TURBINE ENGINE CLEARANCE CONTROL SYSTEMS:
CURRENT PRACTICES AND FUTURE DIRECTIONS

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Turbine Engine Clearance Control Systems:
Current Practices and Future Directions*

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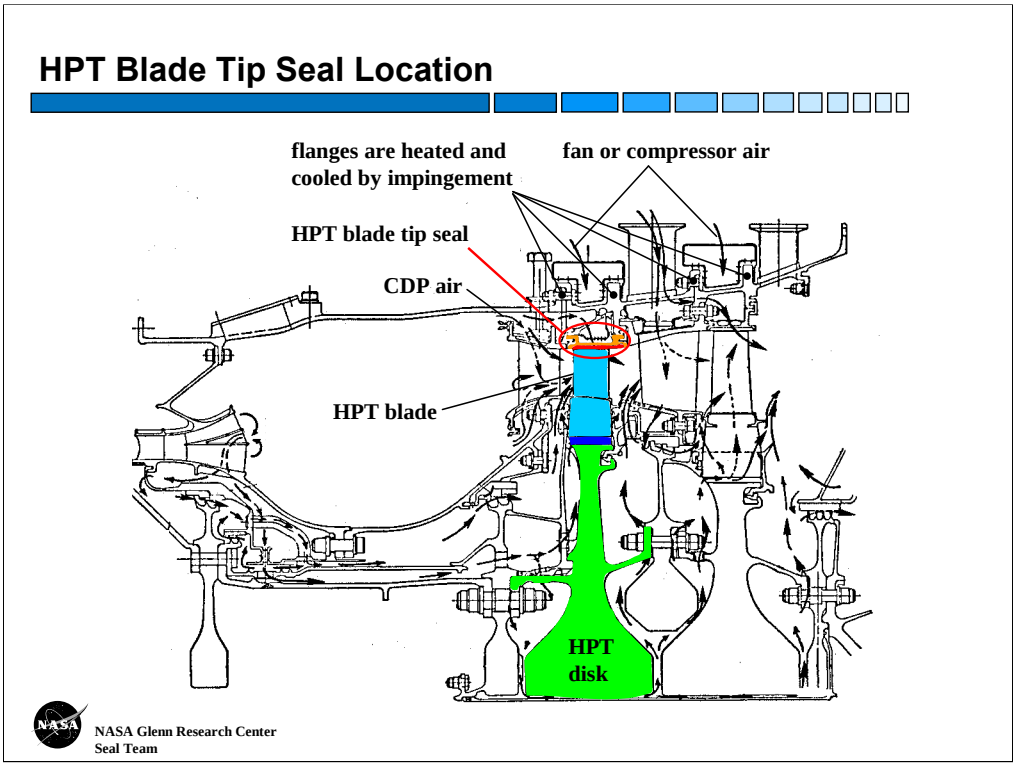
This presentation reviews the

(i) Cause and effect of gas turbine blade tip seal wear

(ii) Current clearance control practices

(iii) Present approaches under investigation at GRC

This work can be found in the recently published NASA/TM-2002-211794.



Blade tip seal location in a modern gas turbine. Cross section combustor and 2-stage turbine.

Tip sealing is a challenging problem due to the speed (1500 fps), temp (2500F), and varying clearance. More so in aero engines due to the frequency of changes in operating points and aero and inertia loads.

Turbine engine is highly evolved. Still room for improvement.

Why HPT Tip Clearance?

Specific Fuel Consumption/Fuel Burn

- 0.010-in tip clearance is worth ~ 1% SFC
- Less fuel burn, reduces emissions

Service Life

- Deterioration of exhaust gas temperature (EGT) margin is the primary reason for aircraft engine removal from service.
- 0.010-in tip clearance is worth ~10 ºC EGT.
- Allows turbine to run at lower temperatures, increasing cycle life of hot section and engine TOW (≥ 1000 cycles).
- Maintenance costs for overhauls can easily exceed $1M.

HPT Reaps the Most Benefit Due to ACC

- Improved tip clearances in the HPT resulted in LCC reductions 4x>LPT and 2x>HPC. (Kawecki, 1979)

