CONTROLS CONSIDERATIONS FOR TURBINE ACTIVE CLEARANCE CONTROL

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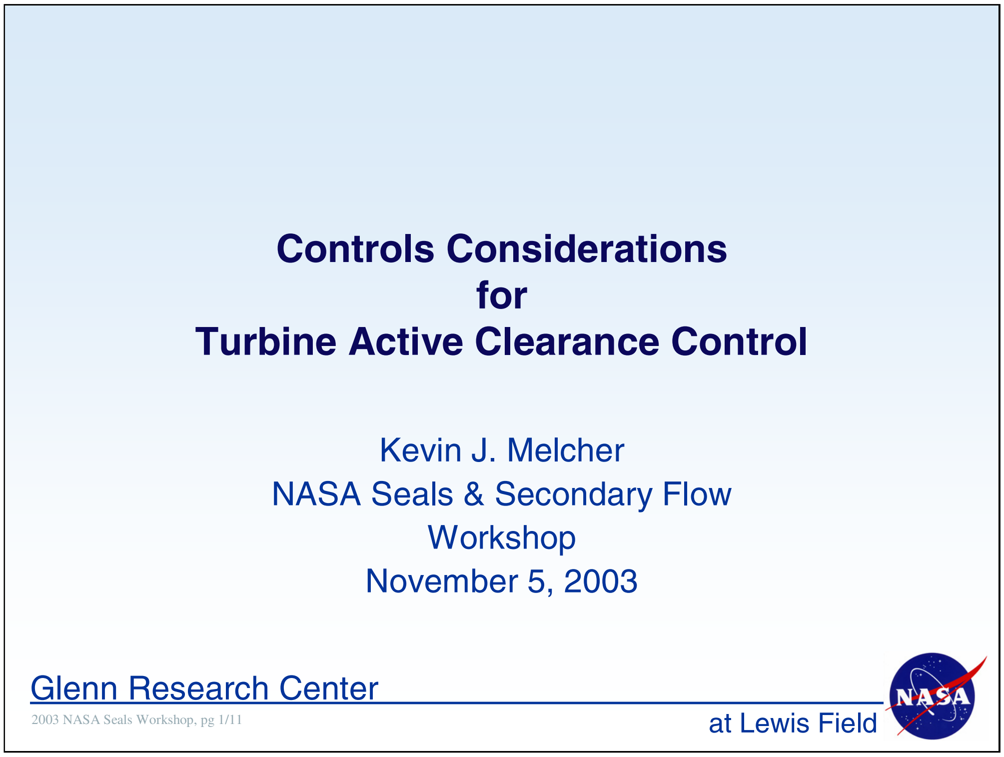
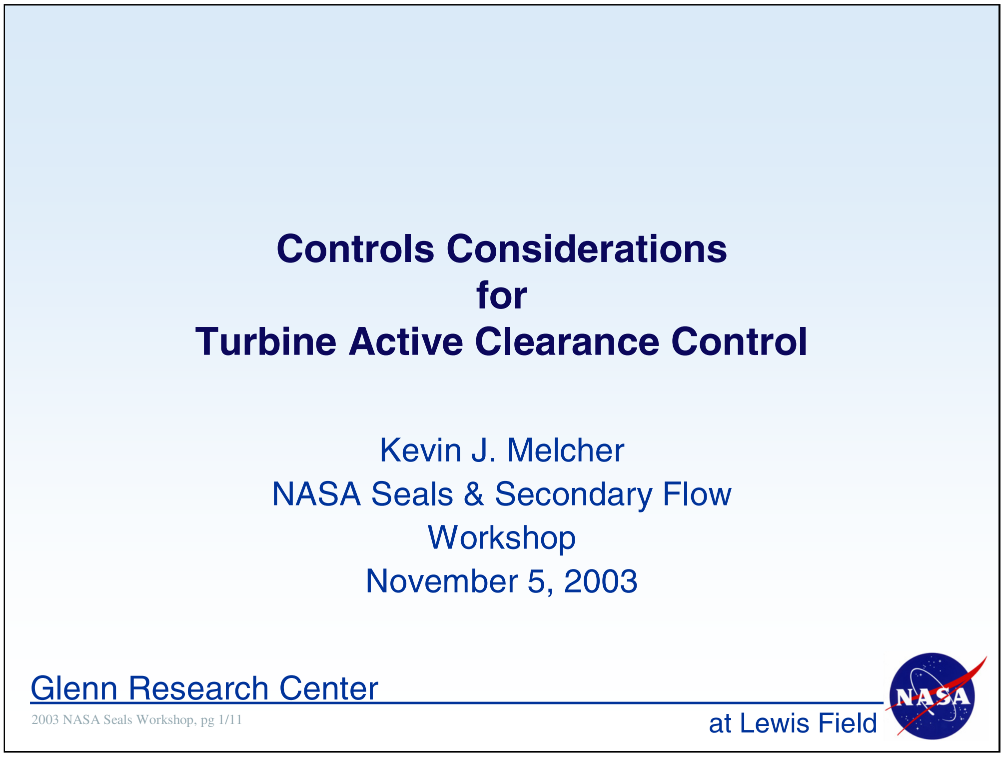


