ABSTRACT

This paper describes the results of a study to determine the performance improvements achievable by circumferentially indexing successive rows of turbine stator airfoils. An experimental / analytical investigation has been completed which indicates significant stage efficiency increases can be attained through application of this airfoil clocking concept. A series of tests was conducted at the National Aeronautics and Space Administration’s (NASA) Marshall Space Flight Center (MSFC) to experimentally investigate stator wake clocking effects on the performance of the Space Shuttle Main Engine Alternate Fuel Turbopump Turbine Test Article. Extensive time-accurate Computational Fluid Dynamics (CFD) simulations have been completed for the test configurations. The CFD results provide insight into the performance improvement mechanism.

Part one of this paper describes details of the test facility, rig geometry, instrumentation, and aerodynamic operating parameters. Results of turbine testing at the aerodynamic design point are presented for six circumferential positions of the first stage stator, along with a description of the initial CFD analyses performed for the test article. It should be noted that first vane positions 1 and 6 produced identical first to second vane indexing. Results obtained from off-design testing of the “best” and “worst” stator clocking positions, and testing over a range of Reynolds numbers are also presented.

Part two of this paper describes the numerical simulations performed in support of the experimental test program described in part one. Time-accurate Navier-Stokes flow analyses have been completed for the five different turbine stator positions tested. Details of the computational procedure and results are presented. Analysis results include predictions of instantaneous and time-average mid-span airfoil and turbine performance, as well as gas conditions throughout the flow field. An initial understanding of the turbine performance improvement mechanism is described.

NOMENCLATURE

\[ \eta(i) \quad \text{Efficiency at circumferential location "i"} \]
\[ T_{in} \quad \text{Average inlet total temperature} \]
\[ T_{tex}(i) \quad \text{Exit total temperature at location "i"} \]
\[ P_{in} \quad \text{Average inlet total pressure} \]
\[ P_{tex}(i) \quad \text{Exit total pressure at location "i"} \]
\[ \gamma \quad \text{Ratio of specific heats (Cp/Cv)} \]
\[ C_p \quad \text{Specific heat at constant pressure} \]
\[ C_v \quad \text{Specific heat at constant volume} \]
\[ N \quad \text{Shaft rotational speed} \]
\[ \Gamma \quad \text{Shaft torque} \]
\[ W \quad \text{Weight flow} \]
\[ K \quad \frac{(2\pi \text{ rad/rev})}{(60 \text{ s/min})} \]
\[ J \quad 778 \text{ ft-lb/Btu} \]

INTRODUCTION

A series of tests was recently conducted at the National Aeronautics and Space Administration’s (NASA) Marshall Space Flight Center (MSFC). The objective of the test program was to experimentally investigate vane wake clocking effects on the performance of the Space Shuttle Main Engine (SSME) Alternate Turbopump...
Design (ATD) Turbine Test Article (TTA). These tests developed as a result of data analyses from previous baseline ATD aerodynamic rig tests (Gaddis et al., 1992) which indicated possible performance benefits for properly aligning the first vane wakes relative to the downstream vanes. Turbine efficiency contours generated from a complete circumferential mapping of the turbine exit not only showed a 54 cycle pattern corresponding to the second stage vane count, but also a 2 cycle secondary pattern of +/- 0.5% points. Figure 1 shows the measured efficiency contours along with a Computational Fluid Dynamics (CFD) prediction for the circumferential position of the first vane wake as it approaches the second vane leading edge. The higher efficiency was measured in regions where the first vane wakes were predicted to be in general alignment with the second vane leading edges.

![Image of efficiency contours]

Figure 1. Circumferential Efficiency Contours for Baseline Turbine

In order to test this theory, the hardware of the baseline ATD Turbine Test Article was modified to allow experimental investigation of the vane clocking effect. Modifications included an increase in the first vane count from 52 to 54 airfoils to match the second vane count and a clocking mechanism to allow the first stage vanes to be moved circumferentially relative to the second stage vanes and the inlet case struts. An external vernier was also incorporated in order to accurately measure first vane circumferential position. These modifications permitted the first stage vanes to be indexed circumferentially in a minimum amount of time without hardware disassembly, or stopping the test program.

TEST OVERVIEW

Facility

This test series was conducted in MSFC’s air flow Turbine Test Equipment (TTE). The TTE is a blowdown facility which operates by expanding high pressure air from two 6000 cubic feet (170 cubic meters) tanks through a heater section, quiet trim control valve, calibrated subsonic mass flow venturi, and into a plenum section. The air then passes through the test article and an exhaust system to atmosphere. This facility can deliver 220 psia (1517 kPa). The tests described in this paper typically were run with 100 psia inlet pressure. The heater allows a blowdown controlled temperature between 530 R and 830 R (954-1494K). The TTE has manual set point closed-loop control of the model inlet total pressure, inlet total temperature, shaft rotational speed, and pressure ratio. In addition to these control parameters, the facility can accurately measure mass flow, torque, and horsepower. Facility instrumentation also allows measurement of 400 pressures, 120 temperatures, and various health monitoring variables (Carter, 1991, and Kauffman et al., 1992).

