

**ADVANCED MULTISTAGE TURBINE BLADE AERODYNAMICS,
PERFORMANCE, COOLING & HEAT TRANSFER**

FINAL REPORT

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CONTRACT INFORMATION

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EXECUTIVE SUMMARY

The gas turbine has the potential for power production at the highest possible efficiency. The challenge is to ensure that gas turbines operate at the optimum efficiency so as to use the least fuel and produce minimum emissions. A key component to meeting this challenge is the turbine. Turbine performance, both aerodynamic and heat transfer, is one of the barrier advanced gas turbine development technologies. This is a result of the complex, highly three-dimensional and unsteady flow phenomena in the turbine.

The overall objective of this experimental research program is to improve the design capability for high temperature turbines by providing a thorough and detailed understanding and data base of the turbine unsteady flow field. To achieve these goals, a set of experiments is performed in the Purdue Research Turbine facility. These experiments serve to quantify the detailed unsteady flow through the turbine, including the effects of vane clocking.

Particle Image Velocimetry Measurements

Particle Image Velocimetry (PIV) is an innovative whole field velocimetry technique that provides visualization and quantitative measurement for a two-dimensional velocity vector field. Although PIV is a powerful measurement technique, there have been few attempts to apply it to turbomachines. This is a result of the fact that the application of PIV to measure complex turbomachine flow fields presents many challenging obstacles. These include optical access, laser energy management, seeding, and the acquisition of rotating frame data. This work is directed at providing PIV data defining the flow field through a turbine first vane row, axial gap, and leading edge of downstream rotor in a multistage low speed turbine. A series of experiments is performed to investigate and quantify the flow field with and without leading edge

showerhead film cooling. Data are acquired that demonstrate the ability of PIV to characterize the complete variation of the axial and circumferential velocity field. This velocity information shows that PIV is an accurate method, comparing favorably with traditional measurements. Each obstacle to the application of PIV to turbomachinery is addressed, with the technique shown to provide information previously obtained only from an impractical number of point measurements.

The characterization of the flow field in the first stage vane of the research turbine was achieved through PIV measurements that investigated the spanwise variations in the axial and circumferential components of the velocity field entering the first stage vane, thus characterizing the stage inlet boundary condition.

The flow field between the first vane and the downstream rotor blade row was investigated, with a goal of characterizing both the vane wake and the unsteady potential effects associated with the rotor blade as it traversed the vane passage. The vane wake convection path and instantaneous flow structure were investigated, including both vane-rotor blade relative position and spanwise variations. The PIV technique allowed, for the first time, whole field unsteady images of these effects to be observed and quantified. The PIV data from each image acquired to examine this flow field represented 2,000 individual point measurements, with each ensemble average containing 20 images.

The wake instantaneous behavior was investigated by examining both the instantaneous velocity and vorticity information. Distinct vortex pairs of positive and negative vorticity were shed from the vane trailing edge. Near the vane trailing edge, the vane exit absolute flow angle exhibited underturning in the flow region associated with the vane wake. However, nearer to the rotor blade leading edge, this underturning was dominated by the overturning effect of the rotor blade potential field.

The spanwise variation of the vane-rotor axial gap flow was also investigated. By examining PIV velocity data at several spanwise locations (30%, 50%, 70%, and 90%), the entire spanwise variation of the axial and circumferential flow field through the axial gap and around the leading edge of the rotor was characterized. The highest velocities and largest vane wake width were found near the hub, while the lowest velocities and the smallest vane wake width occurred near the tip. The PIV velocity data were validated by favorable comparison with hot wire anemometry.

PIV was also used to characterize the effect of the rotor potential field on the vane exit absolute flow angle. Near the trailing edge of the vane the flow field at 50%, 70%, and 90% span, the flow exhibited vane exit absolute flow angles that were well below the design values for each case but exhibited the correct trend when compared with design values. However, nearer to the rotor blade leading edge the overturning associated with the rotor camber was demonstrated for all locations except 90%. At 90% span, the vorticity data showed that there was independent behavior of the positive and negative vorticity shed from the vane trailing edge. This was the source of the severe underturning seen at 90% span both near the vane trailing edge and the rotor leading edge.

