ENGINE TRANSIENT THERMAL BEHAVIOR AND TURBINE BLADE TIP CLEARANCE CONTROL

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Prior and Future Presentations on the Subject:
Presentation Objectives

• ADDRESS IMPORTANCE OF THERMAL TRANSIENTS FOR ENGINE DURABILITY AND PERFORMANCE

• EMPHASIZE CRITICAL ROLE OF BLADE TIP CLEARANCE (TC) VARIATION DURING TRANSIENTS

• INVESTIGATE TYPICAL REASONS CAUSING TIP CLEARANCE PROBLEMS

• DEMONSTRATE EFFECTS OF ENGINE APPLICATION ON TC CONTROL FOR AERO AND INDUSTRIAL ENGINES

• ILLUSTRATE POSSIBLE MEANS OF TC IMPROVEMENT
Two Realistic Extremes Of Turbine Structure

Industrial Application

Aircraft Application
<table>
<thead>
<tr>
<th>Problem</th>
<th>Affected component</th>
<th>Main cause</th>
<th>Possible solutions</th>
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<tbody>
<tr>
<td>Transient thermal stress from high radial $\Delta T$ (LCF)</td>
<td>Rotor discs, stationary diaphragms and rotating plates exposed to cyclic yielding stresses</td>
<td>High heat flux at the rim coupled with low conductivity toward center</td>
<td>Prevent hot gas ingress into inner cavities, increase blade shank length, minimize blade-to-disc contact area</td>
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<tr>
<td>Excessive local transient thermal stress</td>
<td>Combustor liner and cooled nozzle vane trailing edge (buckling)</td>
<td>High heat load from combustor side versus intensive backside cooling; high vane axial $\Delta T$</td>
<td>Apply hoi side TBC; use curved radially vane trailing edge and/or matching shroud thickness</td>
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<tr>
<td>Blade tip rubs (performance loss and possible severe damage)</td>
<td>Primarily first turbine stages and last compressor stages</td>
<td>Relative rotor-to-stator/case transient displacements, circumferential temperature variation in a stator</td>
<td>Attempt thermal matching; apply passive and active methods for tip clearance control</td>
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<tr>
<td>Labyrinth seal damage</td>
<td>Primarily rim seals and interstage seals</td>
<td>Excessive radial and axial rotor-to-stator transient travel</td>
<td>Use honeycombs, consider brush seals, ceramics</td>
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Main Engine Thermal Transient Issues
Sources of Efficiency Losses in Turbine Stage
(Ref. various NASA studies)
Non-equal rotor-to stator axial thermal displacement relatively to thrust bearing

Different radial transient thermal grows for discs and stator

Tip Clearance Issues in Compressors
Time constant during a component heating or cooling corresponds to a moment when $\Delta T_i = 63.2\%$ of the total $\Delta T$ at the steady state.

Transient temperature response of lumped capacitance solids corresponding to different thermal time constants $\tau_t$. 

$$\tau_t = \frac{\rho \cdot c \cdot V}{h \cdot A s}$$
Temperature Response of Typical Compressor or Turbine Disc During Start
Blade Tip Clearance Loss Mechanism
Effect of Tip Clearance on Turbine Performance

(Ref. Sjolander, 1997)
Effect of Blade Reaction and Clearance/Blade Height Ratio on Stage Efficiency
Effect of Blade Tip "Unloading"
Main Contributors To TC Problem:

- Lack of rotor-stator thermal matching
- Poor thermal isolation of shroud support structure from the gas stream
- Failure to provide concentricity between rotor and corresponding shroud location during transients
- Overlooking effect of thrust bearing location when axial thermal growth is important
- Lack of design provision for minimal damage from tip rub
- Excessive accumulated assembly tolerances
Importance of Support Structure and Bearings
Position for Tip Clearance Control
Different Options for Turbine Nozzle Support

Self supported integral nozzles – blade tip shroud

Integral nozzle casting

Very sensitive to thermal distortions related to circumferential $\Delta T$

Typical two-vane per segment nozzles need support casing
Examples of Tip Shroud Segments Support and Sealing
Effect of Different Options for Casing Tip Support on Tip Clearance Variation
• Differences in thermal radial growth between the turbine rotor assembly and stator supporting structure during transients

• Relative axial rotor-to-stator thermal displacements in the cases when the blade tips are flared.

• Circumferential thermal distortion of the tip shroud support structure resulting from non-uniform combustor exit temperatures during transient or steady state operation.

• Bowing of tip shroud segments (due to radial temperature gradients across the shroud wall).

• Variations of turbine inlet and cooling air temperatures

• Bearing housing distortion and variation of bearing clearance.