Controls Considerations for Turbine Active Clearance Control

Kevin J. Melcher
NASA Seals & Secondary Flow Workshop
November 5, 2003

Glenn Research Center
2003 NASA Seals Workshop, pg 1/11
at Lewis Field

This presentation discusses active control of turbine tip clearance from a control systems perspective. It is a subset of charts that were presented at the 2003 meeting of the International Society of Air Breathing Engines which was held August 31 through September 5 in Cleveland, Ohio. The associated reference paper is cited at the end of the presentation. The presentation describes active tip clearance control research being conducted by NASA to improve turbine engine systems. The target application for this effort is commercial aircraft engines. However, it is believed that the technologies developed as part of this research will benefit a broad spectrum of current and future turbomachinery. The first part of the presentation discusses the concept of tip clearance, problems associated with it, and the benefits of controlling it. It lays out a framework for implementing tip clearance controls that enables the implementation to progress from purely analytical to hardware-in-the-loop to fully experimental. And it briefly discusses how the technologies developed will be married to the previously described ACC Test Rig for hardware-in-the-loop demonstrations. The final portion of the presentation, describes one of the key technologies in some detail by presenting equations and results for a functional dynamic model of the tip clearance phenomena. As shown, the model exhibits many of the clearance dynamics found in commercial gas turbine engines. However, initial attempts to validate the model identified limitations that are being addressed to make the model more realistic.



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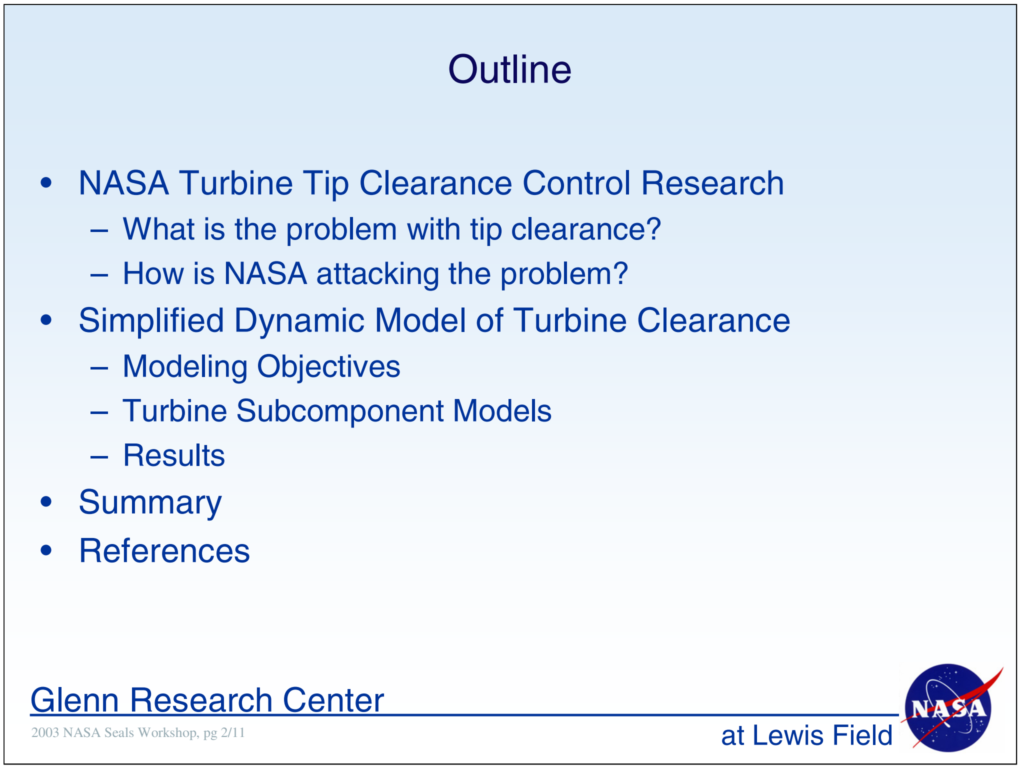
This presentation discusses active control of turbine tip clearance from a control systems perspective. It is a subset of charts that were presented at the 2003 meeting of the International Society of Air Breathing Engines which was held in Cleveland, Ohio. The associated reference paper is cited at the end of the presentation.

Kevin J. Melcher is a member of the Controls and Dynamics Technology Branch at NASA Glenn Research Center. He is currently the team lead for the development and implementation of controls software and hardware in support of a fast-acting turbine tip clearance control system. Other team members are: Mr. Jonathan DeCastro and Dr. Javier Kypuros. Mr. DeCasto works for QSS Group Inc. as a performance-based contractor to NASA Glenn Research Center. He is currently working on control law development and implementation for the project. Dr. Kypuros is an associate professor in the Department of Mechanical Engineering at the University of Texas-Pan American. He is working on developing first-principles-based models of the clearance dynamics.



Outline

- NASA Turbine Tip Clearance Control Research
  - What is the problem with tip clearance?
  - How is NASA attacking the problem?
- Simplified Dynamic Model of Turbine Clearance
  - Modeling Objectives
  - Turbine Subcomponent Models
  - Results
- Summary
- References