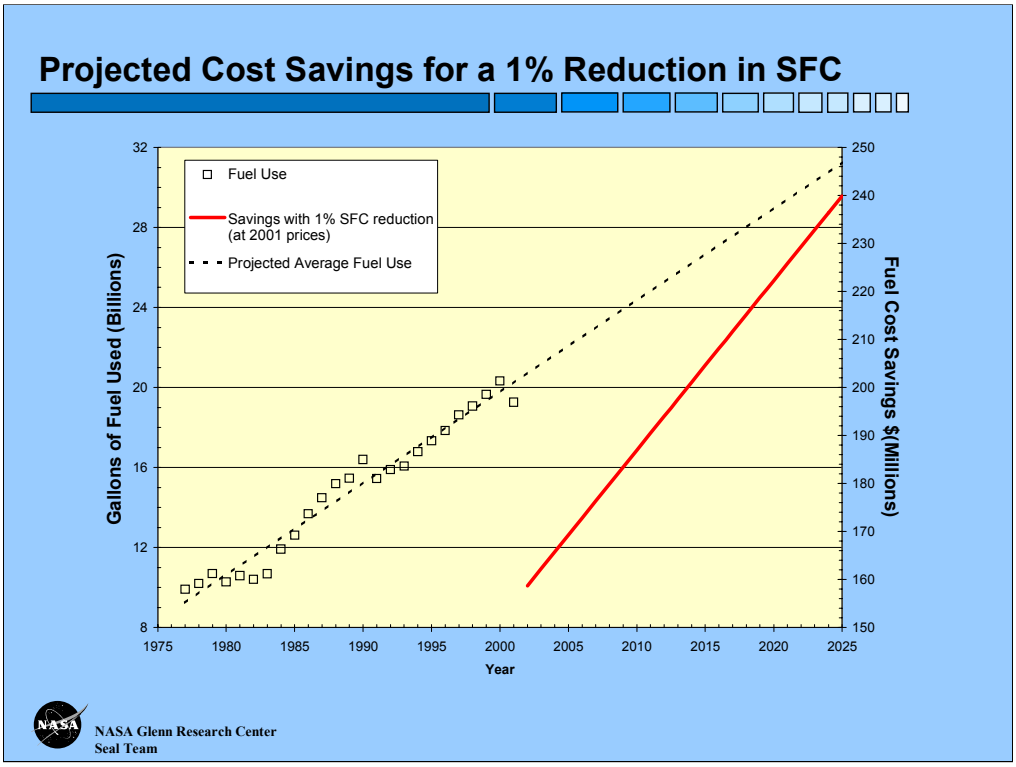


Chart shows the projected U.S. carriers fuel use based on usage over the last 25 years and the projected cost savings for a 1% reduction in fuel use (based on 2001 fuel prices).

For this year alone, a 1% reduction in fuel use is shown to save $160M. Yearly savings are shown to grow to almost a quarter of a billion dollars in 2025.

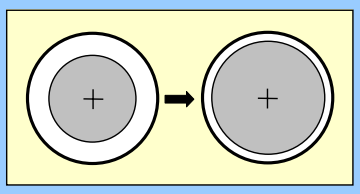
Mechanisms of HPT Tip Clearance Variation

1. **Engine loads** (centrifugal, thermal, internal engine pressure, and thrust)

2. **Flight loads** (inertial, aerodynamic, gyroscopic)

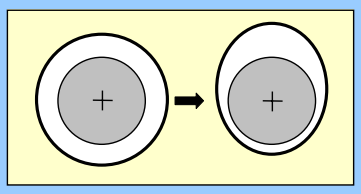
Axisymmetric Clearance Changes

- Centrifugal, thermal, internal pressure loads that create uniform radial displacement



Asymmetric Clearance Changes

- Thermal, thrust, inertial, and aerodynamic loads that create non-uniform radial displacement



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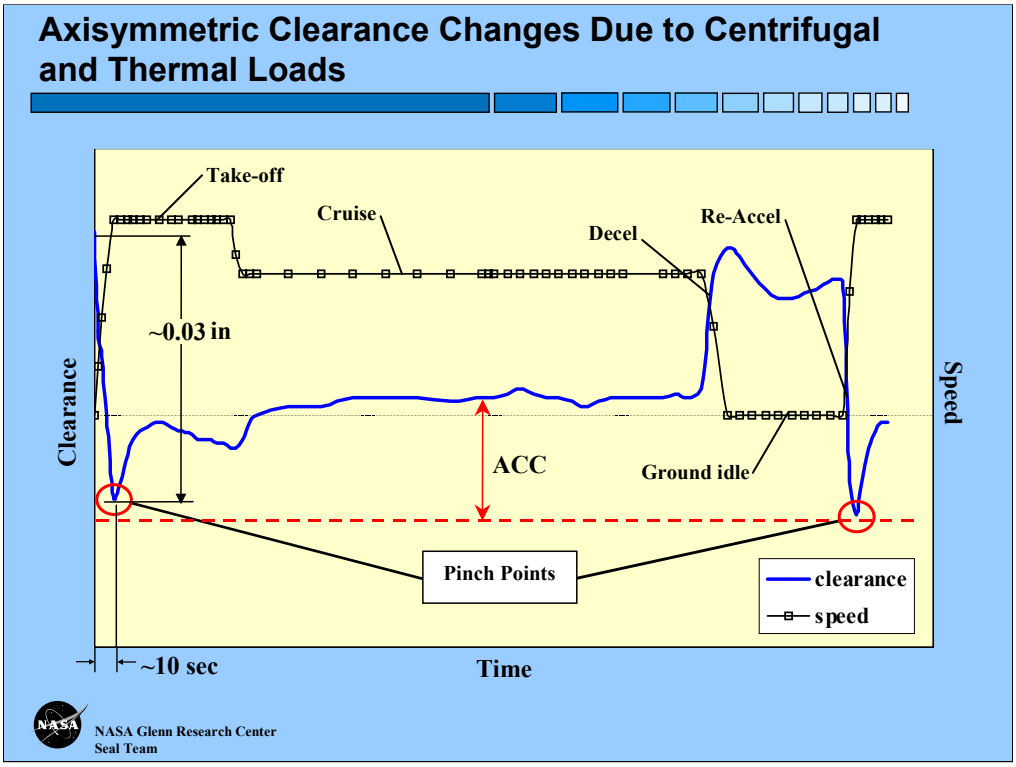
Tip clearance varies over the operating points of the engine.

