

**PROGRESS ON SHAPE MEMORY ALLOY ACTUATOR  
DEVELOPMENT FOR ACTIVE CLEARANCE CONTROL**

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Actuator Development for Active Clearance  
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*NASA Glenn Research Center, Cleveland, OH*

*NASA Seal/Secondary Air System Workshop*

*November 8-9, 2005*

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Results of a numerical analysis evaluating the feasibility of high-temperature shape memory alloys (HTSMA) for active clearance control actuation in the high-pressure turbine section of a modern turbofan engine has been conducted. The prototype actuator concept considered here consists of parallel HTSMA wires attached to the shroud that is located on the exterior of the turbine case. A transient model of an HTSMA actuator was used to evaluate active clearance control at various operating points in a test bed aircraft engine simulation. For the engine under consideration, each actuator must be designed to counteract loads from 380 to 2000 lbf and displace at least 0.033 in. Design results show that an actuator comprised of 10 wires 2 in. in length is adequate for control at critical engine operating points and still exhibit acceptable failsafe operability and cycle life. A proportional-integral-derivative (PID) controller with integrator windup protection was implemented to control clearance amidst engine transients during a normal mission. Simulation results show that the control system exhibits minimal variability in clearance control performance across the operating envelope. The final actuator design is sufficiently small to fit within the limited space outside the high-pressure turbine case and is shown to consume only small amounts of bleed air to adequately regulate temperature.

## **Presentation Outline**

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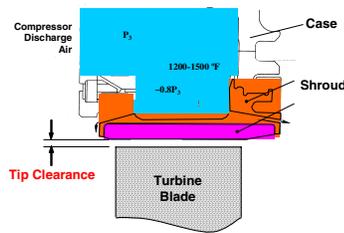
- **Objective and scope for active clearance control**
- **Survey of candidate actuators**
- **Design of a high-temperature shape memory alloy actuator**
- **Analytical evaluation of active clearance control system**
- **Concluding remarks and future work**

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## High-Pressure Turbine (HPT) Clearance



**Tightening HPT clearance leads to improved specific fuel consumption (SFC) and exhaust gas temperature (EGT) margins**

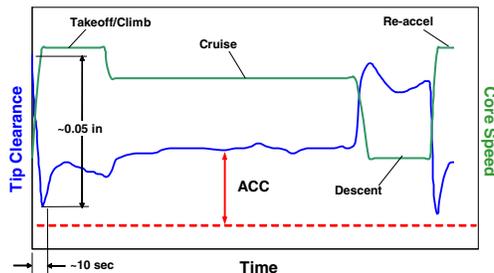
Improved SFC → greater efficiency & lower NOx  
Improved EGT → longer time-on-wing

**Mitigating EGT overshoot requires controlling clearance during takeoff**

**Minimizing SFC requires control at cruise amidst planned and unplanned transient events**

**SOA thermal case cooling methods unable to achieve necessary response**

**Need a precise, faster-response (1 Hz) actuator**



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The gap between the turbine blades and shroud can cause severe leakage of hot combustor gas past the HPT blades. Leakage of this energetic flow can lead to penalties in specific fuel consumption (SFC) and exhaust gas temperature (EGT). If the clearance can somehow be reduced, significant increases in engine efficiencies and substantially improved engine longevity can be realized. Specifically, 10 mils reduction in clearance roughly translates into 1% SFC reduction and 10 deg. C EGT reduction.

As shown by the above plot, clearance varies widely throughout a normal mission. Because of this, engine manufacturers incorporate a cold-build clearance to avoid any detrimental rubs between the turbine shroud and the blades. During takeoff, for example, the blades expand rapidly due to centripetal loads caused by rotor acceleration, creating a pinch point at maximum power. As the slower thermal effects begin to dominate, the clearance again opens up at climb and cruise.

In modern engines, the larger gap at steady-state is only partially alleviated by thermal active clearance control systems, which rely upon preferentially blowing cool fan air on the HPT flange depending upon the operating conditions. These systems suffer from very slow response times, and therefore cannot operate with tight clearances because the possibility exists that re-accel or re-burst events can still cause rubs.

