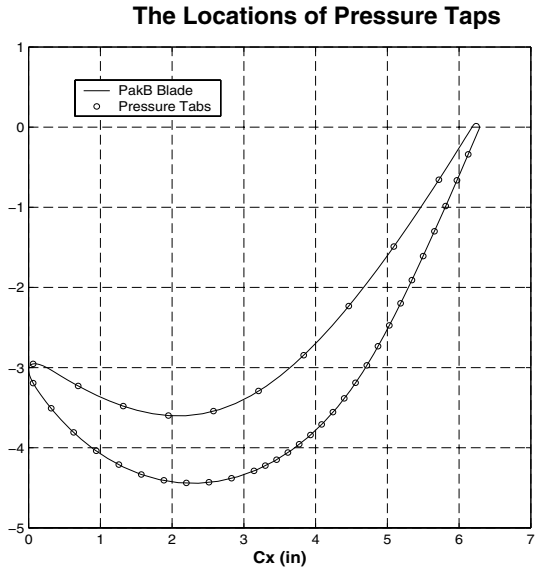


Figure 2: Pressure tap locations on Pak-B blade.

Defining the location of separation requires some judgment. We mark it as the point of inflexion in the region of decreasing $-C_p$, near the trailing edge of the suction side of the blade. For the conditions in Figure 3, this point occurs at $x/C \simeq 0.70$.

The location of reattachment is easier to define. We mark it as where the $-C_p$ value jumps to a smooth curve that follows the inviscid distribution close to the trailing edge. At $Re_c = 100,000$, this occurs at $x/C \simeq 0.85$. For Re_c below 25,000 the flow never reattaches at this low turbulence condition.

The locations of the separation and reattachment for the low disturbance condition are summarized in Figure 4. The dashed region corresponds to a separation bubble that exists on the suction side of the blade. This result forms a parameter space in which we will locate the plasma actuator, and measure its success for separation control.

Turbulence Generators

Turbulence generators were designed to give a range of higher free-stream turbulence levels. Two were selected. The one labeled "Grid 3" corresponds to a perforated plate with 0.25 in. diameter holes, a mesh size of 0.313 in., and a solidity of 0.42. The grid was held in a frame which fit within the straight section, upstream of the Pak-B cascade. The position of the frame could be moved to place the grid at different streamwise distances from the cascade. This distance was referenced to the instrumented center blade.

The other turbulence generator, designated "Grid 0", was a mesh of 0.1875 in. diameter cylinders. The mesh size (centerline spacing) in this case was 1.0 in. This was also held in a frame which fit in the section upstream of the cascade. A photograph of the two turbulence generators is shown in Figure 5.

The turbulence intensities of all three velocity components was measured at different distances downstream of the two grids using a dual hot-wire. The sensors were configured

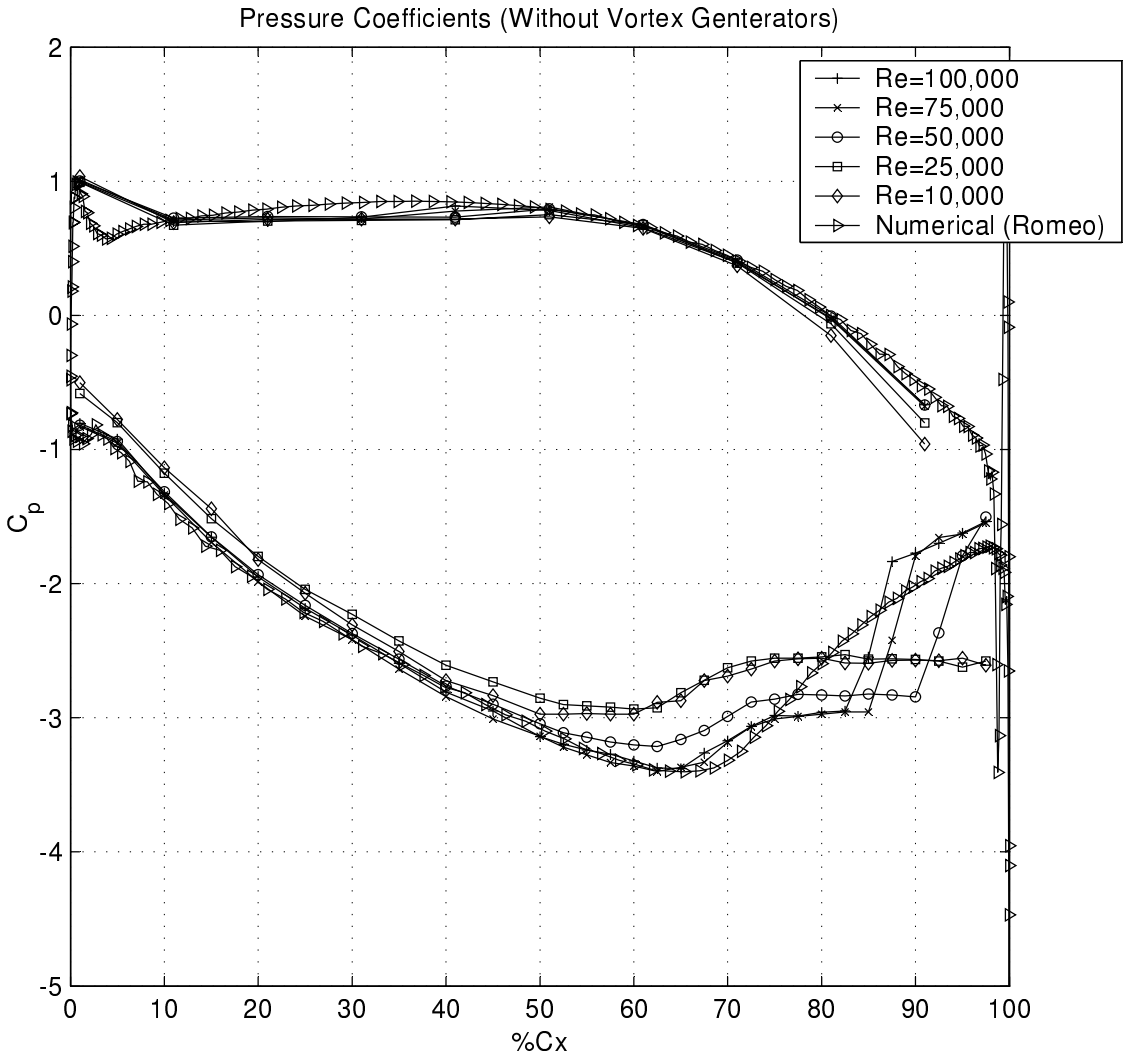


Figure 3: Blade pressure coefficient distributions for different Reynolds numbers, and comparison to Euler simulation for lowest free-stream turbulence level ($u'/U_\infty = 0.08\%$).