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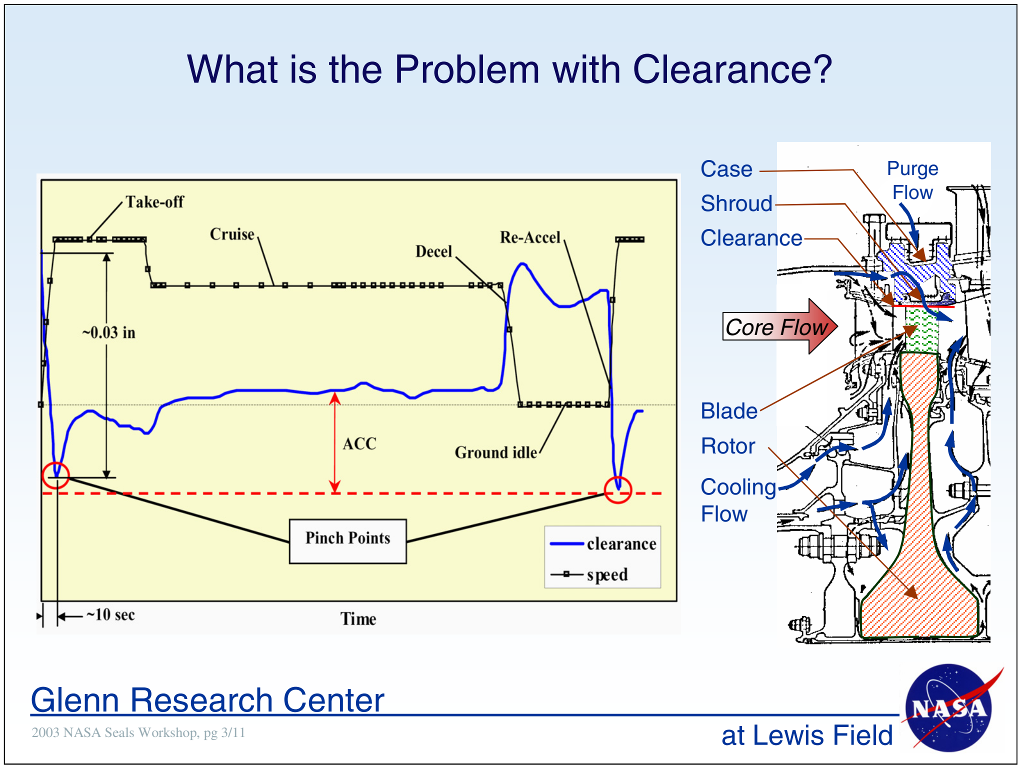
The presentation describes active tip clearance control research being conducted by NASA to improve turbine engine systems. The target application for this effort is commercial aircraft engines. However, it is believed that the technologies developed as part of this research will benefit a broad spectrum of current and future turbomachinery. The first part of the presentation discusses the concept of tip clearance, problems associated with it, and the benefits of controlling it. It lays out a framework for implementing tip clearance controls that enables the implementation to progress from purely analytical to hardware-in-the-loop to fully experimental. And it briefly discusses how the technologies developed will be married to the previously described ACC Test Rig for hardware-in-the-loop demonstrations. The final portion of the presentation, describes one of the key technologies in some detail by presenting equations and results for a functional dynamic model of the tip clearance phenomena. As shown, the model exhibits many of the clearance dynamics found in commercial gas turbine engines. However, initial attempts to validate the model identified limitations that are being addressed to make the model more realistic.

So, “What is the problem with tip clearance?”



What is the Problem with Clearance?

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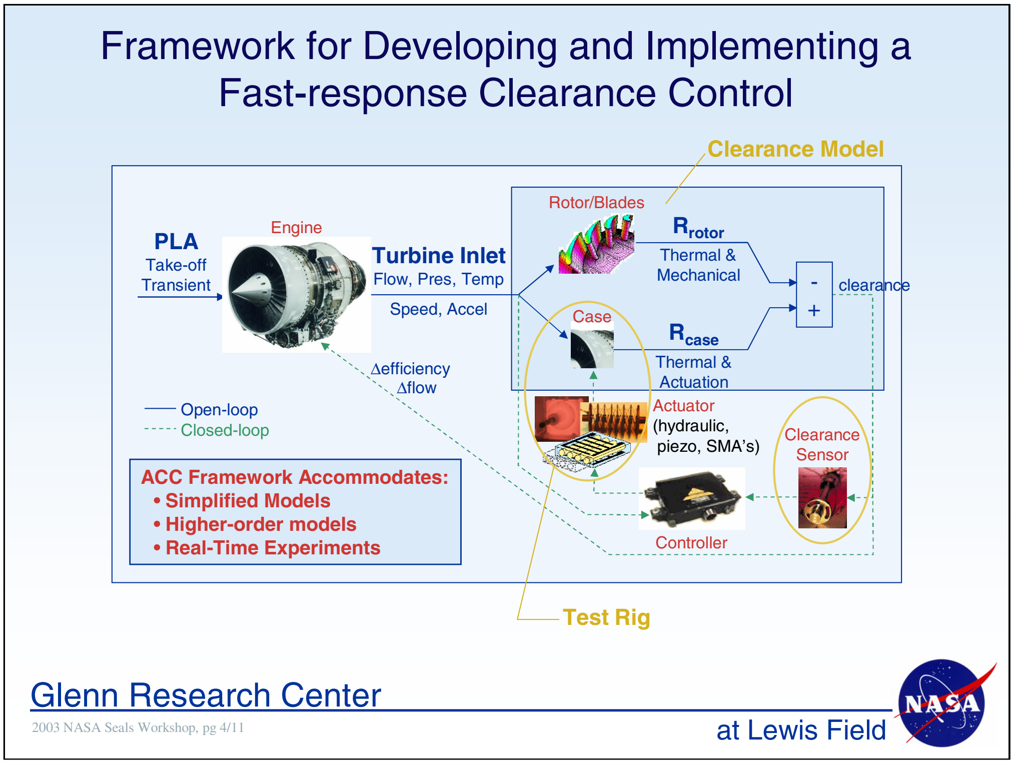
This slide illustrates changes in tip clearance during a notional mission. The clearance transient is the result of changing engine operating conditions and axisymmetric loads. The main operating regimes are takeoff, cruise, decel, and re-accel. The transient may be described as follows.