Mechanisms behind these variations comes from the displacement or distortion of both static and rotating components due to a number of loads.

Loads can be separated into 2 categories: engine and flight.

Engine loads produce both axisymmetric and asymmetric clearance changes.

flight loads produce both asymmetric clearance changes.

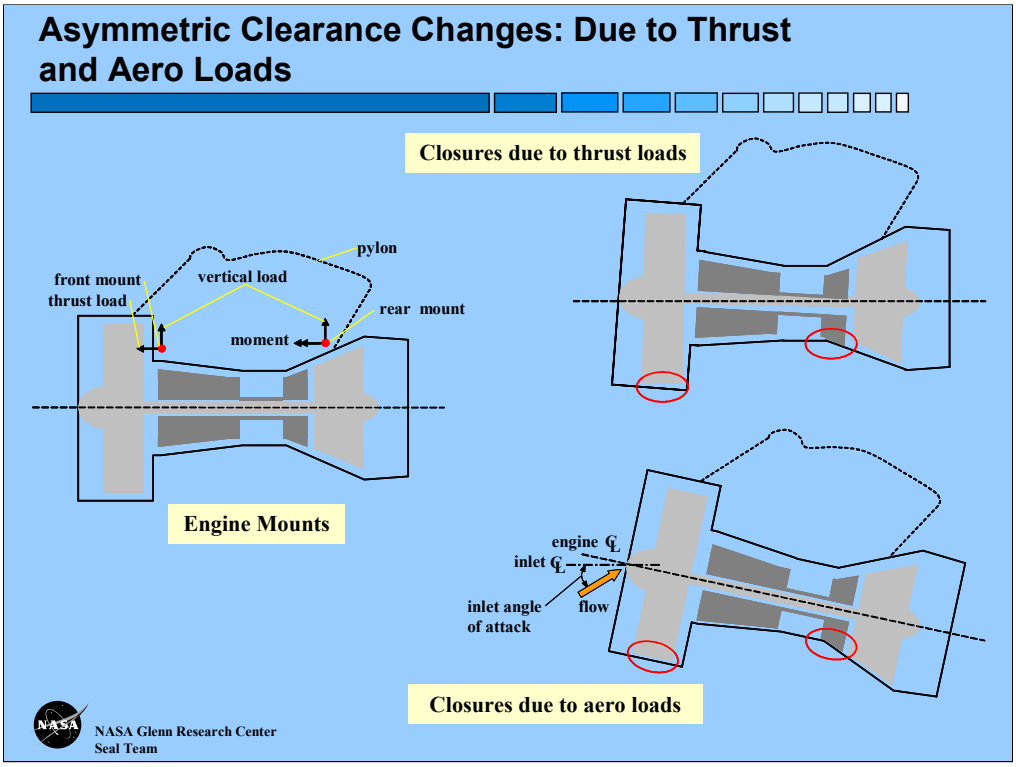


Shows the rotor and case response to axisymmetric centrifugal and thermal loads at various operating points for a given mission profile.

Walk through the major points of the profile: takeoff, cruise, decel, and reaccel.

Object of ACC is to bring down clearance during cruise. Current ACC is not fast enough to respond to throttle transients (step change in altitude maneuver), must maintain adequate clearance.

Fast ACC system can bring down cruise clearance and possible track throttle transients (takeoff, reaccel) to lower EGT and increase service life.



Asymmetric clearance changes are due to non-uniform loading (thermal, thrust, inertial, aero) on the stator components.