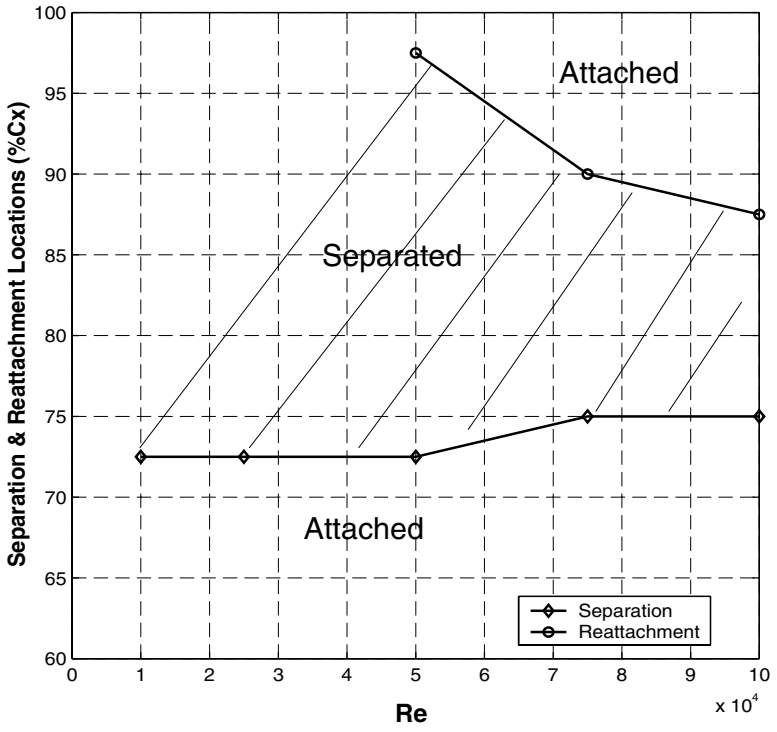


Figure 4: Blade separation and reattachment locations as a function of Reynolds number for lowest free-stream turbulence level ($u'/U_\infty = 0.08\%$).

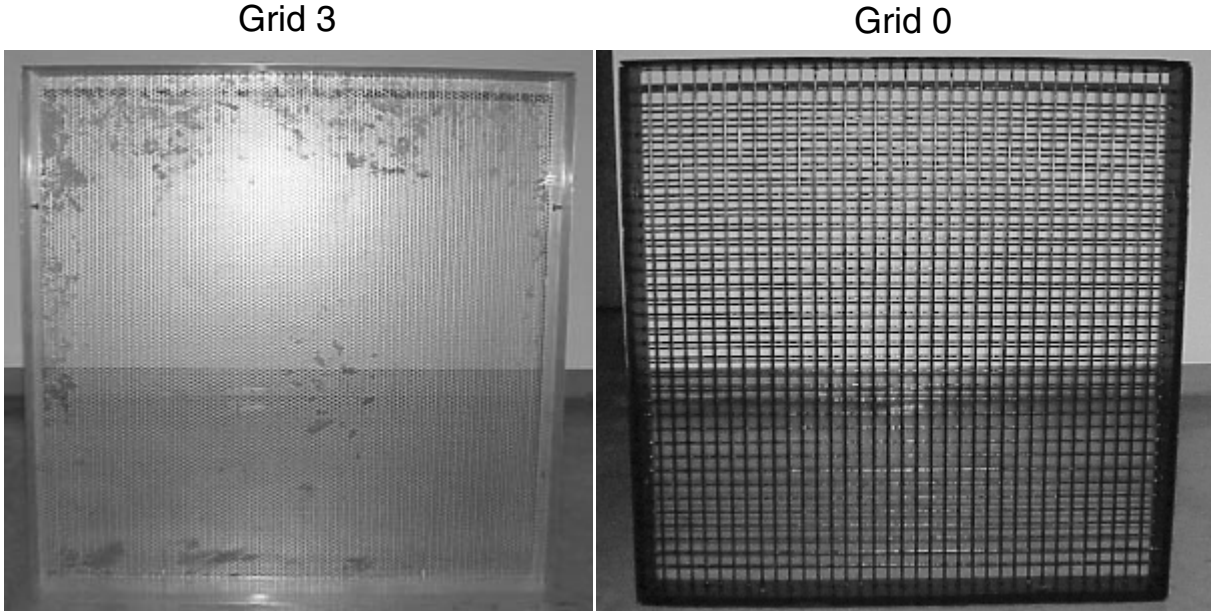


Figure 5: Photographs of turbulence generators used to vary the free-stream turbulence levels upstream of the cascade.

in an "X" arrangement to measure either (u, v) or (u, w) simultaneously. The results are shown in Figures 6 and 7. These show the turbulence intensity, u'/U_∞, and the local ratios u'/v' and u'/w'. These ratios are intended to show the degree of isotropy, which would be perfect if both ratios were 1. In reality, having $u'/v' \simeq u'/w'$ and ≥ 0.9, is considered quite satisfactory as an indication of isotropic nature of the turbulent scales.

With Grid 3, in Figure 6, the turbulence level varied from approximately 2.4 to 1.6 percent. The ratios of the fluctuating components was approximately 0.8 throughout the range of distances from the grid, with the energy evenly distributed among the three fluctuating velocity components. The condition we chose to use for this grid occurred by placing it the furthest distance from the center blade. This gave a free-stream turbulence level of $u'/U_\infty = 1.6\%$. This turbulence level was 20 times larger than the free-stream turbulence level without the grid.

With Grid 0, shown in Figure 7, the turbulence level varied from approximately 5.1 to 2.8 percent. The ratios of the fluctuating components were somewhat better than with Grid 3, having values of approximately 0.9 throughout the range of distances from the grid. Again, the energy was evenly distributed among the three fluctuating velocity components. The condition we chose to use for this grid occurred by again placing it the furthest distance from the center blade. This gave a free-stream turbulence level of $u'/U_\infty = 2.85\%$. This turbulence level was 36 times larger than the free-stream turbulence level without the grid, and 1.75 times that of Grid 3.

The effect of the higher turbulence level of $u'/U_\infty = 1.6\%$ on the C_p distribution is shown in Figure 8. These are shown at the higher three Reynolds numbers, $50,000 \leq Re_c 100,000$. Again the pressure distribution based on an Euler (inviscid) code is also presented.