Therefore, it is extremely important to develop an actuation system with a response time at least as fast as the clearance transients it is likely to encounter. In order to control clearance to much lower levels, about 0.005 inches (indicated by the red dashed line), the actuator must be capable of ultra-precise positioning.

## Clearance Control Actuator Candidates

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### Active Clearance Control System

**Goal:** Control clearance to within 5.0 mils without blade-to-shroud incursions

- Use segmented shroud ring: one actuator per “floating” shroud segment
- Measure clearance gap for feedback (25-MHz microwave probes)

### Actuators

**Near term solution:** *conventional servo-hydraulics*

- Currently in the works

**Longer term solution:** *smart materials*

- Using “smart material” actuators facilitates thrust toward an all-electric engine

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The concept that the active clearance control group is investigating uses a set of actuators that are mounted circumferentially around the turbine, with each one attached to a “floating” shroud segment. Each actuator maintains closed-loop control of clearance based on instantaneous clearance measurements at the shroud by high-bandwidth clearance probes. These independently-actuated shroud segments collectively form the annular shroud ring assembly. Such a concept places high demands on an actuator, as it must not only position precisely to within one thousandth of an inch of the desired set-point, but must do so amidst widely varying pressure loads acting on the ring.

There are two solutions to the active clearance control problem. The first is centered around utilizing established *conventional* actuator technology, which primarily encompasses servo-hydraulic actuators. These actuators are presently used in engine applications such as variable stator vanes and variable area nozzles. They therefore offer the lowest risk for an active clearance control solution. We are investigating this solution presently, as assembly of the servo-hydraulics is underway for evaluation in the NASA tip clearance test rig.

A second solution exists in the realm of *smart material* actuator technology...

## Survey of Actuator Candidates

Actuator	Energy density	Approx. system weight	Rate capability	Max. temperature	Power consump.
Shape Memory Alloy	500 J/kg	0.9 lb	~ 0.1 in/sec	930 °F	Low
Piezoceramics (PZT)	10 J/kg	43 lb	200 in/sec	400 °F	Moderate
Servohydraulics	40 J/kg	58 lb	0.5 in/sec	600 °F	High



### **High-temperature shape memory alloys (HTSMA)**

have high energy densities & demonstrate excellent robustness at elevated temperatures seen in HPT

- Recently developed at GRC
- Composition:  $Ni_{30}Pt_{20}Ti_{50}$

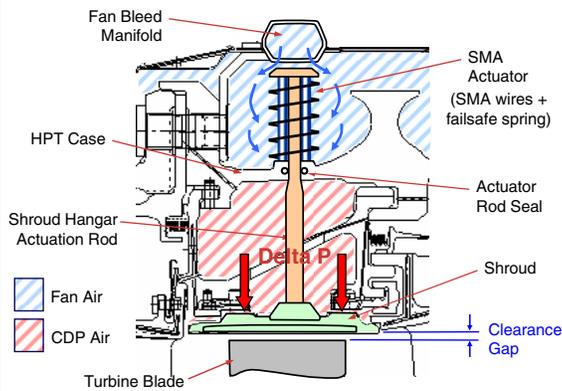
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Based on our preliminary survey of clearance control actuators, shape memory alloy actuators are a strong candidate for clearance control because they offer close to an order of magnitude higher energy density than conventional and piezoelectric actuators. This higher energy density translates into a commensurate decrease in actuator weight or decrease in power consumption, which is extremely advantageous for implementation.

These actuators are generally regarded as higher-risk technologies, but if the technology development is pursued immediately, we can realize the benefits of these actuators as the technology matures. Researchers at Glenn are developing highly robust smart materials just for this purpose. The recently-developed high-temperature shape memory alloy (HTSMA) is capable of operating indefinitely close to the highest temperatures seen in the HPT exterior (900 - 1000 deg. C).