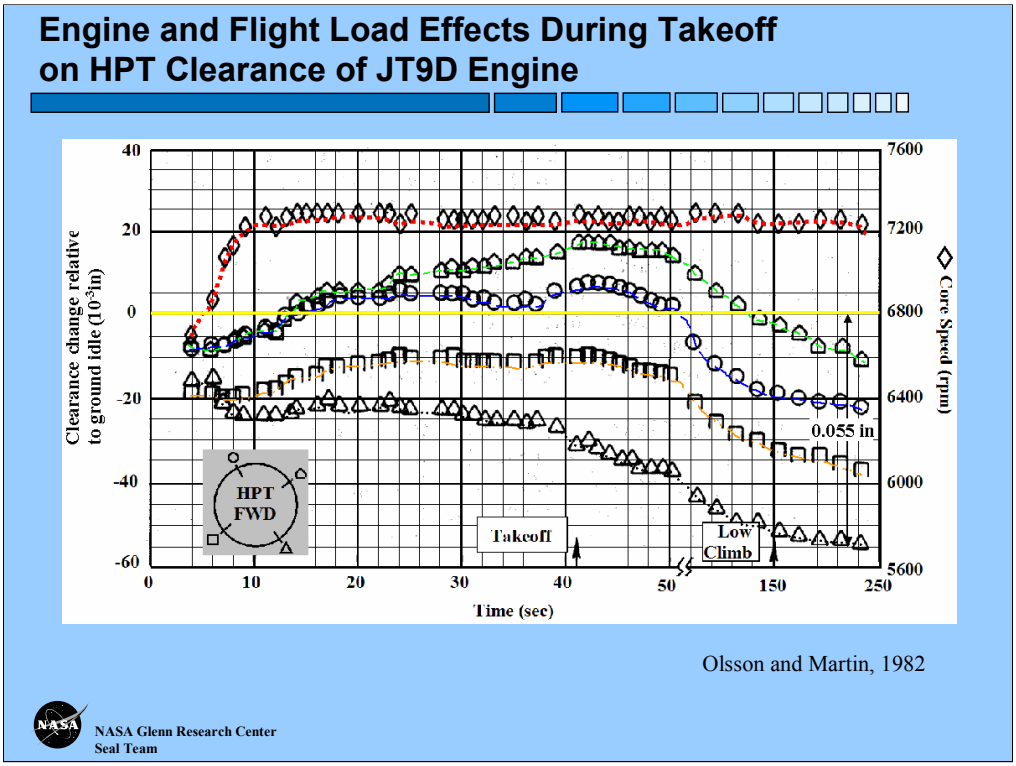
Non-uniform heating can cause ovalization of the case. Asymmetric distortion can also come from aero, thrust and maneuver loads.

Engine not mounted on centerline, aero and thrust load reactions create an applied moment on the case, causing it to bend relative to the rotor.

Aero pressure on the inlet cowl create shear forces and bending moments on the fan case that can carry through the engine. distort the case such that closure occurs at 6 o'clock. Greatest after takeoff rotation.

During takeoff, thrust loads create a downward pitch moment causing clearances to open towards the top of the engine, while closing at the bottom (backbone bending).

The opposite is true during reverse thrust.



Shows actual HTP clearance change due to both engine and flight loads during takeoff for a JT9D engine.

Clearance probe locations are shown.

Minimum clearance shown to occur at the 5 o'clock position.

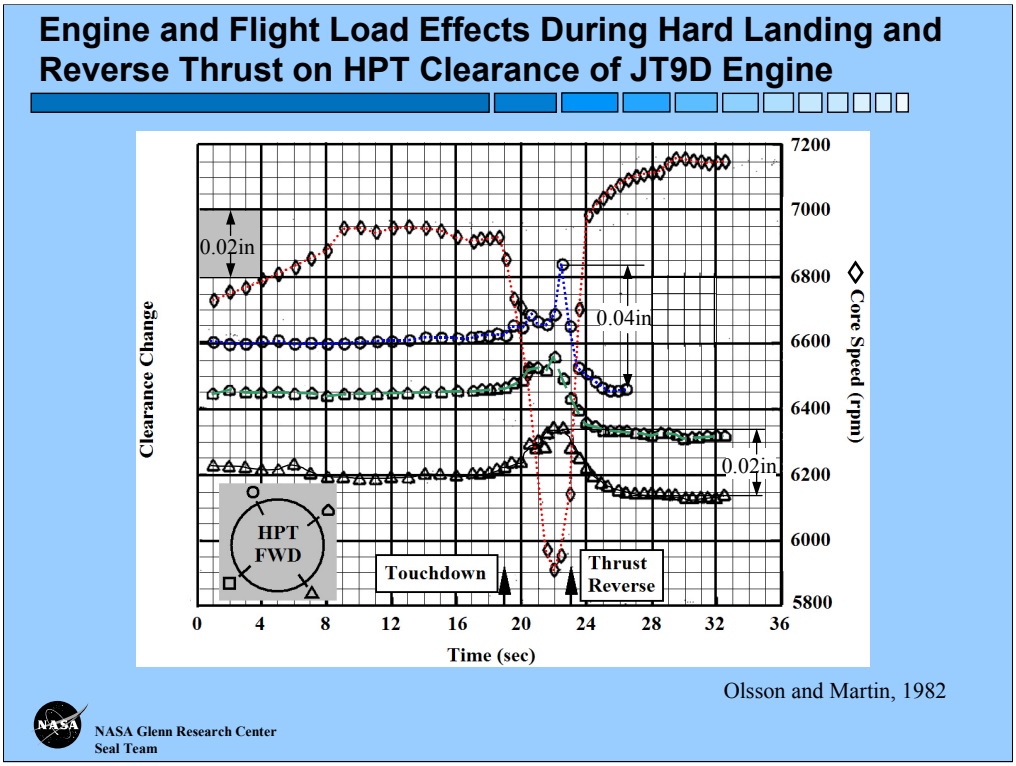
Closure is initially due to centrifugal forces with engine acceleration. As engine continues acceleration to takeoff power, clearances open axisymmetrically due to heating of the case.