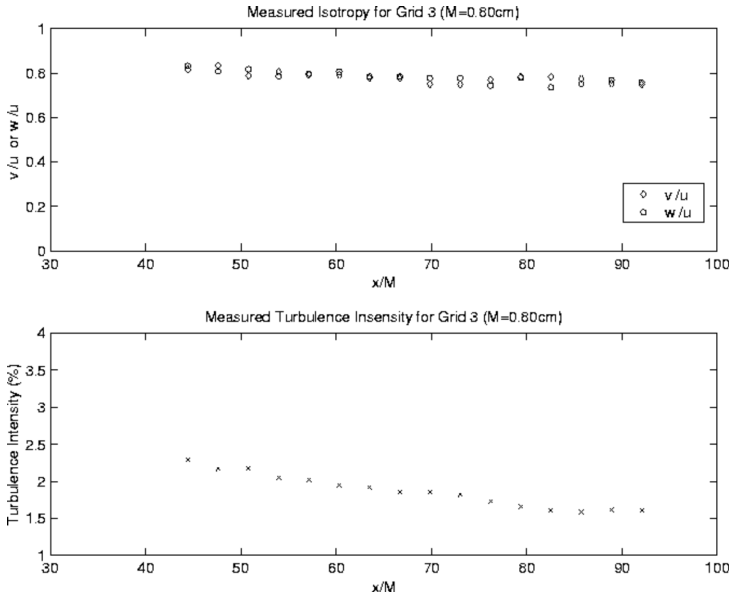


Figure 6: Turbulence intensity (u'/U_∞) and isotropy (v'/u' and w'/u') as a function of streamwise distance for "Grid 3".

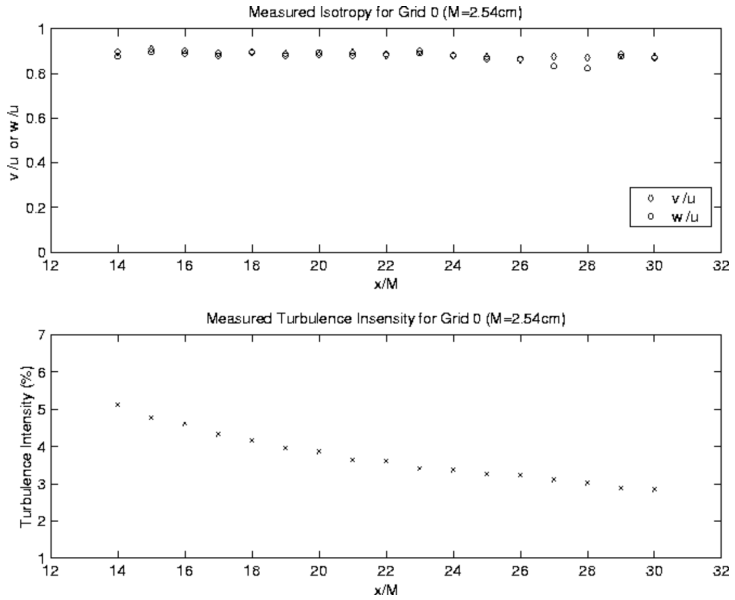


Figure 7: Turbulence intensity (u'/U_∞) and isotropy (v'/u' and w'/u') as a function of streamwise distance for "Grid 0".

These results indicate a relative insensitivity of the separation location with the higher free-stream turbulence. The location is still approximately at $x/C = 0.7$. However, compared to the low turbulence condition in Figure 3, the location for reattachment has moved upstream for the 50,000 and 75,000 Reynolds numbers. These are now approximately the same as for $Re_c = 100,000$, which had not changed appreciably with the higher turbulence levels.

The C_p distributions for the highest turbulence level of 2.85% are shown in Figure 9. This higher turbulence level did no seem to affect the reattachment location compared to the previous case at 1.60%. However, aside from this separation region, the distributions collapse much better onto the Euler solution. In particular, near the leading edge on the pressure side of the blade, we observe much better agreement at the high turbulence level. Comparing this region on the blade to the other cases in Figure 3 and 8, we suspect that a small separation bubble exists just downstream of the leading edge on the pressure side. The highest turbulence levels in this case are enough to cause this to collapse. LDV measurements will be used to investigate this further.

Based on the C_p distributions, the separation and reattachment locations on the suction side of the blade were compiled as in Figure 4, to include the effect of both Reynolds number and turbulence level. This is shown as a 3-D plot in Figure 10. These results include the full range of Reynolds numbers from 10,000 to 100,000, for the three turbulence levels, 0.08, 1.60 and 2.85 percent.

The lower surface in the plot corresponds to the separation locations. In general, these tend to be relatively insensitive the changing conditions, especially compared to the reattachment location, which corresponds to the upper surface. **This is an important result.** Ideally we want the actuator to be placed slightly upstream of the separation location to be most effective. Since the separation location is relatively fixed for all the conditions, only a single actuator, at one location is required.

At the lowest turbulence level (0.08%), the flow does not reattach, regardless of the Reynolds number. Higher turbulence levels result in reattachment, and the effect seems to be more pronounced at the higher Reynolds number. However even for the highest turbulence level and Reynolds number, a separation bubble still remained.

Preliminary Reattachment Study Using Vortex Generators

One of the concepts for the plasma actuator we will investigate, is a design that will produce streamwise vortices, in order to mimic the effect of the surface "bumps" used in the experiments by Bons *et al*, 1999. In preparation for that, we documented the effect of simple vortex generators. A photograph of the vortex generators on the center blade is shown in Figure 11.

The vortex generators consisted of brass shim material that was bent in a 90° angle. They were placed upstream of the separation line, at $x/C = 0.5$, along the span of the blade. The total height of the generators was of the order of the boundary layer thickness. Two spanwise spacings were investigated: 0.5 and 1.0 in. These corresponded to from 5 to 10 boundary layer thicknesses, which was comparable to the bump spacing used by Bons *et al.*

The results were first documented in C_p distributions for the Reynolds number range from 10,000 to 100,000 at the lowest free-stream turbulence condition (0.08%). These are shown for the two spacings in Figures 12 and 13.

The results for the 0.5 in. spacing are shown in Figure 12. Focusing on the suction