For the characterization of the film cooling flow ejecting from leading edge showerhead film cooling holes, PIV data image planes that focused on the vane leading edge corresponding to three blowing ratios (0.35, 0.45, and 0.79) were acquired and analyzed. The PIV data showed three distinct flow regimes in the film cooling structure. As the lowest blowing ratio, the film coolant flow remained in the vane boundary layer, ideal for effective heat transfer. At the intermediate blowing ratio, the film coolant flow still traveled in the vane boundary layer but also exhibited vortices that were highly three-dimensional. At the highest blowing ratio, the film coolant flow lifted off the vane surface and emerged as a jet that is ineffective in protecting the vane from hot combustion gases.

PIV data image planes were also taken to correspond with the three blowing ratios to characterize film coolant entrainment in the vane wake. Once more, the PIV data showed three distinct flow regimes in the film cooling structure. At the lowest blowing ratio, the film coolant flow followed along the vane trailing edge surface and remained in the boundary layer. At the intermediate blowing ratio, the film coolant flow also traveled in the vane boundary layer, but the injection velocity affected the wake characteristics. At the highest blowing ratio, the film coolant was traveling in the freestream passage flow and was no longer contained in the boundary layer of the vane. The high injection velocity causes the dominant characteristics of the wake to be attributed to the film coolant jet behavior.

Turbine Unsteady Loading And Heat Transfer

The primary driver for turbomachinery design has long been improved steady aerodynamic performance and efficiency. However, the unsteady flow field inherent in multistage turbomachines is known to have a significant effect on efficiency, heat transfer, and high cycle fatigue.

Unsteady aerodynamics considers three types of forcing function disturbances to a blade row: entropic, vertical, and potential. Entropic disturbances are associated with variations in total temperature and total pressure. In the Purdue Turbine, the low Mach number flow to the inlet vane row has a uniform temperature. Therefore the entropic disturbance is negligible. The vertical disturbance to a rotor is associated with the shed vorticity convected from upstream airfoils and is characterized by spatial non-uniformity of the steady or time-mean velocity field in the stationary reference frame. The potential or pressure disturbance to a rotor blade arises from the rotating blade cutting through the steady potential fields of closely spaced adjacent stator rows.

The blade response to these forcing functions consists of both the unsteady lift and unsteady heat flux. The rotor blade loading response is measured with on-blade dynamic pressure transducers, with the thermal response quantified by on-blade heat flux gages.

Stator indexing to minimize the unsteady aerodynamic loading of closely spaced airfoil rows was studied. Over a range of turbine stage loadings and reduced frequencies,

the inlet vane row was indexed to six positions over one vane-pitch cycle, with the second vane row fixed. The upstream and downstream-generated aerodynamic forcing functions to the first-stage rotor were measured in the rotating reference frame, with the resulting rotor blade unsteady aerodynamic response quantified by rotor blades instrumented with dynamic pressure transducers.

These experiments demonstrate that stator indexing to minimize the unsteady aerodynamic loading of closely spaced airfoil rows is a viable new technique for the passive control of flow-induced vibrations of turbomachinery blade rows. Specific results include the following.

- Indexing the inlet vanes resulted in decreased rotor-blade unsteady lift at all six turbine operating points, with attenuation ranging from 37% to 74% of the maximum unsteady lift.
- For the six turbine operating points, the vane index position which minimized the unsteady lift ranged from 0.0 to 0.2 fractional vane-pitch cycle (fvpc), averaged 0.13 fvpc, with standard deviation 0.10 fvpc. This variation was within the least vane position count increment of 0.2 fvpc.

Vane indexing has been shown to alter the unsteady heat transfer coefficient on a turbine blade as well. Attenuation of the unsteady heat transfer coefficient with vane indexing is (1) location dependent, occurring in unison for only small regions of the blade, and (2) blade loading dependent.

Therefore, for turbine blades in spatially non-uniform temperature fields, passive heat transfer control is viable only for controlling the unsteady heat transfer in a small region of the blade, e.g., local hot spots. This is because only small regions are minimized simultaneously by vane indexing, and depending on the controlled location, possibly effective only for small changes from design loading.