A cold engine is designed to have a large amount of turbine clearance. This clearance is rapidly diminished as engine speed is increased from ground idle to maximum power during takeoff. In fact, changes of over 30 mils are not uncommon during takeoff and reaccel events in large commercial engines. During this event, the rotor/blade assembly expands rapidly causing the rotating components to grow radially outward. The rotor grows primarily due to rotational forces, and the blade due to rapid heating. The case/shroud surrounding the rotating components also expands radially due to heating, but at a much slower rate due. The result is a minimum clearance condition known as a “pinch point”. The rotor and blade growth eventually reach steady conditions while the case/shroud continues to grow somewhat allowing the clearance to increase. As the engine approaches cruise conditions, the radial growth reaches thermal and mechanical equilibrium and the clearance remains relatively constant. However, throttle transients that can occur will also effect the clearance and must be accounted for when designing in the cold clearance in order to avoid rubbing the blades on the case. Of particular concern is the decl/re-accel transient that can generate pinch points with less clearance than takeoff.

Unfortunately, the additional clearance added to accommodate the pinch point results in excess clearance and reduced performance during what is typically the longest portion of the mission, cruise. In addition, EGT blooms tend to occur just after the pinch point. These blooms can use up EGT margin and cause the engine to be pulled for maintenance prematurely. The red-dashed line illustrates the objective of active clearance control – That is to maintain tight clearances throughout the flight decreasing fuel use and EGT bloom.

Active clearance control systems exist on some of the more advanced engine systems. However, state-of-the-art systems are based on a thermal approach that uses cooling air to manage the growth of the shroud, and hence the clearance. These systems tend to be slow due to the large thermal masses involved and so, cannot eliminate the pinch points. The systems do not use direct sensor measurements resulting in limited or no ability to handle unanticipated events during the flight. Our goal is to develop an advanced fast-acting clearance control system addresses the important concerns by using direct sensor feedback to maintain optimally minimal clearance throughout a given mission.



Framework for Developing and Implementing a Fast-response Clearance Control

ACC Framework Accommodates:
- **Simplified Models**
- **Higher-order models**
- **Real-Time Experiments**

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This slide shows the framework we have developed for implementing a fast-response clearance control system. In this frame work, the engine provides inputs to the turbine. The various parts of the turbine expand or contract in response to the changing engine conditions. A clearance sensor measures the changing gap between the case and the blades and provide that information to the controller which adjusts the actuator to maintain the desired clearance.

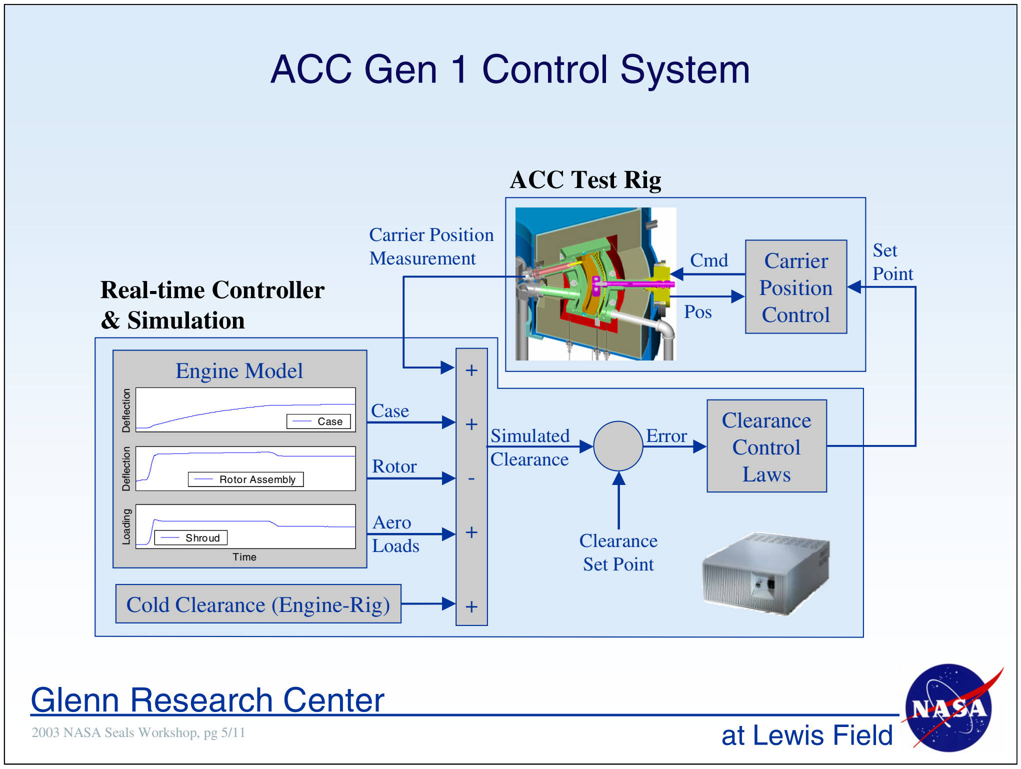
The intent of this framework is allow the individual elements to be represented by simplified models, higher-order models, and real-time experiments. And so, provide a path for moving the technology development from analytical simulation to hybrid analytical/experimental simulation to engine test. Elements of the framework are label in red. Critical technology gaps are highlighted in gold.

Bruce Steinetz from NASA Glenn's Mechanical Components Branch and Scott Lattime of QSS Group Inc. have developed a method for mechanically actuating the turbine shroud to control clearance. This is the ACC Test Rig identified in the previous presentation.

Clearance sensor technology is another technology gap. Current clearance sensors do not have the desired accuracy or reliability needed to meet strict turbine engine applications. Under the UEET Program, NASA is working with its industry partners to fill this gap.