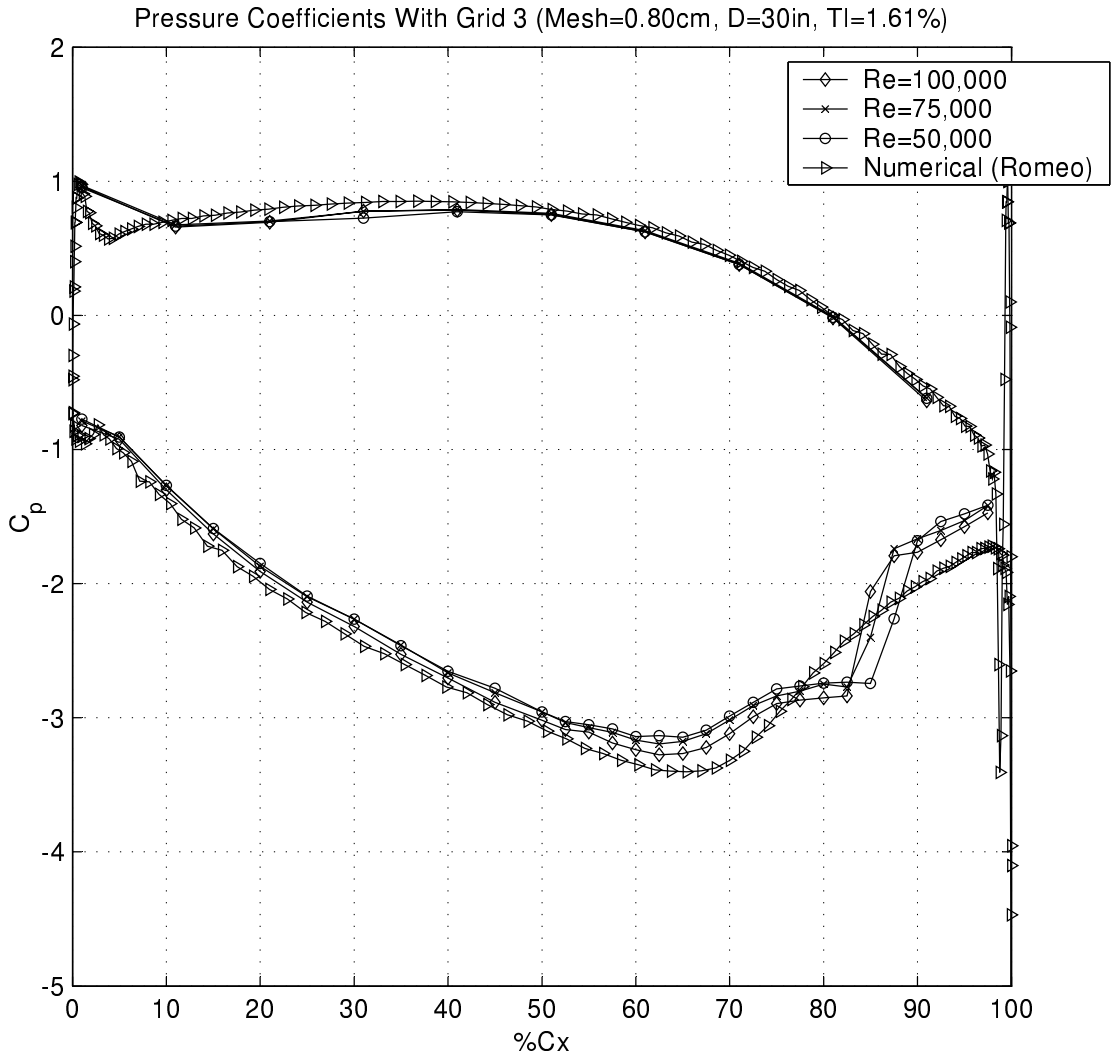


Figure 8: Blade pressure coefficient distributions for different Reynolds numbers, and comparison to Euler simulation for middle free-stream turbulence level ($u'/U_\infty = 1.60\%$).

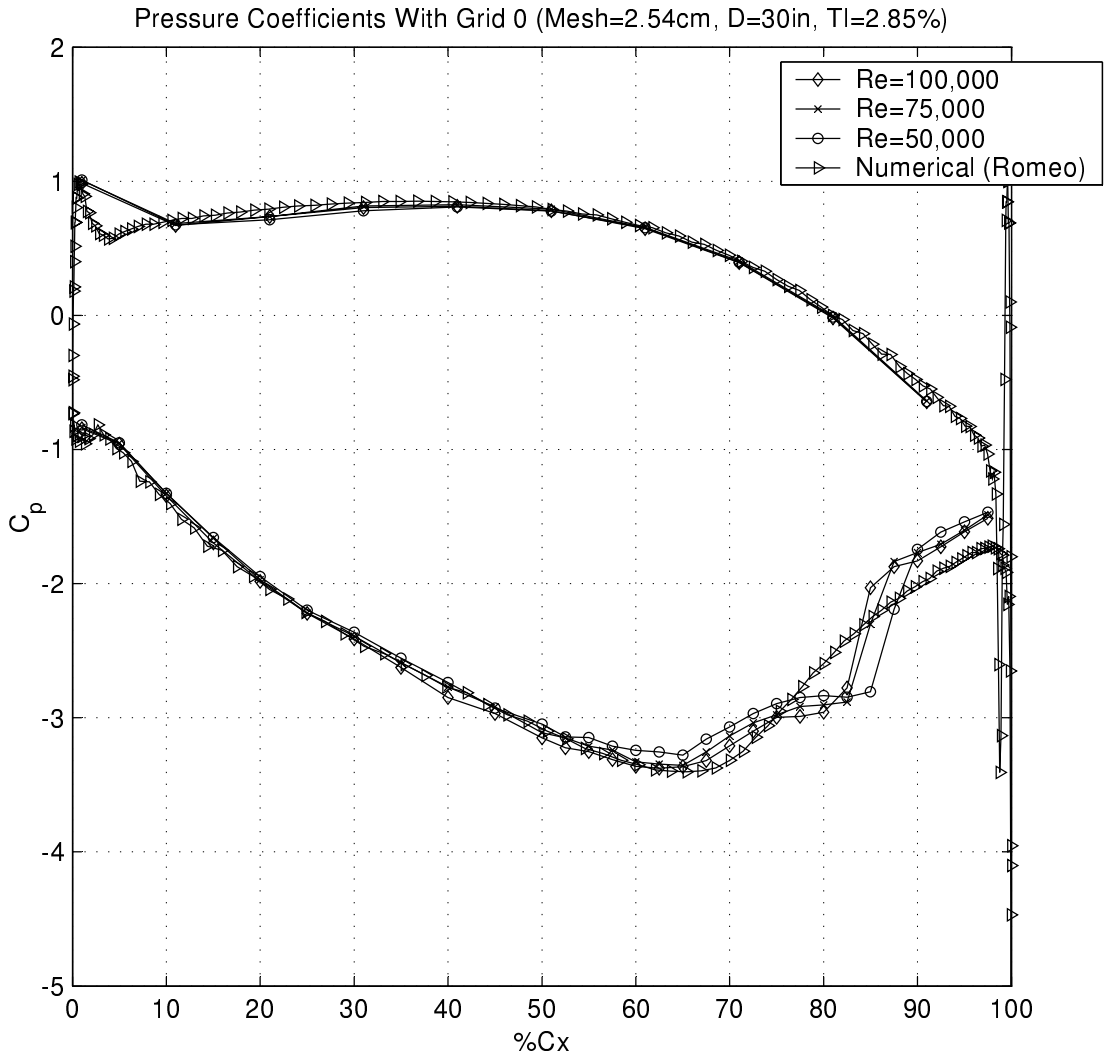


Figure 9: Blade pressure coefficient distributions for different Reynolds numbers, and comparison to Euler simulation for middle free-stream turbulence level ($u'/U_\infty = 1.6\%$).