Main Thermal Factors Influencing Tip Clearance at Steady State
Stator Structural Design Requirements

- Attempt to achieve close transient thermal matching between rotor and stator.
- Stator design has to provide circumferentially uniform temperatures and stator roundness regardless gas path temperature variations.
- Components assembly has to keep segmented shroud elements round and centered.
- Strive to achieve minimal tip clearance at max power steady state.
- Light tip rubs during transients should not compromise rotor integrity.
- Blade tip design should permit tip wear without metal transfer to the shroud.
- Tapered blade tips require optimized location of rotor thrust bearing.
- Design and cooling of stator components should prevent tip rubs at hot restarts.
- Bearing housing design has to keep rotor centered at all operating conditions.
- Design should have flexibility to tune stator configuration and cooling.
- Passive or active tip clearance control means are required when transient thermal matching between rotor and stator is not achievable.
Effect of Tip Clearance on Turbine Efficiency

Examples of Shrouded Blades
Examples of unshrouded blades
Tip Durability Concerns

- Local material build up on shroud segments leading to a progressive rub
- Rotor “freeze”
- Excessive Vibration
- Blade damage/failure
Transient thermal displacement is primarily a function of part’s volume, temperature and expansion coefficient.

Transient TC = Build TC + \( \Delta R_{\text{st}} \) - \( \Delta R_{\text{r}} \)

Typical Transient Rotor and Stator Growth
(Midsize Turbine)
Main operating conditions requiring detailed analysis:

- Cold start - takeoff
- Steady state - cruise
- Emergency shutdown / instant restart
- Gradual shutdown / normal cool-off
- Hot restart

Effect of Engine Operating Modes on Transient T. Cl.
Example of Numerical Modeling of Turbine Structure
Tip Clearance Control Options

- **PASSIVE** – BASED ON TURBINE DESIGN PROVISIONS
- **SEMI-ACTIVE** – OPEN/CLOSED POSITIONS FOR COOLING/HEATING MEDIA
- **ACTIVE** – CONTINUOUS MODULATION OF STATOR COOLING/HEATING
Passive Tip Clearance Control Methods

- Near perfect transient thermal growth matching between rotor and shroud support structure. (Usually requires very good isolation of the stationary structure from the gas path and high effectiveness of stator cooling) OR NON-TRADITIONAL DESIGN
- Exclusion of operating conditions resulting in a tip rub (Especially elimination of hot restarts within certain period of time after shutdown)

- Application of soft honeycomb type shroud seals or rub tolerant coatings for designs with small relative rotor-to-stator travel. Can be coupled with application of abrasive blade tip layer (like cubic boron nitride)

- Application of new structural materials with very low coefficients of thermal expansion (Ceramics)

- Utilization of axial rotor-to-stator thermal displacement for tapered blade tip designs providing proper positioning of thrust bearings

- Machining shroud segments in stator assembly to reduce manufacturing tolerances and provide concentricity of rotor-to-stator at steady state operation
Heavy Duty Shroud/ Nozzle Support Structure (Courtesy Toshiba Corp) (Four Layers)
Design Practice for Heavy Industrial Shroud Support Structure (Courtesy of Westinghouse)
Thermal Droop of Bearing Housing (oil sump) and Resulting Loss of Rotor Concentricity
Coefficients of Thermal Expansion for Medium and High Temperature Materials
Examples of Application of Ceramics in Shrouds and Shroud Support Structures
Minimizing Transient TC by Employing Axial Thermal Travel
Active Tip Clearance Control Modulating Bypass Air Flow
Typical Design for Stage 1 HPT Cooling Supply
(E³ Engine, ref. NASA CR-168069, Dec 1982)
Example of a Successful Aeroderivative Engine
(GE LM6000)
Potential Benefits for Transient TC from St.1 Blade Cooling Supply Through Interstage Diaphragm

(probably used in CF6-80/LM6000, zoomed from open GE publication)
Turbine Disc Semi-Active Thermal Growth Control
Turbine Discs Thermal Growth Control (Proven Concept)
Semi-Active Tip Clearance Control by Reversing Cooling/Heating Flows

(Solar Turbines Patent)
Electric contact system with multiple inserted rub indicators*
Optical devices providing direct observation and measurement of the clearances* through borescope port
Non-contact systems with traversing capacitance probes*
Pneumatic system*
Reflective laser system
X-ray system
Microwave system
Concluding Remarks
(10 blade tip clearance commandments)

- Performance gains justify outmost efforts in minimizing tip clearances.
- Rotor-to-stator thermal matching is a key for passive TC control.
- Uniform no-rub TC require minimal temperature gradients in stator components.
- Low thermal expansion alloys and ceramics can assist in achieving small TC.
- Proper design of rotor support structure is required for obtaining uniform tip and seal clearances.
- Thrust bearing positioning plays important role for tapered blade TC.
- Active TC control is usually required for lightweight aeroengine structures.
- Creative design techniques for achieving transient thermal matching can significantly improve TC.
- Thorough relative rotor-to-stator transient displacement analyses must be carried out after completion of preliminary design.
- Final design validation requires application of accurate TC measurement methods.