Another critical technology gap is dynamic modeling of the clearance phenomenon. Dynamic models are critical elements in the design and development of advanced control systems. Existing models of the clearance phenomena are proprietary models that are not generally available and are not documented in the open literature. These range from high-fidelity finite element models to more simple empirical approximations.

The following slide shows how this framework will be used to tie the test rig, models, and real-time controller together for a hardware-in-the-loop demonstration of our ACC system.



ACC Gen 1 Control System

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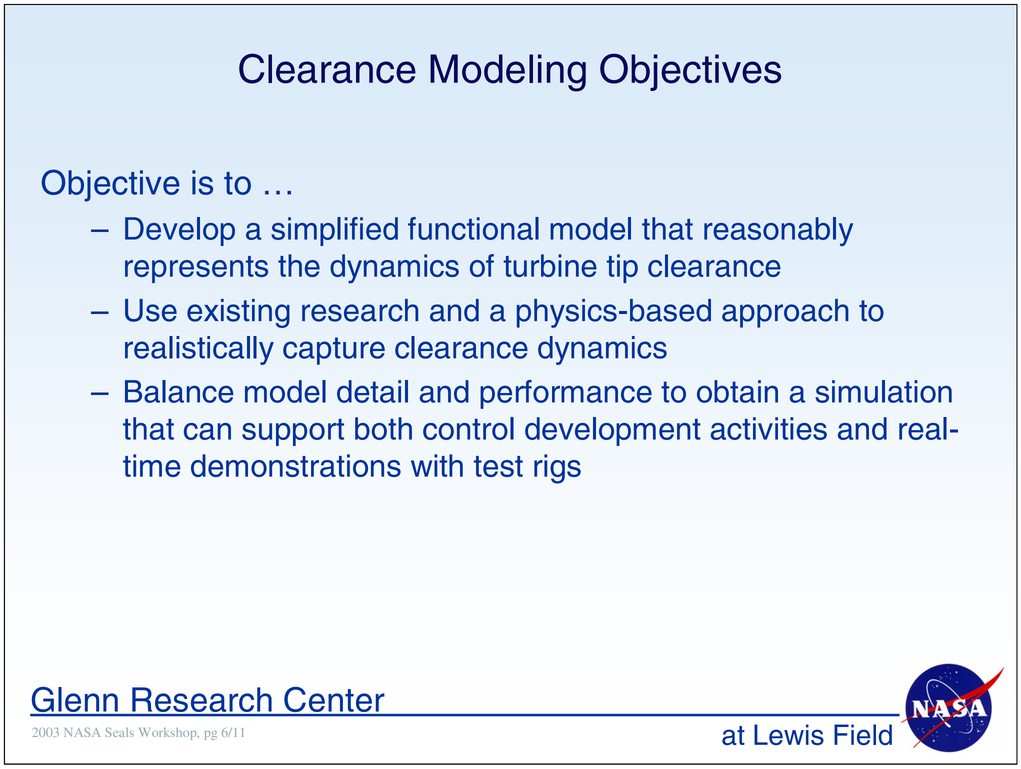
As envisioned in this slide, the research control system consists of two blocks – the real-time control and the test rig. The test rig includes the seal carrier, the clearance sensor, and the actuator with position control. The control block contains a dynamic model of pertinent time-varying engine parameters and the control laws.

For a given mission, the engine model calculates deflections for the case and rotor assembly due to thermal and mechanical loads. Thus simulating the rotational effects absent in the test rig. It also calculates the changing pressure loads that the actuator would be exposed to if it were in a real-engine. An ongoing trade study suggests that these loads have a larger effect on transient performance of the control system than the thermal or mechanical loads. They must be taken into account when designing the control laws. The cold build clearance of both the engine and the test rig must also be considered when computing the error between the clearance set point and the measured clearance. The control laws use the error to compute a new set point for the actuator.

The carrier position control adjusts the position of the seal carrier. The resulting change in gap is measured by the sensor, and fed back to the error closing the loop on clearance. The initial implementation will focus on controlling changes in axisymmetric clearance.



Clearance Modeling Objectives

Objective is to …

- Develop a simplified functional model that reasonably represents the dynamics of turbine tip clearance
- Use existing research and a physics-based approach to realistically capture clearance dynamics
- Balance model detail and performance to obtain a simulation that can support both control development activities and real-time demonstrations with test rigs