Clearances soon begin closing along the bottom half of the HPT and open along the top due to increased thrust load.

The asymmetric effect is further increased due to aero pressure loads on the inlet cowl which transmit back to the HPT during climb.

The chart shows the aero effects to be most intense just after takeoff rotation when the angle of attack is greatest and begin to decrease after low climb when this angle decreases.

We see that the maximum closure relative to ground idle is about 55 mils, occurring at the 5 o'clock position.



This chart again shows clearance data for a JT9D but this time during a hard landing and thrust reverse.

The landing had a sink rate of 5 ft/s and a gross weight of 690,000 lb, which was much higher than revenue service. Chart shows that the landing had no effect on HPT clearance.

Reverse thrust, however, is shown to produce backbone bending with closure effects opposite to that during takeoff. We see that closure now occurs along the top half of the engine rather than the bottom.

HPT Blade Tip Clearance Management Concepts

Control Schemes:

1. **Active Clearance Control (ACC) -desired clearance at multiple operating points.**
2. **Passive Clearance Control (PCC) -desired clearance at one operating point.**

Categories of Clearance Management Concepts

1. **Active Thermal**
2. **Active Mechanical**
3. **Passive Thermal**
4. **Active Pneumatic**
5. **Passive Pneumatic**
6. **Regeneration**

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Tip clearance management categorized by 2 control schemes: active and passive.

PCC is any system that sets the desired clearance at one operating point, namely the most severe transient condition.

ACC is any system that sets the desired clearance at more than one operating point.

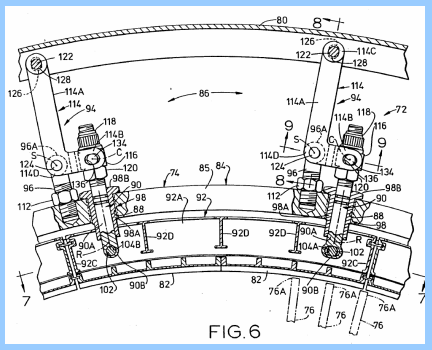
Problem with PCC is that the minimum clearance that the system must accommodate leaves an undesired larger clearance during the cruise portion of the flight where the most benefits of SFC are gained.

PCC systems include matching of rotor and stator growth, using abrabables to limit blade tip wear, using stiffer materials and applying maching techniques to limit distortion of static components to improve roundness.

Engine manufacturers began using ACC in the late 70's and early 80's. These systems utilize fan air to cool the support flanges of the HPT and LPT during cruise, and hence reducing tip seal clearance.

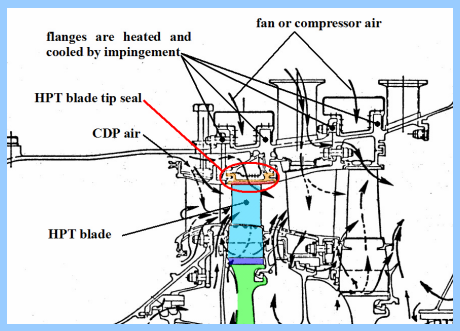
There have been an abundance of PCC and ACC concepts patented in the U.S. alone. Most of these concepts can be placed into 5 categories: active thermal, mechanical, and pneumatic, and passive thermal and pneumatic.

HPT Blade Tip Clearance Management Concepts Cont'd



Active Mechanical
(Corsmeier & Petsche, 1991)

Active Thermal (E^3, 1982)



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Active thermal concepts utilize both fan and compressor stage air to respectively cool (contract) or heat (expand) the HPT shroud and hence vary tip clearance.

These concepts remain the staple technology for clearance control in modern engines.

These systems are limited by their slow thermal response and must therefore allow for adequate clearance in the event of throttle transients during cruise (step change in altitude).

Active mechanical concepts combine linkages and some actuation (hydraulic, electro-mechanical, magnetic, etc.) to vary tip clearance.