## SMA Clearance Control Actuator Concept



### SMA actuator consists of wire bundle

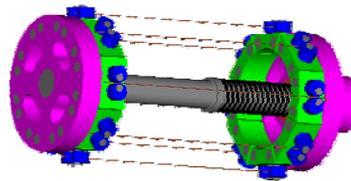
- Facilitates heat transfer
- Provides failure redundancy
- Lowers fabrication costs

### Outward-biased spring imparts wire tension and restores clearance gap upon deactivation

- Shroud pressure forces always act inward toward the blades

### Bleed air from the engine's fan used to cool actuator below transition

**Intent of present work is to design and model actuator concept to determine feasibility in a simulated HPT environment**



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By virtue of the fact that these alloys can be manufactured into a number of different configurations, we have the freedom to optimize the actuator design for clearance control. The actuator concept shown above consists of several SMA wires attached to the exterior of the HPT case, where more “benign” temperatures are expected (<900 deg. C), and attached at the other end to a push rod that moves the shroud toward and away from the blades. When the SMA wires are heated up, the material constricts, causing the shroud to move inward toward the blades. When cooled, the wires expand, causing motion away from the blades. The delta P across the shroud always acts toward the blades, so a biasing spring must be incorporated in the design in order to keep the SMA wires in tension and furthermore guaranteeing a failsafe upon wire failure.

An important feature of this concept, which is a testament to the alloy itself, is that it may be possible to completely operate this material via modulated fan bleed air, thereby eliminating the need to draw power from the engine’s power bus. Note that this is exactly how SOA thermal clearance control systems operate, a therefore requiring little to no modification to the bus. The major barrier for implementing many smart material actuator concepts is in the fact that they require large power draws to operate, however it will be shown that HTSMAs do not suffer from this limitation.

The goal of our present work was to perform a system-level feasibility study of such actuators for active clearance control. Shape memory alloys have a large amount of hysteresis as well as moderate response times, due to a dependence on thermal activation. This can potentially thwart rub-free clearance control.

## HTSMA Actuator Feasibility Study

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### Assessment will determine:

- Whether precise clearance control can be established with hysteresis and response time limitations
- How much fan air bleed is necessary to retain performance specs
- What control law is necessary for precise actuator positioning

### A detailed model of HTSMA actuator used to:

- Optimally design clearance control actuator
- Perform closed-loop evaluation in “test bed” engine simulation

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The feasibility study itself was concerned with the question of whether or not the actuator can operate in a simulated HPT environment, knowing the material properties and having a representative model of the material. What would be gained by such a study is an understanding of: 1) how well the actuator can position a shroud segment amidst hysteresis and heat transfer time lags; 2) how much power draw, in this case bleed air, is necessary for clearance control; and 3) what control laws are required to compensate for nonlinearities and maintain a constant clearance gap through control of the shroud position.

## Optimal Actuator Design

### Design Requirements – Candidate Engine

Stroke capability	> 0.05 in
Rate capability	> 0.01 in/sec
Force capability	> 2200 lbf
Number of actuators	20
Actuator headroom	2 in
Temperature inside case	> 1300 °F
Temperature outside case	900 °F

Actuator must be lightweight

Actuator must fit within available limited headroom

Installation on exterior of high-temp/ high-pressure case

### Optimization Results

Length	2.0 in
Peak Strain	2.5 %
HTSMA Area	0.0664 in <sup>2</sup>
Cold Clearance	0.090 in
Preload Force	8040 lbf
Spring Constant	16080 lbf/in

### Design optimization

9 steady-state operating points, excluding ground idle

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The desired requirements are as follows. The actuator stroke should be large enough to cover the entire operating envelope, and therefore be on the order of 0.05 inches. The maximum rate-of-change should be about 0.01 inches, which is based upon the rates seen during takeoff. The maximum force that the actuator must be designed to withstand is 2200 lbf, which occurs at the max power condition. This force plays a large role in how the failsafe spring is designed. Of course, we must also obey spatial and environmental constraints. Given that the actuator must be placed outside of the case due to temperature considerations, we are limited to a radial headroom of 2 inches.

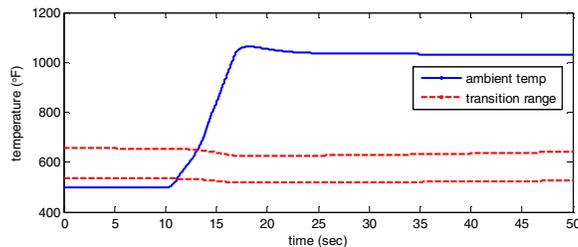
To achieve a feasible design, the optimization consisted of nine operating points, representative of the majority of the flight envelope. Ground idle was not included in the optimization because this would require a longer (by about 20%) actuator to accommodate this operating point. Active clearance control benefits are much less significant at that point, so this is a reasonable course of action. The optimal design results are as shown in the table. Of further note is that the peak strain is limited to less than 2.5% to avoid life cycle deterioration of the material.