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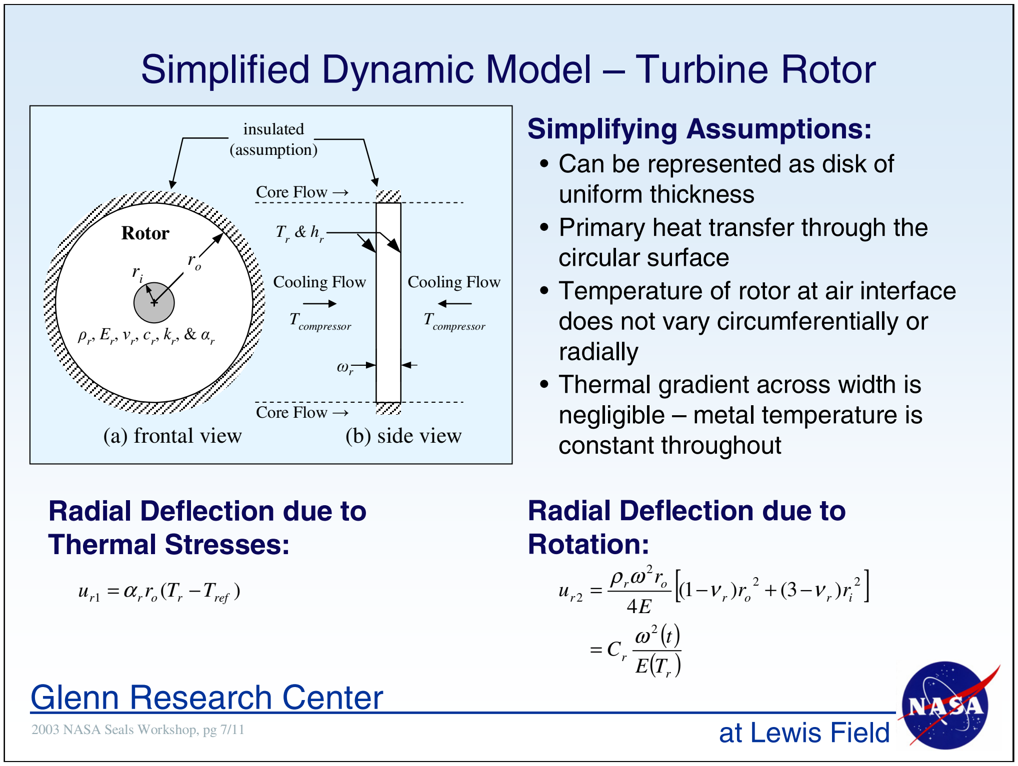
Objectives for the clearance modeling effort are shown on this slide. The primary goal is to create a model that reasonably reflects the steady state trends and dynamic response of turbine tip clearance to changes in engine operating condition. A model of this sort is all that is necessary to develop and demonstrate the control laws for proof-of-concept. In order to adequately model the system, a physics-based approach that captures the first-order effects is preferred. Modeling efforts will balance model detail with computational performance so that the model can be used to support both development of a realistic controller and real-time demonstration of the controller with the ACC test rig being developed at NASA Glenn.

The next slide will provide a brief overview of the approach used to develop the clearance model by examining the turbine rotor.



Simplified Dynamic Model – Turbine Rotor

(a) frontal view (b) side view

Simplifying Assumptions:

- Can be represented as disk of uniform thickness
- Primary heat transfer through the circular surface
- Temperature of rotor at air interface does not vary circumferentially or radially
- Thermal gradient across width is negligible – metal temperature is constant throughout

Radial Deflection due to Thermal Stresses:

$$u_{r1} = \alpha_r r_o (T_r - T_{ref})$$

Radial Deflection due to Rotation:

$$u_{r2} = \frac{\rho_r \omega^2 r_o}{4E}\left[(1-\nu_r){r_o}^2 + (3-\nu_r){r_i}^2\right]$$
$$= C_r \frac{\omega^2(t)}{E(T_r)}$$

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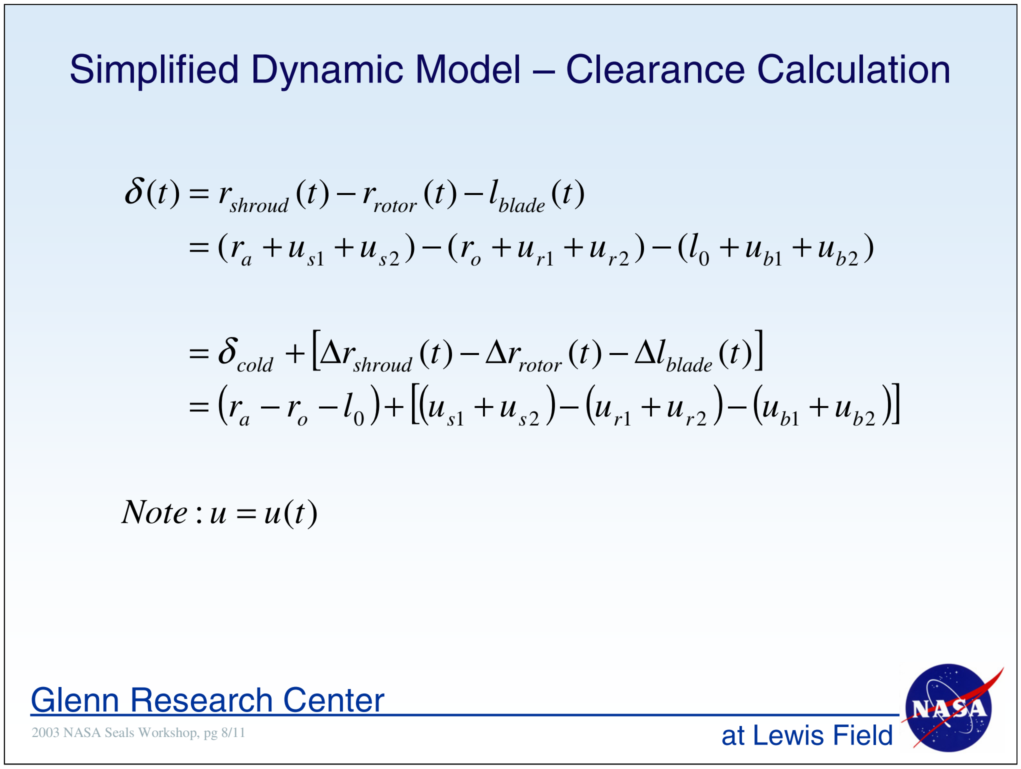
In general, the rotor (or disk) has a complex shape that requires rather complex finite element analysis to define the thermal and mechanical deformations. To simplify the analysis for controls purposes, a number of assumptions and constraints are implemented. First, the rotor is treated as a disk of uniform thickness simplifying the calculation of the deformation due to mechanical and thermal stresses. Second, since the circumferential tip are of the disk is relatively small compared to the radial cross section, heat transfer is assumed to occur primarily across the radial cross section. Third, the circular surface is assumed to be at the same temperature, that is , the temperature does not vary circumferentially or radially. Finally, the thermal gradient across the width is assumed negligible, potentially ignoring the thermal inertia of this large mass.