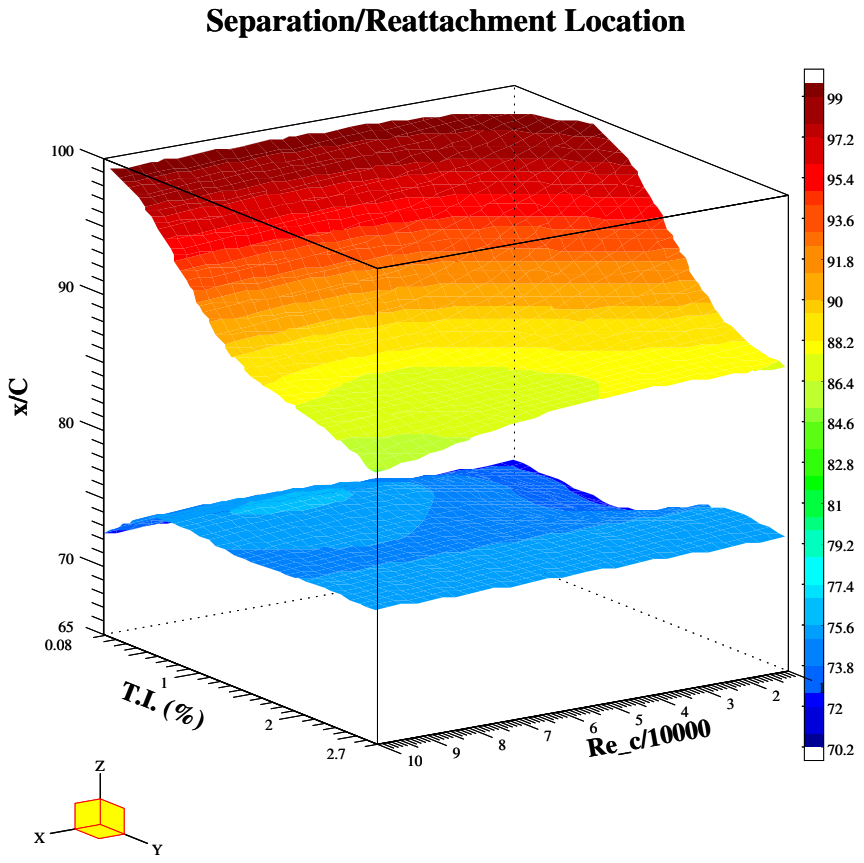


Figure 10: Blade pressure coefficient distributions for different Reynolds numbers, and comparison to Euler simulation for middle free-stream turbulence level ($u'/U_\infty = 1.6\%$).

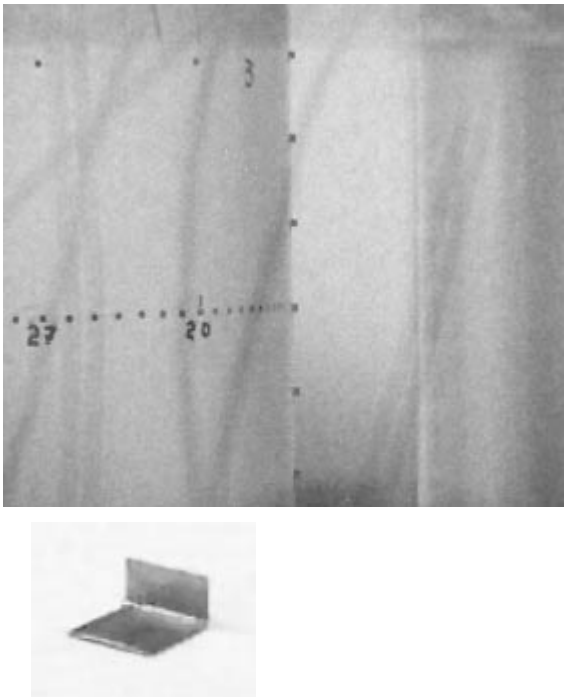


Figure 11: Photograph of vortex generators on center blade in cascade, and an individual vortex generator.

side, the "sawtooth" variation at $x/C \simeq 0.5$ is due to the vortex generators which partially obstruct the pressure taps at that location. Comparing the results to those in Figure 3 (without vortex generators) indicates that for $Re_c \geq 50,000$, the vortex generators eliminated the flow separation. This is evident by the overlap of these C_p distributions with the Euler distribution. The vortex generators also substantially reduced the extent of the separation region at $Re_c = 25,000$, but did not eliminate it. It had a minimal effect at the lowest Reynolds number.

The results for the larger spacing (1 in.) spacing are shown in Figure 13. It is apparent from these C_p distributions that the larger spacing was not as effective. In particular a separation zone is visible for $Re_c = 50,000$, where for the smaller spacing, based on the C_p distribution, the flow was fully attached.

The resulting changes in the separation and reattachment locations due to the vortex generators have been compiled in Figure 14. This includes the base condition that was shown in Figure 4. These illustrate the dramatic decrease in the separation zone, except for the lowest (10,000) Reynolds number. Above $Re_c = 50,000$, the flow is fully attached by the vortex generators of either spacing.

Such vortex generators as these tabs or bumps, produce a drag penalty when they are not needed (at Sea Level for example). This is the potential of the plasma actuators, which can be made to be flush to the surface, and only operated when necessary.