This can be done with a segmented shroud with the segments connected to a unison ring.

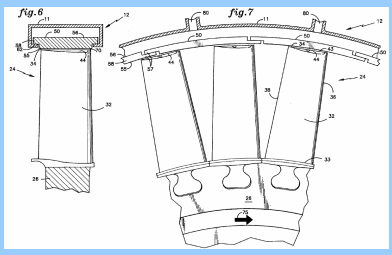
These concepts usually require actuation through the case due to the lack of radial space and high temperature actuators.

Mechanically active systems are subject to secondary sealing, tolerance stack-ups, as well as increased weight and complexity. While these issues may be overcome, the biggest issue is positioning control.

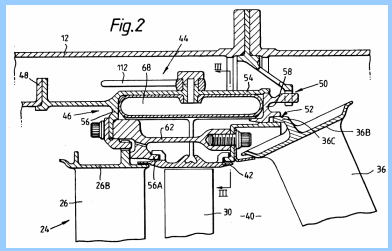
Currently, no clearance measuring systems exist which can reliably survive the operating temps and vibration levels at the HPT tip seal location for extended periods of time (50hrs).

Hopefully this issue will soon be resolved with on-going research in high temperature sensor electronics.

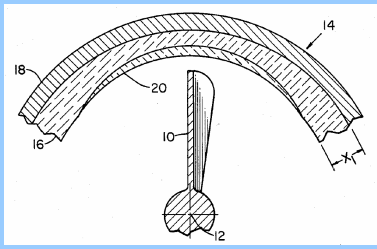
HPT Blade Tip Clearance Management Concepts Cont'd



Passive Pneumatic (Lyon, 1994)



Active Pneumatic (Catlow, 1991)



Passive Regeneration
(Cawley, 1985)

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Active pneumatic concepts utilize internally generated engine pressures or externally generated pressures and valving to load deflectable, sealed shroud segments directly or through some bellows arrangement to radially vary tip clearance.

These concepts would be subject to HCF and are very sensitive to pressure balancing. They could require a great deal of system or auxiliary pressure.

Passive pneumatic systems are driven by engine generated pressures or hydrodynamic effects.

These systems are again subject to HFC, pressure balancing, and in the case of hydrodynamic, extremely high positioning and alignment tolerances.

The previous systems all dealt with passive or active variation of tip clearance with the intent of avoiding rubs. Another category exists called regeneration.

Concepts in this category utilize passive and active control to restore worn tip seals due to rubs and erosion.

HPT ACC Requirements

Actuation	
Range	~0.05-in
Rate	~0.01-in/s (per FAA takeoff requirement)
Positional Accuracy	~0.005-in
Force	~150 psi (shroud cooling and purge)
Environment	
Inlet Rotor Gas Temperature	2500-3000 °F
Shroud Backside Temperature	1200-1300 °F
Case Metal Temperature	500-700 °F
Air Temperature Outside Case	100-300 °F
Shroud Backside Pressure	~500 psi
Shroud I.D. Pressure	~350 psi
Radial ΔP Across Shroud	~150 psi

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The largest HPT tip clearance variations are due to centrifugal and thermal growth of the rotor during takeoff and reburst conditions.

The FAA requires engines reach 95% rated takeoff power from flight idle in 5.0 seconds. this would require actuation systems that can provide radial clearance change on the order of 0.010-in/s.

Positional and dimensional accuracy is extremely important in a gas turbine engine. Sealing and rotor dynamic issues depend on high manufacturing and assembly tolerances.

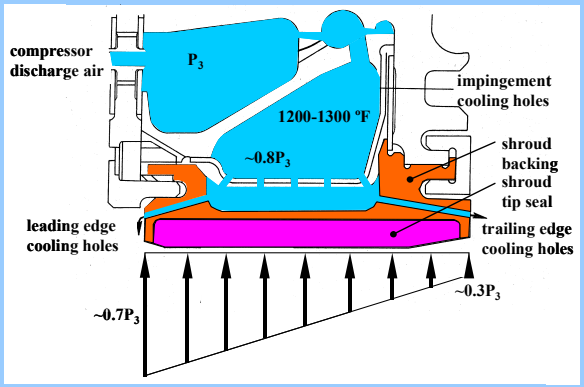
Any mechanical ACC system that is attempting to control tip clearances to within 0.010-in or better must be precisely designed.

The backside of the HPT shroud is cooled and purged with compressor discharge air (1200-1300 ºF). The radial pressure difference across the shroud creates a load inward to the shaft centerline.

An ACC system must be able to overcome this load as well as the resultant moment created by the non-uniform axial pressure distribution.

