Unsteady RANS Analysis of Distortion Transfer Through Multistage Fans

Jixian Yao
GE Global Research

Steve Gorrell
Air Force Research Laboratory

Aspi Wadia
GE Aviation

ASME Turbo Expo, Montreal, Canada
May 2007
Outline

• Background/Objective
• Challenges
• Configurations
• CFD Procedure
• Validation/Analysis
• Summary/Future Work
Background/Objective

Inlet flow distortion: a real world challenge
- a non-uniform total pressure, temperature, swirl condition and turbulence at the engine inlet; can be radial, circumferential or combined; steady or transient
- has profound influence to engine stability, performance, structural integrity, and noise

- An old problem with new challenges – new aircraft/engine development
- Limited success in correlating (data) to design parameters
- Distortion generation and transfer (fan & compressor)
- Distortion sensitivity (fan response)
- Flow physics dictates
- General perception: distortion sensitivity goes hand-in-hand w/ performance
Background

C17 “Sand blast”

gun gas ingestion

Transverse inlet flow by screen

Bifurcated inlet

More complex inlet

Inlet distortions a real challenge in real world
Background

- Swirl ingestion - taking off after A380
- Cross-wind - vortex shedding over fuselage

Gas turbine damage due to 1/rev Pt distortion

Distortion management will become an indispensable part of design
Background/Objective

Need/Benefit

• Physics-based, designed-in, engine-inlet compatibility to maximize engine-airframe system benefits
• Capability to design for distortion sensitivity and transfer
• Analytical capability (not just tools) for
  - distortion transfer & sensitivity prediction
  - flow physics
  - inlet-fan interaction
• Numerical experiments for verification of distortion insensitive design concepts

• Provides virtual test bed for
  - stage matching
  - component performance evaluation with distortion
  - application early in design process

Hi-Fi, large-scale CFD for a purpose
Background/Objective

- Design rules and tools
  - Design capability & modeling for distortion sensitivity and engine stability
- Integrated simulation: Coupling inlet and fan
- Understand fan response to distortion
  - Per-rev type
- Understand distortion generation/transfer
- Performance correlations, prediction capability for rotating instabilities
Challenges

• Level of details to resolve
  - flow physics dictates
  - HPC resource constrains
  - Jugular experiments, CFD validation experience

• Grid
  - numerical algorithm related
  - stator row w/ most vanes as a guide
  - resolution in area of interest

• CFD limitations
  - robustness in unsteady flow calc
  - accuracy (tip flow; near stall condition)
  - boundary conditions

• Large data-set post-processing
  - focus on flow physics - *much details often conceal rather than reveal*
Configurations

• Two 3-stage fans
• 1\textsuperscript{st} fan
  - rear block (Stator-Rotor-Stator; 108/50/118)
  - 1/rev Pt and Tt distortion @S2 inlet
• 2\textsuperscript{nd} fan
  - front block (IGV-Rotor-Stator; 13/24/62)
  - 1/rev Pt distortion @IGV inlet
• Full annulus for each row
• Flow solver: Pturbo (NASA/MSU/GE)
• Simulations at WPAFB, OH, on an SGI Origin 3900 and SGI Altix Bx2. (supported by DoD HPCMP Challenge Award)
CFD Procedure

• 1st fan, rear block, S2/R3/S3

Full Annulus with Moderate Grid Resolution

• 108 S2 vanes, 50 R3 blades, 118 S1 vanes
  - 218 million cells; 444 processors

• Inlet BC’s From Engine Data
  - Sine function fit through S2 inlet data
  - Amplitude and phase a function of span

• Exit BC Static Pressure data at Exit Plane
  - From data match
CFD Procedure

- 2\textsuperscript{nd} fan, front block, IGV/R1/S1

Full Annulus with Moderate Grid Resolution
- 13 IGV’s, 24 R1 blades, 62 S1 vanes
  - 130 million cells; 200 to 246 processors

Inlet BC 1/Rev Total Pressure, from engine data
- 20% peak to peak magnitude

Exit BC Static Pressure, from engine data
- Downstream of Stator 1
- Non-uniform – distortion not attenuated yet
Validation, 1\textsuperscript{st} Fan

\(~90\) deg phase diff btw Pt & Tt distortion

S3 inlet, 56\% imm
Validation, 1st Fan

S3 inlet, 7% imm

S3 inlet, 91% imm

• Excellent circumferential profile match
• Proper phase diff (btw Pt & Tt) captured
• Overall prediction within 3.5% of data or less
Validation, 2\textsuperscript{nd} Fan

- Tt distortion generation captured - both level and phase
- Pt peak leads Tt peak in direction of rotation
- Induced swirl and its transfer

S1 LE, 50% imm

- Pt phasing
- Tt phasing
Validation, 2nd Fan

PTA and TTA at about 10% immersion

PT Prediction
△ PT Data
TT Prediction
■ TT Data

10% imm @ S1 LE

PT and TTA at about 30% immersion

PT Prediction
△ PT Data
TT Prediction
■ TT Data

30% imm @ S1 LE
Validation, 2\textsuperscript{nd} Fan

PTA and TTA at about 70\% immersion

\begin{itemize}
  \item Excellent profile match
  \item Axi-symmetric Pt, Tt level higher near hub
  \item \approx 90 \text{ deg} phase diff btw Pt & Tt distortion
\end{itemize}

PTA and TTA at about 90\% immersion

70\% imm @ S1 LE

90\% imm @ S1 LE
Validation, 2\textsuperscript{nd} Fan

R1 casing statics

![Graph showing R1 casing statics with various data points and lines representing CFD R1 Inlet, data R1 Inlet, CFD R1 exit, and data R1 exit.]
Summary

• Preliminary CFD capability for distortion generation and transfer is demonstrated on two different fans.
• Circumferential profiles of Pt and Tt distortion well captured. Key item: Pt/Tt phasing predicted well.
• Validation is based on straightforward unsteady RANS simulations, not a knob-turning data match.
• This verifies URANS capability in overall prediction for distortion transfer and generation.
• CFD challenges remain, i.e. tip flow, separation, near stall prediction, etc.
• Next step –
  - build up: validation & analysis for larger domain
  - analysis: don’t look at it, look through it
Today’s Wing/Body/Tail

Engine tests w/ distortion screens

Tomorrow’s Blended Wing/Body
Simulation of the entire 2nd fan

Develop Enabling Technology
Understand Flow Physics
Design for Distortion Sensitivity

Simulation of the entire 2nd fan

Distortion transfer in a multi-stage fan