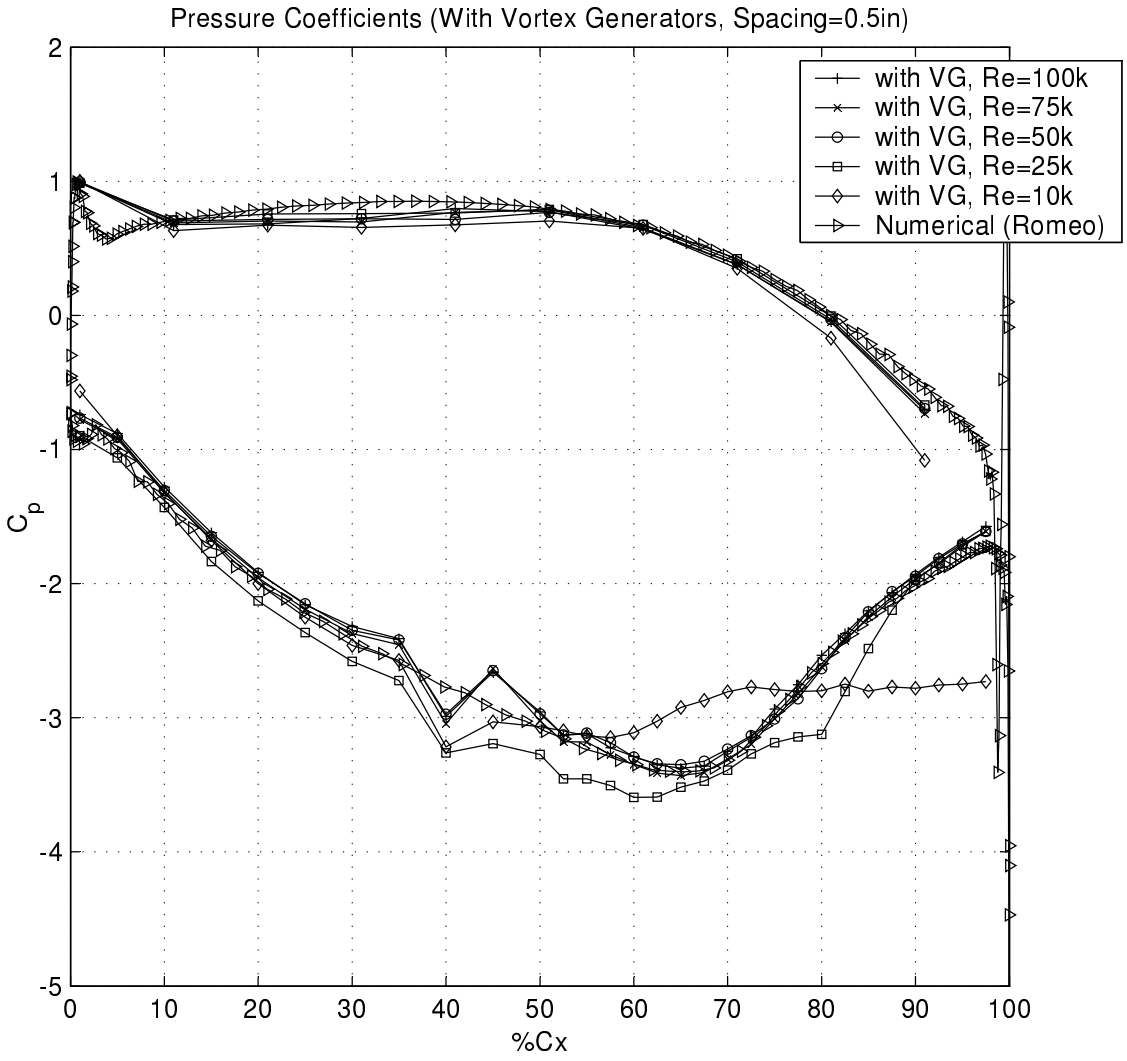


Figure 12: Blade pressure coefficient distributions for different Reynolds numbers, and comparison to Euler simulation for vortex generators spaced 0.5 in. apart (u'/U_∞= 0.08%).

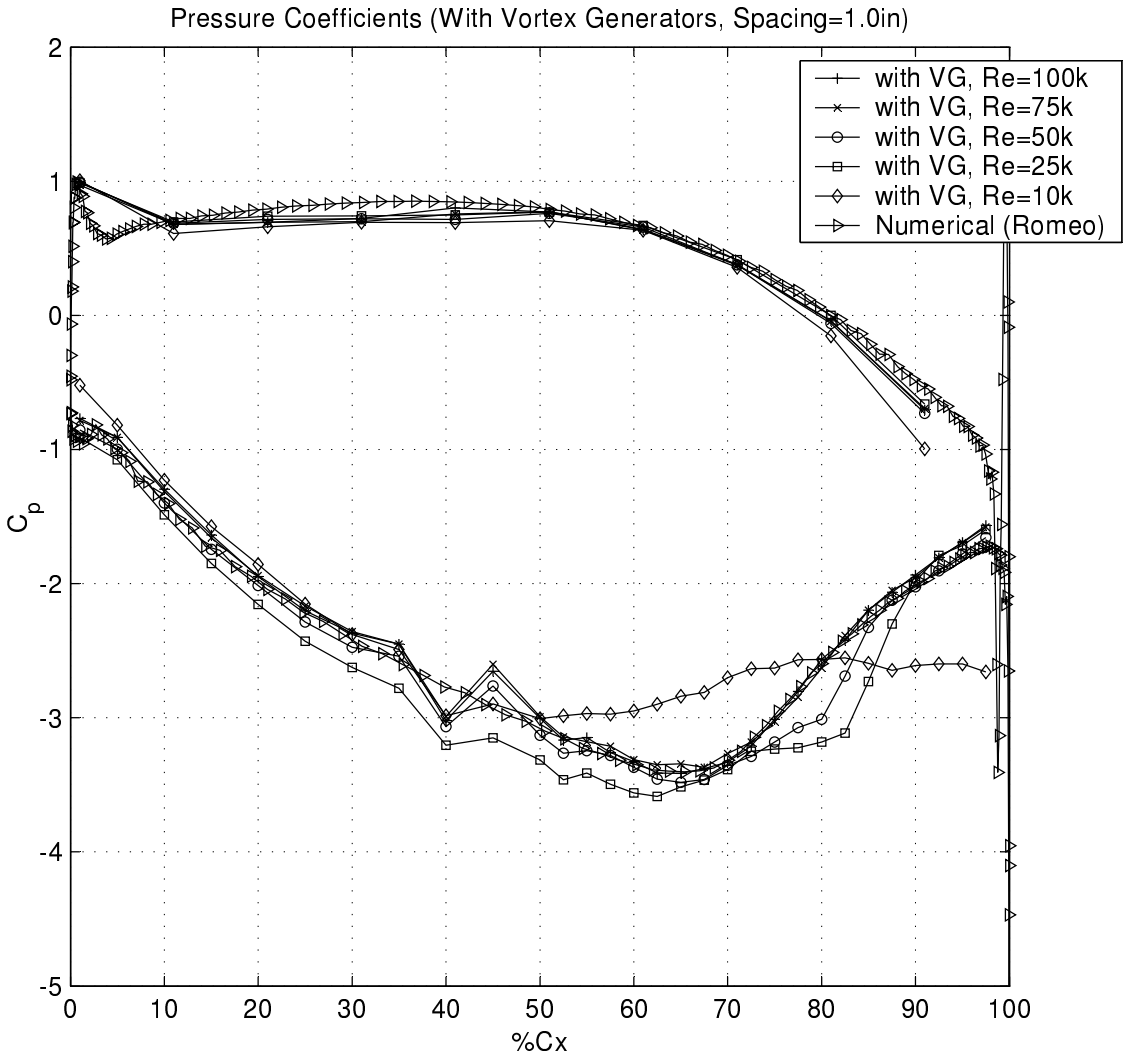


Figure 13: Blade pressure coefficient distributions for different Reynolds numbers, and comparison to Euler simulation for vortex generators spaced 1.0 in. apart (u'/U_∞= 0.08%).