Actuator Force Due to Shroud Cooling and Purge

- A radial pressure difference exists across the shroud due to backside cooling (P_3 air).
- Must maintain a positive backflow margin (purge) from the rotor inlet air.
- Pressure inside the shroud varies axially due to the work extracted by the turbine blades.
- An ACC system must be able to overcome this load as well as the resultant moment created by the non-uniform axial pressure distribution.



Example:

Shroud i.d: 30-in, width: 2-in
ave Δp: 120-psi
→ 240 lbf/in on the shroud diameter

no. of shroud segments: 16, ~6-in long,
→ 1,440 lbf per segment.

HPT ACC Requirements Cont'd

Sensor	
Accuracy	~0.001-in
Response	~50kHz
Debris Tolerant	moisture, dirt, combustion products
Service Life	>20,000 flight hours
On-Wing Maintenance	e.g., flight checkout/ sensor calibration
Failsafe	redundancy, biased open, and health monitoring

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Researchers and engine manufacturers have been using blade tip sensors for over 30 years.

Many different technologies have been utilized for this purpose including x-ray, capacitive, inductive, optical, eddy-current, microwave, and acoustic.

Typical blade passage sensors provide the ability to measure blade tip clearance and time of arrival.

Tip clearance measurement may be required for any ACC systems that are to improve upon and replace the current technology.

The sensors should have accuracy on the order of 0.001-in. The sensors must have accuracies well below the inherent engine and ACC system tolerance stack ups.

For clearance measurement, sensor response should be on the order of 50kHz. This response will allow multiple clearance measurements per blade for large engines.

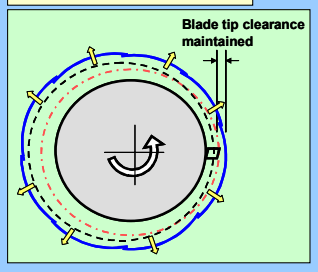
Any system that can affect the operation of the engine must be failsafe. For ACC systems, if adequate clearance is not maintained during any portion of engine operation, significant damage to shrouds and rotor components may result.

This could create an in-flight engine failure if closure is severe enough.

Sensor and actuator redundancy, biased clearance opening, and ACC system health monitoring are techniques that can be used to achieve failsafe operation.

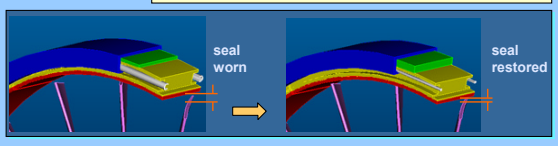
Approaches Under Investigation & Benefits

Fast rub-avoidance ACC system

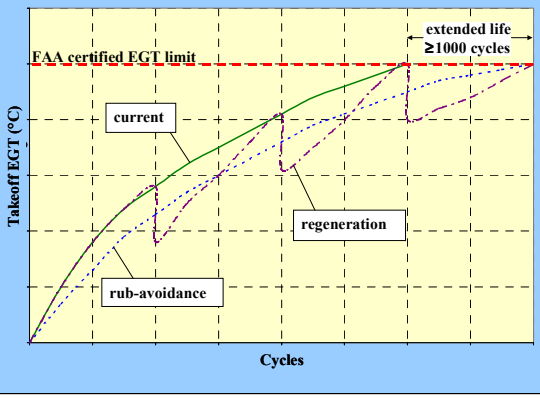


- Smart case avoids blade rubs
- 50x faster and provides 30-50% reduced clearances over current, slow-response case cooling systems

Regenerative seal material systems



- Specially engineered materials grow to restore clearance
- Potential for operating in HPT using passive or active control



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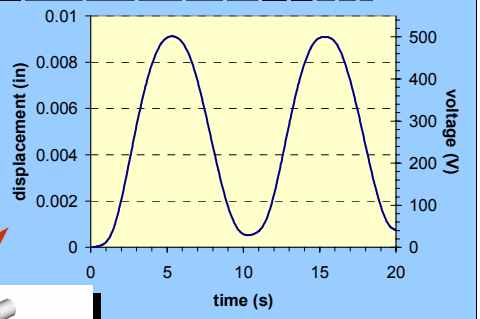
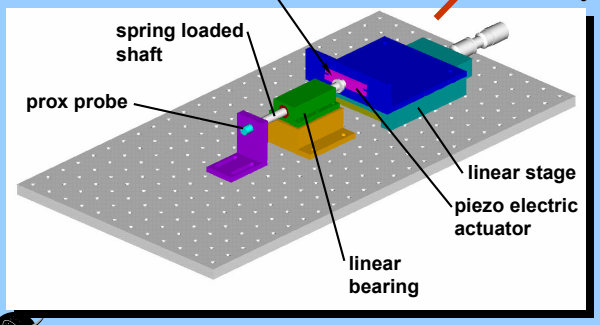
Smart Materials & Actuators: Piezoelectric