## Active Clearance Control Evaluation

### PID controller with anti-windup protection developed for simulation

#### Resistive heating was used for actuation

- Slow heating times → slight degradation in performance
- Slow cooling times → *blade rubs*



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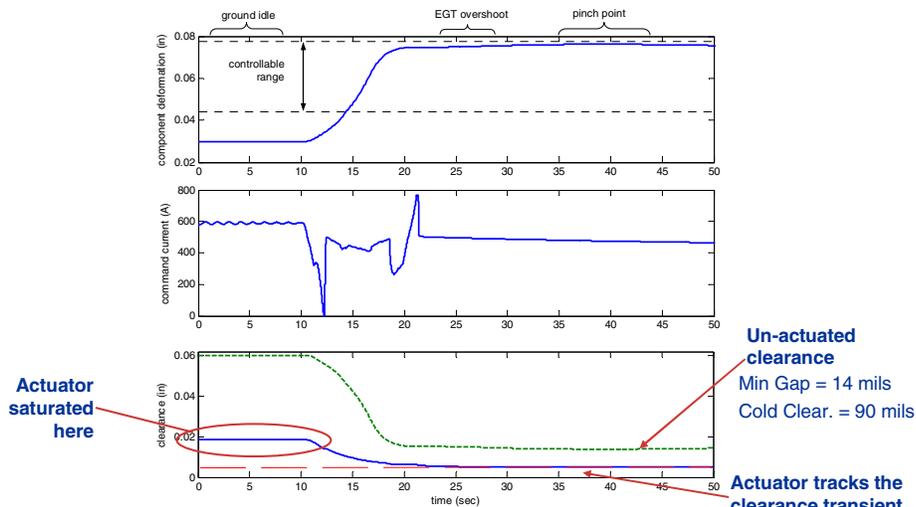


Now that a static design is complete, transient evaluation of the actuator can be conducted. For the subsequent experiments, a simple proportional-integral-derivative (PID) controller was designed with anti-windup protection to avoid problems when saturation limits are encountered. Being that the controller is linear, it cannot directly compensate for the highly nonlinear hysteresis effects. As stated earlier, one of the goals of the evaluation is to assess the efficacy of this approach.

Because transition temperatures of the present HTSMA are higher than the ambient temperature at low-power operating conditions, resistive heating was employed as the actuation mechanism. Because of the actuator configuration, the actuator's cooling time is much more important than heating time, because slow cooling times can result in blade rubs, while slow heating times do not. It is therefore of utmost importance to avoid prohibitively slow cooling times. We can still obtain an assessment of this cooling time, as this heat transfer mechanism is the same whether active cooling or resistive heating is employed.

## ACC Amidst a Takeoff Transient

**Baseline:** Bleed air = 100% SOA; 10 wires - 0.092-in dia. (to satisfy 0.0664-in<sup>2</sup> design area)



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For the baseline design case, fan bleed air was set to a value identical to SOA thermal clearance control, and the wire count was set to 10, with a wire diameter of 0.092 inches. The higher the wire count, the lower the diameter, allowing faster heat transfer. If response time becomes problematic, it may be possible to explore higher wire counts.

The plot shows the actuator's response during a takeoff transient. The top plot shows the sum total of HPT component deformation (shroud, blades, case), the middle plot shows the command current, and the bottom plot shows the HPT clearance. Because of the exclusion of ground idle, the actuator is saturated at its full excursion toward the blades until takeoff occurs. At this point, the clearance quickly converges to the 5-mil set point within a few seconds, as shown by the blue line.

During failsafe operation, the clearance follows a profile similar to the green line, with the larger conservative clearances restored over the course of the transient. Of note is that the failsafe spring correctly prevents the un-actuated shroud from causing blade rubs.