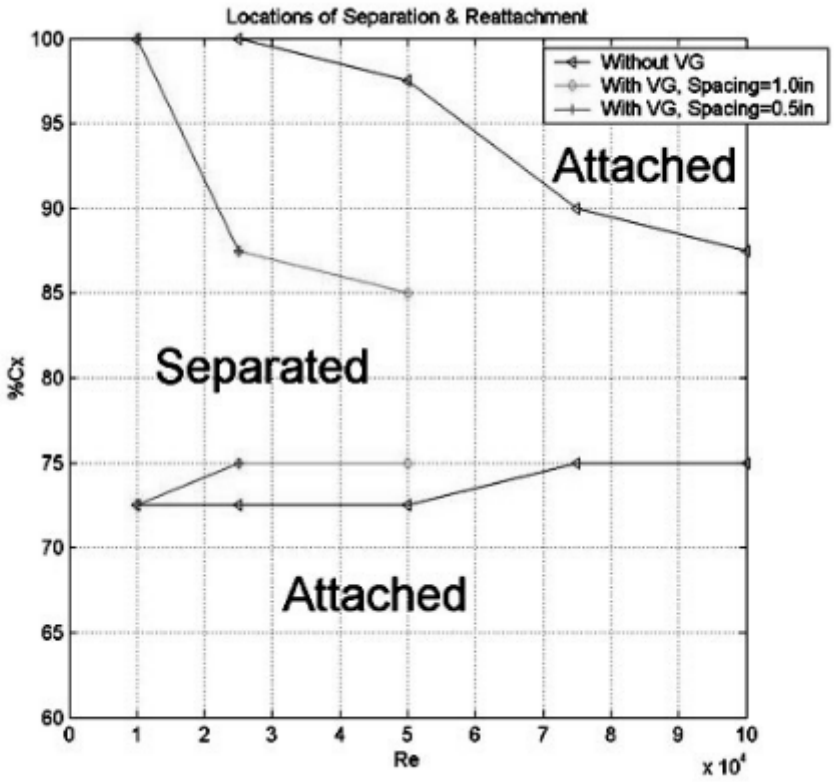


Figure 14: Effect of vortex generators on blade separation and reattachment locations as a function of Reynolds number for lowest free-stream turbulence level ($u'/U_\infty = 0.08\%$).

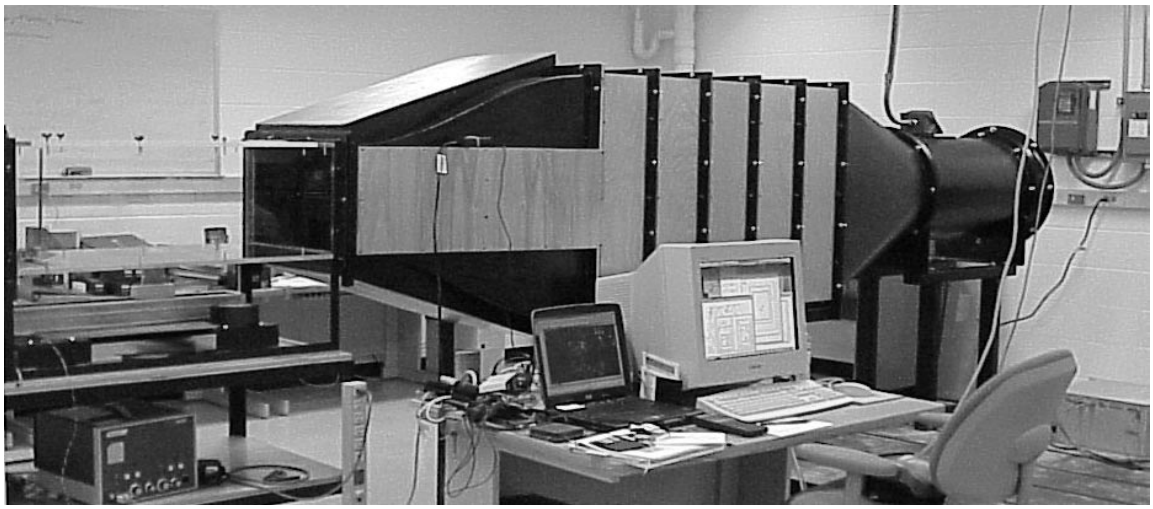


Figure 15: Photograph of new, general purpose wind tunnel that was built to develop new moving wake concept. Test section dimensions are 12 × 18 in. cross-section, by 36 in. long. Maximum velocity is 50 m/s.

Development of Moving Wake Concept

During this period of the grant, we began development of the concept for producing a moving wake, without moving parts (such as cylinder belts) using phased plasma actuators. To be able to test this independently of the large cascade facility, we built a smaller, general purpose wind tunnel. The tunnel is shown in Figure 15. The test section has a 12 × 18 in. cross-section, and a length of 36 in. It has a motorized 2-D traverse mechanism which is designed to move sensors under computer control. The maximum velocity is 150 f/s (50 m/s).

The moving wake device consists of a spanwise array of airfoils. The airfoils have a symmetric cross-section, and are placed at a zero angle of attack, so that passively they will produce a relatively narrow wake. This arrangement is shown in the photograph in Figure 16.

Plasma actuators will be placed just downstream of the maximum thickness point on either side of the airfoils. The actuators will be designed to produce a wall jet in the **upstream direction**. When activated, the actuators will cause the flow past the maximum thickness point to separate. This will substantially increase the drag and substantially increase the wake velocity defect. With an array of airfoils, phasing between the actuators will translate the larger wake defect in the spanwise direction.

The proof of concept will be performed at first, on a only a fewer number of airfoils with a larger t/c. This will be refined to increase the number of airfoils and decrease their spacing to approach a more continuous motion of the wake. An anticipated offshoot of this device will be its use as a turbulence generator, where the turbulence level could be controllable and varied. This could replace the passive grids that we presently use. A further option is to use the moving wake device in conjunction with passive turbulence generators. All of these

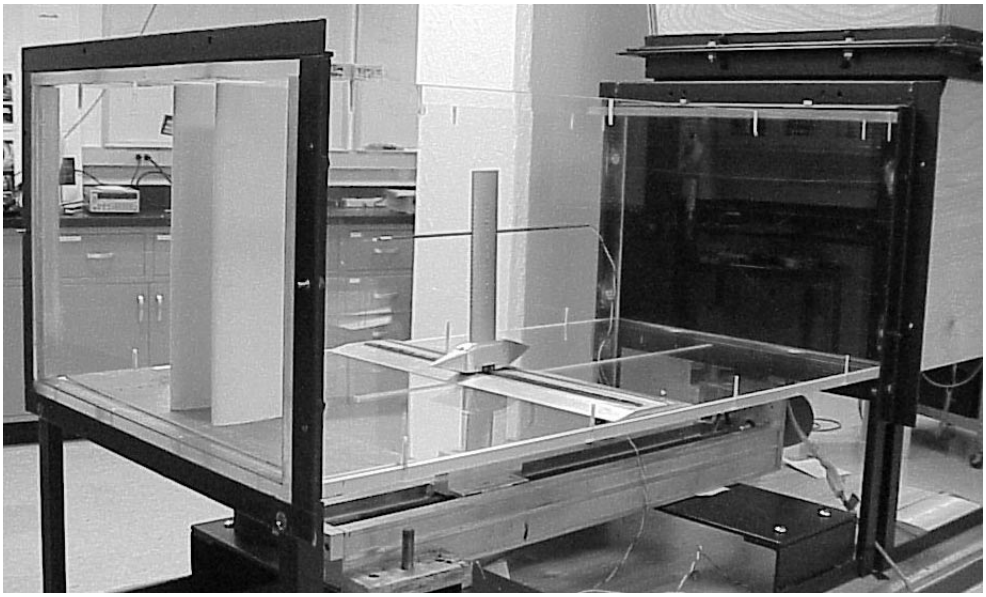


Figure 16: Photograph of tunnel test section which shows two of the airfoils used for the moving wake setup.

options will be investigated in the next period of the grant.

