Multipurpose Rotating Rake Arrays for Integrated Inlet and Fan Stage Performance Measurement

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Boundary Layer Ingestion: Benefits and Application

Because average inlet velocity is lower for BLI, jet velocity is also lower when thrust and airflow are fixed.

BLI offers significant propulsive efficiency and fuel burn benefits relative to conventional propulsion.

Our reference configuration was the N2A-EXTE HWB aircraft, but other configurations could benefit from BLI.

\[ U_{\text{in,conv}} = U_0 \]

Conventional Propulsion

\[ U_{j,\text{conv}} \]

\[ U_{\text{in,BLI}} < U_0 \]

Boundary Layer Ingesting Propulsion

\[ U_{j,BLI} < U_{j,\text{conv}} \]

\[ T = \dot{m}(U_j - U_{\text{in}}) \]

\[ P = \dot{m}(U_j^2 - U_{\text{in}}^2) \]
Boundary-Layer-Ingesting Inlet / Distortion-Tolerant Fan (BLI²DTF) Experiment

NASA 8’x6’ Supersonic Wind Tunnel
(6.5’x6’ Transonic BLI Test Bed Configuration)
Integrated BLI²DTF Test Article

Mach 0.78
BL Thk = 4.80in

Inlet Pre-Entry Diffusion Ramp
Inlet
Fan
Exit Guide Vanes
High-response Variable Area Nozzle
UHB Drive Rig (existing)
Aerodynamic Interface Plane Rotating Rake Array (AIPRRA)
Fan-stage Exit Rotating Rake Array (FERRA)
Other Rotating Rake Arrays

Active Inlet Flow Control Rig

Active Noise Control Fan Rig
Rotating Microphone Rake
Rotating Rake Arrays

- Rotating Rake Arrays (RRA) measured $P_T$, $T_T$, $P_S$, angularity
- Adiabatic efficiency, flow rate, inlet total pressure recovery, and distortion are derived from RRA measurements upstream and downstream of the fan stage.
- High data density achieved through rotations and probe arrangements (FERRA 24 radial x 72 circumferential measurements; AIPRRA $P_T$ 13 x 72)

![AIPRRA Rakes (2 types)](image1)

![FERRA Rakes (4 types; $P_T$ and $T_T$ reversed on types not shown)](image2)

a) Aerodynamic Interface Plane RRA; b) Fan-stage Exit RRA
The Adiabatic Efficiency Measurement Challenge

• When fan stage pressure ratio \((s_P)\) and stage temperature ratio \((s_T)\) are close to unity, measurement of adiabatic efficiency becomes challenging.

• Accurate measurement of entrance/exit conditions is critical.

\[ \eta_A = \frac{\gamma - 1}{s_P^\gamma - 1} \]

\[ s_P = \frac{P_{T,Fan\_stage\_exit}}{P_{T,Aerodynamic\_interface\_plane}} \]

\[ s_T = \frac{T_{T,Fan\_stage\_exit}}{T_{T,Aerodynamic\_interface\_plane}} \]
Methods

• Simulations of the rake surveys were performed by sampling from a CFD flowfield with a variety of rake measurement patterns.

• CFD data for surveys were derived from time-averaged, full-circumference solutions by UTRC, using UTCFD, a Reynolds-averaged Navier-Stokes solver using the k-ω turbulence model.

• Two rounds of CFD solutions were used.
  – First round: conventional inlet and fan exposed to BLI flowfield
  – Second round: BLI²DTF inlet and fan exposed to BLI flowfield

Methods: Simulated Survey Sampling

a) FERRA Rakes

b) overlapped

c) survey pattern

Mach, Massflow, Massflow-Averaged $P_T$ & $T_T$

Standard Deviations of Variables

d) offset patterns

$\square$ $P_T$
$\triangle$ $P_s$
First Round Simulated Survey Results (FERRA) – Total Pressure

“Spikes” appear in data at 56, 112, 168 circumferential measurements
First Round Simulated Survey Results (FERRA) – Total Temperature

…Likewise for temperature, though less dramatic

8 Rakes

9 Rakes
Explanation for 8-Rake vs. 9-Rake Difference

- Shadows represent wakes behind 8 exit guide vanes
- A represents 8 rakes, behind wakes
- B represents 8 rakes, away from wakes
- C represents 9 rakes

In-Phase Measurements
Results from Second Round Simulated Surveys (FERRA) – Mass Flow Rate

- Colors indicate calculated uncertainty due to four variables
- Goal is to reliably measure variables while minimizing measurements
- Arrow indicates selected option
Uncertainty Estimates

• Estimates based on measurement and discretization uncertainties
• Efficiency estimates primarily influenced by pressure/temperature ratios
• Weight flow estimates relatively flat

Adiabatic Efficiency

Weight Flow Rate

Uncertainty of Adiabatic Efficiency

Weight Flow Uncertainty as Percent of Measured
Similar patterns between CFD and experimental data
No apparent artifacts from the heterogeneous rake arrangements
The sampled data does not capture all of the EGV wakes; however, a sufficiently representative sample has been obtained.
Conclusions

• Low-pressure-ratio fans require precise performance measurements for accurate calculations of fan-stage performance.

• When using rotating rake array measurements, care should be taken to avoid “in-phase” measurements. For this reason, the wakes of the EGVs strongly influenced the design of the FERRA.

• The density of measurements in the radial and circumferential directions is the next-most-important factor in reducing measurement error.

• AIPRRA distributions, driven largely by other factors, were checked using the simulated survey method and found adequate.

• Heterogeneous rake probe arrangements can achieve accurate measurement of flowfield variables, if sufficient control of test conditions is achieved.

• Uncertainty of the measurements was adequate for test objectives.
For Further Details

• More on the rotating rake arrays:

• More on Boundary Layer Ingestion
  6.5'x6' Transonic Wind Tunnel Testbed for the Evaluation of Aircraft Embedded Propulsors
  *Presenter: Mr David Arend - NASA GRC*
  Airframe Propulsion Integration Testing Innovations Session
  *Thursday, October 26, 2017*
  1:30 PM - 2:00 PM