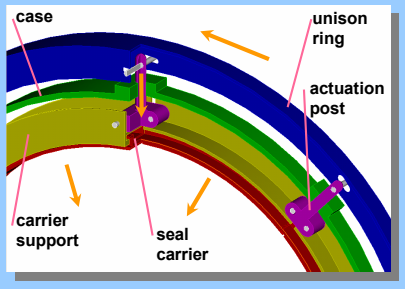


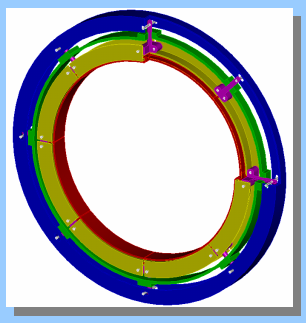


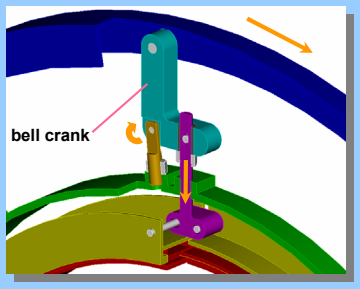
Active Mechanical Concepts: Structural Modeling

Analytical evaluation
- positional accuracy
- stiffness
- weight

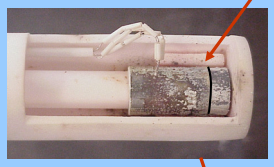
Experimental evaluation
- positional accuracy
- response
- distortion

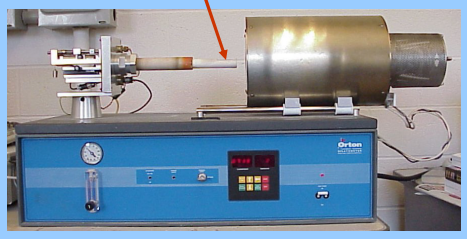


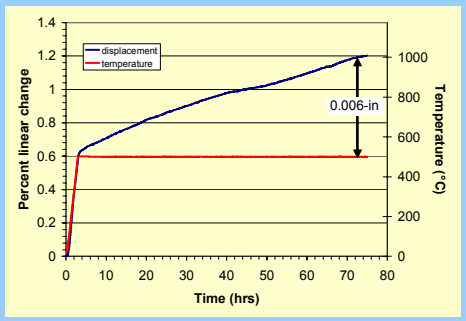




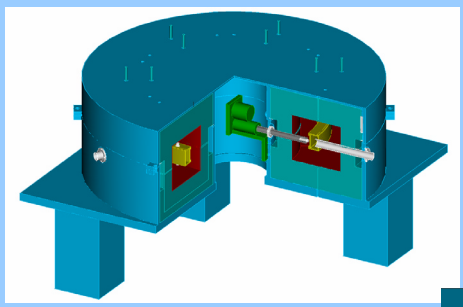
Regenerative Material Systems







Simulated Testing Environment

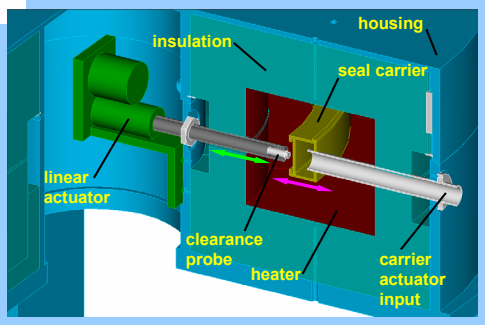


Purpose:

- Evaluate actuator concepts response and thermal effects in a non-rotational hot environment.
- Evaluate clearance sensor response and thermal effects in a non-rotational hot environment.
- Evaluate support structure effects on actuator (misalignment, concentricity, frictional effects).

Capabilities:

- Chamber temperatures up to 2200deg F.
- Simulate rotor centrifugal growth (0.01-in/s).
- Allows both heating and cooling of components.
- Sized for actual seal carrier hardware (20" diameter turbine).



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Summary

- HPT performance degradation begins early in a new or refurbished engine (usually in the first few flights of operation).
- This initial wear can account for losses in HTP performance of 1% or more.
- Improved tip clearances of 0.01-in can produce fuel and maintenance savings over hundreds of millions of dollars per year.
- Reduced fuel burn will also reduce aircraft emissions, which currently account for 13% of the total U.S. transportation sector emissions of CO_2.
- Presently, these savings are unrealized due to the slow response of current ACC systems and the lack of direct tip clearance measurement.

Summary- continued

- Improved ACC systems are required to meet aggressive operating cost, life, and fuel burn goals of next generation gas turbine engines.
- It is envisioned that advanced ACC systems would provide:
  1-1.5% reduction in SFC and extended service life (≥ 1000 cycles).
- Currently investigating two parallel approaches to meet these goals:
  1) Fast Response ACC
  2) Regenerative Tip Seal Systems