LDV Measurements Over Pak-B Blades

We have begun LDV measurements in the boundary layer on the center blade that is instrumented with pressure taps. Figure 16 shows a photograph of the laser fiber-optic element and photo-multiplier assembly placed above the cascade section. The LDV is operated in a back-scatter mode. The beams enter through the clear Plexiglas ceiling of the cascade section. The optical assembly is held on a 2-D traverse mechanism that is computer controlled. The data acquisition computer has been programmed to move the laser measurement volume in small increments in the wall-normal direction at different locations over the blade surface. These cover the full blade on both the pressure and suction sides.

The LDV is being operated to measure two velocity components, streamwise (u) and wall-normal (v). From these we desire to obtain wall-normal mean velocity, r.m.s., and (u, v)-Reynolds stress profiles.

The seeding has proved to be a challenge. We have investigated two approaches. The first is a Propaline-Glycol mixture that is heated to produce a vapor. Although this produces a good distribution of particle diameters (these have been measured in a separate experiment) the heating results in a small degree of buoyancy. In other experiments this has not produced a problem. However, in the presence of the blades, the flow straining produced by the curvature and acceleration, was found to lead to a **buoyant instability**. This resulted as the growth of streamwise vortices in the heated particle stream which dominated the flow field.

The other seeding approach we have investigated uses a Olive Oil in a pressure-driven aerosol sprayer. This approach does not heat the oil, so that buoyancy is not a factor.

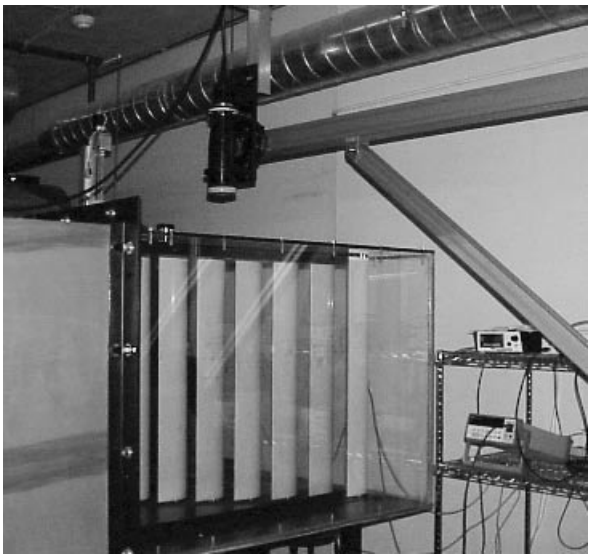


Figure 17: Photograph of LDV fiber-optic element and photo-multiplier assembly positioned on 2-D traverse and extending over cascade test section.

Although this has worked reasonably well in the free-stream region between the blades, it has produced relatively low data rates in the boundary layer on the blades, even upstream of separation. These data rates are requiring from 4-5 hours to obtain sufficient data sets to calculate an accurate mean velocity profile at **one x station**. The data rates are not sufficient to measure the u, v-Reynolds stress.

Measurements of the particle diameters seems to indicate that they are on the lower end of what we feel is desired. Therefore we are presently looking at alternatives (eg., oil types) to increase the particle size, and data rates.

Milestones for the next 6 months:

The progress for the next period of the grant will include the following:

1. Solve the seeding problem for the LDV measurements and measure wall-normal mean velocity, r.m.s., and u, v-Reynolds stress profiles over center blade for same conditions used in C_p measurements.

2. Install plasma actuator on center (instrumented) blade in linear cascade. Two types of actuators will be examined:

   (a) One that is designed to produce streamwise vortices. This will have a spanwise spacing of 0.5 in. based on the vortex generator experiments described here.

   (b) One that is designed to produce a tangential wall jet in the flow direction.

   Both of the actuator types will be located just upstream of the separation location. Based on the experiments with different conditions, this will be at $x/C \simeq 0.6$.

3. Investigate the effect of the different flow conditions, Re_c and turbulence levels, on the ability of the plasma actuator to control separation.

4. Complete development of moving wake prototype.

Key Personnel:

This research is being led by Professors Thomas Corke and Flint Thomas. It involves two graduate assistants; Jenhui Huang and Michael Klapetsky. This work represents Jenhui's Ph.D. thesis research. He is expected to complete his research by December, and graduate in May 2003. Michael is expected to complete a M.S. degree in May, 2003.

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13. ABSTRACT ***(Maximum 200 words)***

This work deals with the documentation and control of flow separation that occurs over turbine blades in the low-pressure turbine stage at low Reynolds numbers that exist at high altitude cruise. We utilize a specially constructed linear cascade that is designed to study the flow field over a generic LPT cascade consisting of Pratt & Whitney "Pak B" shaped blades. This facility was constructed under a previous one-year NASA Glenn RC initiative (NRA–99–GRC–2). The center blade in the cascade is instrumented to measure the surface pressure coefficient distribution. Optical access allows two-component LDV measurement for boundary layer profiles. Experimental conditions have been chosen to give a range of chord Reynolds numbers from 10 to l00K, and a range of free-stream turbulence levels from u'/U_∞ = 0.08 to 3 percent. The surface pressure measurements were used to define a region of separation and reattachment that depend on the free-stream conditions. The location of separation was found to be relatively insensitive to the experimental conditions. However, reattachment location was very sensitive to the turbulence level and Reynolds number. Excellent agreement was found between the measured pressure distributions and predictions from Euler and RANS simulations. Two-component LDV measurements are presently underway to document the mean and fluctuating velocity components in the boundary layer over the center blade for the range of experimental conditions. The fabrication of the plasma actuator is underway. These are designed to produce either streamwise vortices, or a downstream-directed wall jet. A precursor experiment for the former approach was performed with an array of vortex generators placed just upstream of the separation line. These led to reattachment except at the lowest Reynolds number. Progress has also been made on the proposed concept for a laterally moving wake. This involved constructing a smaller wind tunnel and molding an array of symmetric airfoils to form an array. Following its development, it will be scaled up and used to introduce lateral moving wakes upstream up the Pak-B cascade.

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