The rotor is stressed radially by thermal stresses due to changing engine temperatures and by centrifugal forces that change with engine speed. In this simple representation, the radial deflection due to thermal stresses is a function of the coefficient of thermal expansion (α_r,), the difference between the bulk metal temperature (T_r) and a reference temperature (T_{ref}), and the rotor radius (r_o) at the specified reference temperature. The total radial deflection of the rotor is thus a sum of the deflections due to temperature and rotation.

The shroud (tip seal) and the blade are modeled with similar simplifying assumptions. Similar to the rotor, the blade deforms radially due to both rotational and thermal loads. However, deformation of the shroud is caused by variations in temperature and pressure. Models for the blade and shroud are described in reference 1 at the end of this presentation.



Simplified Dynamic Model – Clearance Calculation

$$\begin{aligned}\delta(t) &= r_{shroud}(t) - r_{rotor}(t) - l_{blade}(t)\\ &= (r_a + u_{s1} + u_{s2}) - (r_o + u_{r1} + u_{r2}) - (l_0 + u_{b1} + u_{b2})\end{aligned}$$

$$\begin{aligned}&= \delta_{cold} + \left[\Delta r_{shroud}(t) - \Delta r_{rotor}(t) - \Delta l_{blade}(t)\right]\\ &= (r_a - r_o - l_0) + \left[(u_{s1} + u_{s2}) - (u_{r1} + u_{r2}) - (u_{b1} + u_{b2})\right]\end{aligned}$$

$$Note : u = u(t)$$

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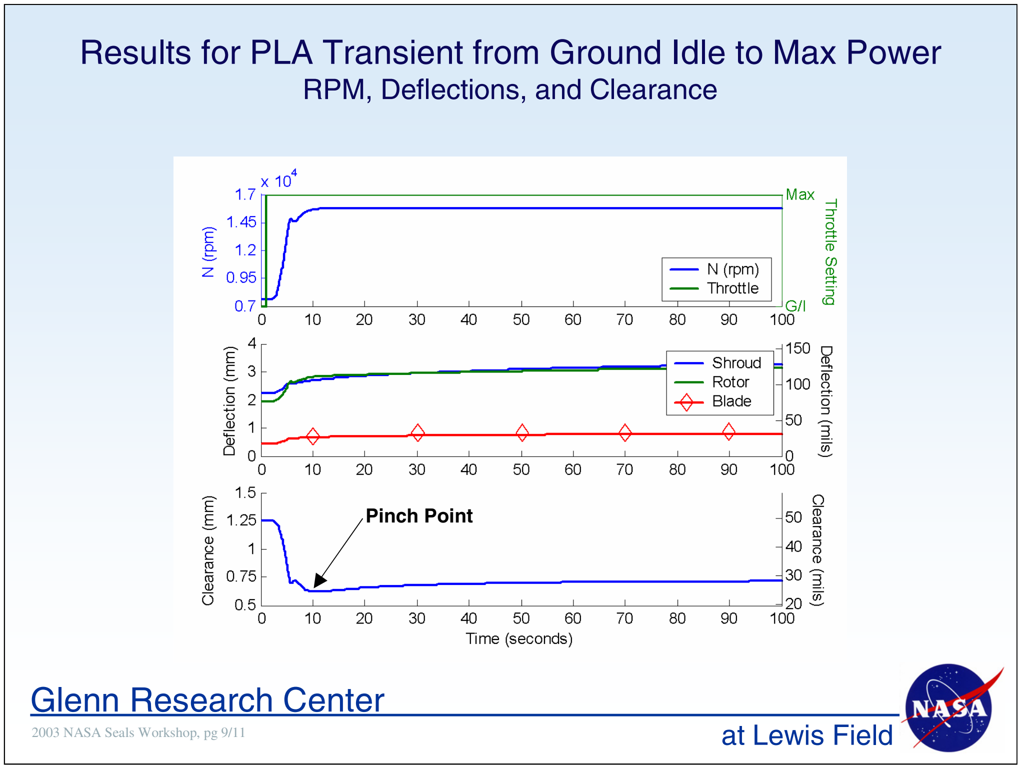
This slide shows simple algebraic equations used to obtain clearance from the computed deformation of the turbine subcomponents. In the first form, the radius of the rotor assembly (rotor radius + blade length) is subtracted from the radius of the shroud. In the second form, the deflection of the turbine subcomponents are summed to obtain the change in clearance relative to the constant cold-build clearance. This is summed with the cold-build clearance to obtain the clearance as a function of time.

The following slide shows results from a Matlab/Simulink implementation of the model just described.