## Air Consumption Assessment

### Effect of fan air bleed quantities on control performance

#### 10 wires – 0.092-inch diameter

PID gains re-tuned for each test run

Bleed air (% of SOA)	Min. clearance (in)	Set point convergence (sec)	Current at $A_1$ (A)
100%	5.0	21.8	562
20%	5.0	22.0	407
5%	1.1	35.2	322
1%	-18.4	85	268

**Wire count of 10 allows about 80% reduction in bleed air vs. SOA**

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By virtue of the fact that the HTSMA's transition temperatures reside just below the ambient temperatures at high power, only small portions of fan bleed air are necessary to maintain wire temperature below transition, in order to preserve full actuator authority. It is because of this that only small bleed air quantities are needed, as shown in the above table. For the 10-wire baseline case, only 20% of the present bleed air is needed in order to provide full authority without blade rubs. If the number of wires is increased to 30, which allows the diameter to be reduced to 0.053 inches, the required air is only 5%. Both scenarios are substantial improvements over state-of-the-art.

For reference, employment of resistive heating requires approximately 0.4 kW for the 100% bleed air case (0.66V at 562A). It important to note here that the designer can trade current draw for voltage by modification of the electrical configuration, for example, by placing wires in parallel instead of in series.

## Step Response Evaluation

### Response to step changes in clearance at key engine operating points – Baseline Case

CES operating point	Martensite fraction (%)	Settling time (sec)	
		+0.005 in	-0.005 in
Pinch Point	95.4	3.14	3.19
Climb	37.3	3.03	3.26
Cruise	20.5	3.01	3.27
Descent	0.9	3.03	3.38

*Away from blades      Toward blades*

**PID controller demonstrates uniform response across the operating envelope despite nonlinearities**

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Evaluating the step responses at various operating conditions revealed that the system's response was uniform across the operating envelope. The results provide a strong indication that the linear PID controller is able to successfully control of the HTSMA with the nonlinear actuator, particularly amidst the prominent hysteresis.

## Research Contributions

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### **Developed shape memory alloy-based active clearance control actuator**

- Based on GRC-developed robust hi-temp shape memory alloy (HTSMA)
- Very high energy density (actuation energy-to-weight ratio)
- Capable of fast clearance changes during fast transients, i.e. takeoff
- Failsafe design avoiding blade rubs due to HTSMA failure

### **Demonstrated Active Clearance Control Analytically**

- Demonstrated control of clearance over critical portions of flight envelope
- Developed modified PID control law that meets clearance control objectives in the presence of actuator nonlinearities (delays, hysteresis, and saturation)

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In summary, a shape memory alloy actuator has been designed analytically for active clearance control. The actuator used here consists of HTSMA material recently developed at GRC exhibiting high robustness at the elevated temperatures of the HPT. Active clearance control simulations confirm that the wire-based actuator exhibits very high energy density, requiring much less air than SOA thermal control systems, and provides the heat transfer rate necessary for fast actuation during transients such as takeoff. Additionally, the design is failsafe to blade rub events. Use of a linear PID controller showed that tight control of clearance can be maintained throughout the operating envelope, to within 1 mil of the set point, given that the actuator is prone to slow response and highly nonlinear behavior in open loop.

## Future Work

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### **Develop application-specific HTSMA**

- Design for active cooling via engine bleed air to control position (eliminating draw from power bus)

### **Perform studies on a simplified single/multi-wire actuator**

### **Detailed actuator design, fabrication, & bench test**

### **Closed-loop demonstration of tip clearance control system in NASA Static Tip Clearance Test Rig**

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For future work, it would be desirable to iterate upon HTSMA composition to obtain transition temperatures just below the ambient temperature of the HPT. The tailored HTSMA would allow for full authority control over the engine's operating envelope using modulated fan air bleed.

Further studies on a single-wire and multi-wire actuator to confirm results from this study are also warranted. Such foundational work would permit a detailed actuator design to be pursued, with eventual testing in the NASA tip clearance test rig.

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**Thanks for listening.**

**Questions?**

***Reference:***

**J. DeCastro, K. Melcher, & R. Noebe:** “System-Level Design of a Shape Memory Alloy Actuator for Active Clearance Control in the High-Pressure Turbine,” *Proceedings of the 41<sup>st</sup> AIAA Joint Propulsion Conference*, AIAA paper AIAA-2005-3988.

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