Model

The clocking concept was evaluated in a modified Alternate Turbopump Development (ATD) High Pressure Fuel Turbopump (HPFTP) Turbine Test Article (TTA), which is a full scale model of the Pratt & Whitney ATD HPFTP Turbine (Figure 2). The inlet dome/strut assembly, stators, and rotors accurately duplicate the ATD HPFTP Turbine gas path geometry by utilizing engine hardware fitted and instrumented in the model casings within engine tolerances (Figure 3). For this series of tests, the first vane count was increased from 52 to 54 airfoils to match the second vane count. The first vane was then restaggered slightly open to maintain the nominal first vane flow area. Also, a first vane clocking mechanism was added along with an external vernier scale to indicate the vane position. This mechanism provided a means for accurately changing the circumferential position of the first stage vanes, while the turbine inlet struts and second stage vanes remained in their original positions. The model flow entered axially into the turbine inlet, and exhausted axially into a collector, which directed the flow downward while diffusing to minimize possible circumferential pressure gradients. This test was designed to evaluate uncooled turbine performance; therefore all internal coolant flow and leakage paths were sealed.
Eight circumferentially spaced static pressure taps were placed on the inner and outer diameter of the flow path at the turbine inlet plane, the turbine exit plane, and between each airfoil row with the exception of the first vane inlet and exit. Other instrumentation included speed pickups, accelerometers, disk cavity pressures and temperatures, and venturi pressures and temperatures.

Test Matrix
The test series was conducted at "cold-air" equivalent conditions in three parts:

In Part A, the turbine exit flow field was measured in detail for six first vane clocking locations at the aerodynamic design point (P_{\text{in}} = 100 \text{ psia} (689 \text{ kPa}), T_{\text{in}} = 550 \text{ R} (990 \text{ K}), P_{\text{in}}/P_{\text{ex}} = 1.463, N=7000 \text{ rpm}). The six first vane clocking positions were spaced 1°20' apart, for a total of 6°40', or one vane pitch (360°/54 vanes = 6°40', Figure 5).

In Part B, the turbine was evaluated off-design at the "best" and "worst" positions, as determined from Part A. The turbine was tested at design pressure ratio over a wide speed range (P_{\text{in}} = 100 \text{ psia} (689 \text{ kPa}), T_{\text{in}} = 550 \text{ R} (990 \text{ K}), P_{\text{in}}/P_{\text{ex}} = 1.463, N=2000-10000 \text{ rpm}).

In Part C, the turbine was evaluated at reduced Reynolds number, by lowering the inlet pressure, for the six vane clocking positions of Part A (P_{\text{in}} = 35 \text{ psia} (241 \text{ kPa}), T_{\text{in}} = 550\text{R} (990 \text{ K}), P_{\text{in}}/P_{\text{ex}} = 1.463, N=7000 \text{ rpm}).
TURBINE PERFORMANCE

Aerodynamic Design Point Testing

Measured turbine efficiency was used to quantify the effect of vane clocking position on performance. The test program consisted of extensive flow field surveys at the turbine exit plane, approximately two chord lengths downstream of the second rotor. Pressure and temperature measurements were acquired for a full 360 degrees at 1 degree increments, and then used to generate efficiency contours. Figure 6 shows the resulting contour map for vane position 1.

\[
\eta(i) = \left[ \frac{T_{tin} - T_{tex(i)}}{T_{tin}} \right]^{\gamma - 1}
\]

Measured efficiency contours for the six vane clocking positions all showed the 54 cycle pattern associated with the first and second vane count. However, it is noted that the average efficiency at vane position #2 was slightly higher than that at position #4 or #5. An area average of the efficiency contours produces a sinusoidal curve that shows an delta of 0.3% points between these vane clocking positions (Figure 7).

A review of local spanwise efficiency variations with first vane clocking positions reveals local efficiency deltas up to 1.0% point. However, the root and tip cyclic variations are out of phase with those of the quarter-root, mid-span, and quarter-tip, (Figure 8). A detailed look at the mid-span data indicates that if the first vane wake could be properly aligned with the second vane leading edge from root to tip, a 0.8% point improvement in turbine performance is possible (Figure 9).
Turbine performance can also be calculated with the torque and mass flow as follows (mechanical method):

\[
\eta = \frac{K \cdot \Gamma \cdot N}{J \cdot C_p \cdot W \cdot T_{in}} \left( \frac{\gamma - 1}{\gamma} \right)
\]

Although this method cannot give performance measurements at specific locations in the flow field, it can give an accurate check on the overall average turbine performance. Comparison with the performance as calculated by the thermodynamic method shows close agreement in the measured trend with vane clocking position (Figure 10). The offset in levels is probably due to unknown biases in one or both of the performance calculation methods.