Results for PLA Transient from Ground Idle to Max Power

RPM, Deflections, and Clearance

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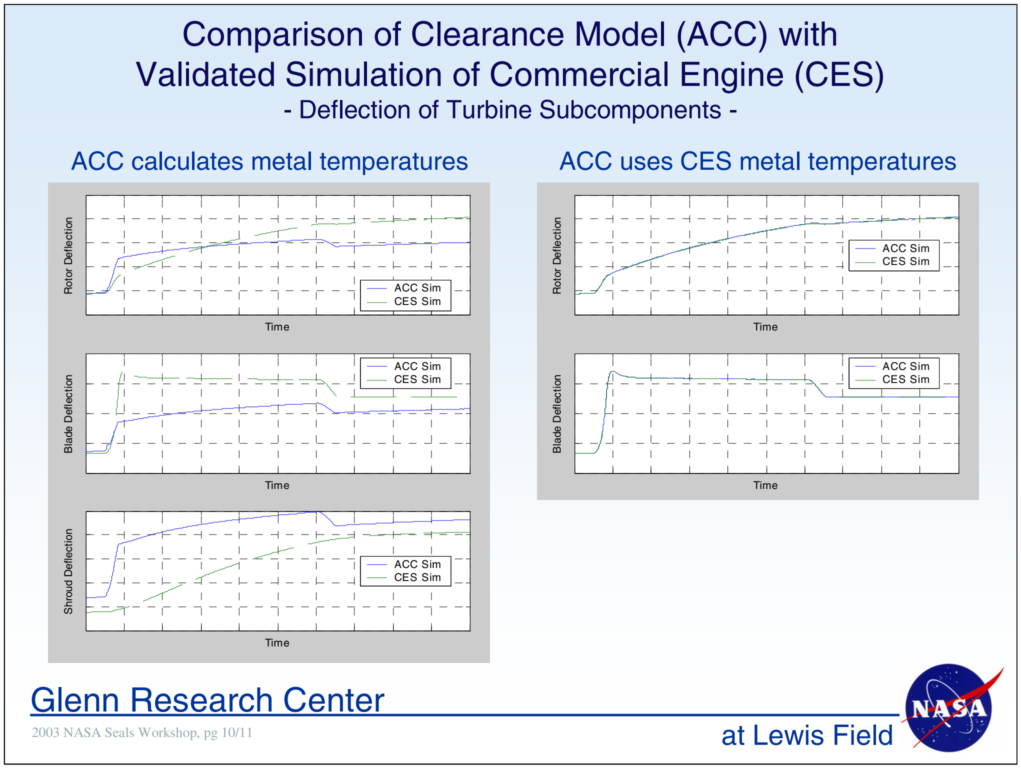
Shown here are preliminary results from the clearance model for a transient where the engine power command was stepped from ground idle conditions to maximum power. To generate the results, a dynamic model of a “fighter-like” aircraft engine was used to generate temperatures, pressures, and rotor speed as a function of time. The time-dependent engine operating conditions were used as input to the clearance model described in previous charts. Some of the expected trends are evident in these results.

The upper plot shows the step in power lever angle and the associated change in engine turbine speed. In addition to these inputs, compressor exit pressure & temperature, and turbine inlet pressure & temperature were used to define changes in engine operating condition during the transient.

The middle plot shows the simulated response of the shroud, rotor, and blades to the changing engine operating conditions. The blades elongate rather quickly due, primarily, to the large thermal transients. The rotor initially expands quickly in the radial direction as the rotational loads dominate the response. At about 5 seconds, the growth slows as the rotational loads reach steady state and the thermal stresses dominate the rate of deformation. The shroud response is initially dictated by the pressure loads which peak at about 5 seconds. After that, the large thermal inertia of the shroud provides continued sustained growth due to thermal stresses. The changing growth rates of the shroud and rotor+blades produces the pinch point shown on the lower plot.

Ongoing efforts are focused on validating and improving the model. The following slide highlights some of the work that still needs to be done by comparing the NASA/UTPA model with a validated empirical model.



Comparison of Clearance Model (ACC) with Validated Simulation of Commercial Engine (CES)

- Deflection of Turbine Subcomponents -

ACC calculates metal temperatures

ACC uses CES metal temperatures

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Here, output from the NASA/UTPA clearance model (ACC Sim) is compared with that from the simulation of a large commercial engine (CES). Comparisons are made for two different cases. The results on the left show the radial deflection of the turbine subcomponents as a function of time for both the CES and ACC simulations. For this case, bulk metal temperatures for the ACC Sim were computed by heat transfer equations derived for the model. Results on the right are for the case where bulk metal temperatures computed by the CES Sim were used by the ACC Sim to compute thermal deformations. The fact that plots on the left are mismatched and those on the right are not points to un-modeled temperature dynamics in the ACC Sim as the source of the mismatch. In fact, due to the simplifying assumptions used in the ACC Sim, the thermal inertia of the individual subcomponents are un-modeled. The result is that deflections computed by the ACC simulation are faster than those for the baseline CES simulation. Also un-modeled is the heat transfer to/from the cooling flow that occurs between the compressor and the turbine. This is likely the cause of the steady-state errors. Ongoing efforts by NASA and the University of Texas Pan American are focused on resolving these issues to improve the simulation.

Summary

- Fast-response active clearance control identified as a critical technology for improving performance and increasing engine on-wing life.
- Identified gap technologies required to support active clearance control
  - clearance modeling, actuation, and sensing
- Defined framework for developing, implementing, and maturing critical ACC technologies
- Working toward integrating critical ACC technologies in test rig for proof-of-concept demonstration
- Developed functional model of a clearance dynamics that:
  - Captures many of the essential dynamics – good start
  - Has simplified form that meets requirements for real-time implementation
  - With modifications (identified) can provide realistic model for control design and implementation

References

1. Melcher, Kevin J.; and Kypuros, Javier A.: “Toward A Fast-response Active Turbine Tip Clearance Control”, ISABE2003-1102, 16th International Symposium on Air-breathing Engines, August 31-September 1, 2003.
2. Kypuros, Javier A.; and Melcher, Kevin J.: “A Reduced Model for Prediction of Thermal and Rotational Effects on Turbine Tip Clearance”, NASA TM-2003-212226, March 2003.