**Preliminary Analyses**

Three-dimensional unsteady Euler calculations were performed to characterize the first vane wake entering the second vane. The computational model consisted of the first stage stator and rotor along with the second stage stator. These calculations were used to predict how the first vane wake convects through the rotor and its resulting circumferential position and spanwise shape as it approaches the second vane leading edge. The computational results were then used to correlate first vane wake position to measured performance. The code used for this task was a time marching finite volume solver using Ni's scheme (Ni et al., 1981, 1989a, 1989b and Takahashi et al., 1990).

The 16 turbine inlet case struts were not included in the analytical model. The objective of the calculation was to determine how the (circumferential) average first vane wake aligned with the second stage vane leading edge. Since the inlet case struts remained in a fixed position, and the inlet strut count is not an integral multiple of the first vane count, their circumferentially averaged effect on first vane / second interaction was independent of first vane position.

For the Euler calculation the first vane wake was created by applying a calibrated surface shear model to the momentum equation as a source term. The wake was then allowed to pass inviscidly through the rotor such that its trajectory could be plainly seen with entropy contours (Figure 11). The first vane wake is chopped by the passing rotor into discrete pulses that exit the rotor passage at a fixed circumferential location relative to the...
second vane. When this flow field is time averaged these pulses appear as a continuous stream into the second vane. It is these time averaged first vane wakes entering the second vane that can be clocked by changing the circumferential positioning of the first vane to second vane, or by varying the rotor wheel speed such that the velocity triangles change the first vane wake trajectory.

**Figure 11** Predicted Instantaneous and Time Average First Vane Wake.

The measured peak efficiency occurs when the calculated time average first vane wake impinges upon the second vane leading edge. Conversely, the minimum efficiency occurs when the first vane wake is calculated to be in the second vane mid-channel (Figure 12). A Fourier analysis of the full 360 degrees of turbine exit data supports this conclusion. The vane count (54 cycle) signal is maximum at peak performance indicating that the first vane and second vane wakes coincide with each other (Figure 13). Additionally, the spanwise shape of the convective wake entering the second vane tends to explain the variation of the best clocking position versus span. Previously it was shown that the tip and mid-span "best" clocking positions were 50% pitch out-of-phase with each other. The analytical wake entering the second vane is predicted to be skewed 50% pitch between the tip and mid-span which would support this conclusion (Figure 14).

**Figure 12** Predicted Time Average First Vane Wake Impingement on the Second Vane.

**Figure 13** Relative Amplitude of 54E Frequency Component in Measured Overall Efficiency.

**Figure 14** Predicted Time Average First Vane Wake is Skewed Relative to the Second Vane Leading Edge.
**Off-Design Testing**

Off-design testing was done at the "best" (#2) and "worst" (between #4 and #5) vane clocking positions. A plot of turbine efficiency versus speed parameter shows very good correlation between the thermodynamic and mechanical methods of calculation (Figure 15). As with the aerodynamic design point results, an offset between the two measurement methods exist which may be due to a bias that has not been identified. However, this bias appears to be constant throughout the off-design envelope.

![Figure 15. Off-Design Performance (Thermodynamic & Mechanical Methods).](image)

A detail review of the turbine off-design performance data shows the effect of changing speed parameter on the clocking phenomenon (Figure 16). The wakes from the first vane become clocked and unclocked as the turbine operating speed is varied. This test shows the effective speed range in which a particular clocking position is beneficial. As in the aerodynamic design point testing, the efficiency delta was measured to be 0.3% overall. The magnitude of the delta at the mid-span was measured to be 0.8% at the design speed parameter, and as much as 1.0% at higher speed parameters, which also verifies the previous aerodynamic design point results (Figure 17).

![Figure 16. Off-Design Performance at “Best” & “Worst” Clocking Positions.](image)

**Reynolds Number Testing**

Testing was also conducted at low Reynolds number by decreasing the inlet pressure to 35 psia (241 kPa). In general the effect of clocking on turbine performance agreed with testing done at an inlet pressure of 100 psia (689 kPa). However, at the lower operating pressure, uncertainties in measured parameters become larger and may cloud the results. The precision in measured turbine efficiency at an inlet pressure of 100 psia (689 kPa), based on measured data, is 0.07% for both the thermodynamic and mechanical methods of efficiency calculation. At an inlet pressure of 35 psia (241 kPa), the calculation of turbine efficiency becomes approximately three times less precise. A detail view of the vane wake
indexing effect on mid-span efficiency at 35 psia (241 kPa) inlet pressure, shows it is in good agreement with the data obtained at 100 psia (689 kPa) inlet pressure (Figure 18).

Figure 18. Efficiency vs Clocking Position (High & Low Reynolds Number, Mid-span Detail).

SUMMARY
Testing of the ATD Fuel Turbine Test Article, modified to allow first stage vane circumferential positioning, has provided significant insight into the phenomenon of vane wake indexing. Very detailed turbine exit flow field surveys have been obtained. The effect of vane clocking on turbine performance has been quantified at the turbine aerodynamic design point. Off-design performance mapping has quantified the effective design operating range over which the vane indexing concept can be employed. Low Reynolds number data also confirmed the clocking effect, but with higher data uncertainty. This experiment has demonstrated the vane indexing concept and the associated potential turbine performance benefits.

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REFERENCES


