Electro-Thermally Active Seal for Fast Response Tip Clearance Control

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Abstract

The research explores feasibility of electro-thermally activated variable geometry truss as a means of turbine blade tip clearance modulation. A sparsely populated truss actuation mechanism demonstrates an actuation response time one order of magnitude faster than the current shroud contraction approach. It is capable of generating thermal expansion by resistive heating and air cooling to meet the requirement of clearance control. When implemented, it can optimize engine performance in all the flight segments by actively maintaining gas leakage in the hot section to a minimum.

The conceptual design of the control device at a system level is presented along with detailed analysis of the core truss structure. The work has demonstrated analytically that such a modulation is of engineering feasibility kinematically, structurally and thermodynamically. The experimental work reveals the major challenges for implementation in controllability with direct heating.

Introduction

Actively maintaining a tighter blade tip clearance in aircraft turbine engine reduces hot gas leak and offers promise of significant benefits in engine performance and operation economy such as fuel burn, pollution, life cycle and service life. On a large transport engine, a tip clearance modulation of approximately 0.02 to 0.05 inch would prevent unnecessary gas path leakage during cruise and significantly improve overall engine efficiency. Research has showed that a reduction of 0.01-inch in turbine blade tip clearance achieves about 1 percent improvement in specific fuel consumption (SFC) and approximately a 10ºC reduction in exhaust gas temperature (EGT) [1, 2].

Modern large transport engines primarily employ an Active Case Cooling (ACC) system for real-time modulation of turbine clearances [3]. The thermal expansion and contraction of the case takes something on the order of a minute to reach full modulation of clearances because of its enormous thermal mass. Due to the slow response, the steady-state clearance is mostly set to "more open" with respect to the possibility of snap throttle transients. The result is that the engine is not operating as efficiently as possible during long, steady-state flight segments, which dominates the overall commercial transport flight profile. In addition, the current engine case cooling system makes it difficult for asymmetric clearance control, and heating/cooling air management is cumbersome.

The primary reason why the material thermal expansion has been, and still is, the backbone concept for the turbine tip clearance control is the harsh and hostile environment surrounding the turbine blade. Very few approaches having moving parts are considered viable for active tip clearance control. The temperature between gas turbine engine case and its shrouds typically exceeds 1200°F, and the actuation mechanism must move the shrouds against large pressure differential (100~200 PSI) to open or close the clearance in a short notice. Many research efforts have investigated active clearance modulation using axial or radial hydraulic and pneumatic actuators as primary movers located outside of the hot section. More recently, research shifts to solid state induced strain materials as the actuation muscles, such as shape memory alloy (SMA), piezoelectrics and magnetostriction. While most of them have been proven impractical in terms of temperature compatibility, response time, integration into shroud head room, recent work by NASA has demonstrated that SMA in wire form is by far the most promising clearance modulation muscle for its fast response, large actuation and compact design [4, 5]. Furthermore, the high temperature shape memory alloy (HTSMA) with phase transformation strain of 2~3% and temperature over 400º C has been advancing rapidly and the materials in useful product forms are expected to be available in near future [6]. As the thermal clearance modulation is primarily hampered by slow response and small stroke, HTSMA, with large induced strain occurring at high temperature, appears to open a door to a new design opportunity. Yet, a modulation device making full use of SMA as compact muscle power and fast response through thermal activation without moving parts, light in weight and integral to engine shroud environment, remains to be developed.

This research presents and explores the concept of the blade tip clearance modulation by a variable geometry active truss structure located inside the hot section of the engine. The active truss employs thermal expansion of its slender members to substantially enhance the thermal response from ACC approach. The objects are to understand in a high level if a low thermal mass and compliant structure is capable of rapid and adequate modulation, and whether such design can be conceivably made to fit in a typical shroud head room and be effectively controlled. It illustrates a path of using conventional high temperature alloy or HTSMA toward ultimate applications of the active thermal truss to high efficiency large transportation propulsion systems.

Technical Innovation

The fast response tip clearance control under research employs an intelligent variable geometry truss structure that is sparsely populated and possesses a very low thermal capacity. The active truss structure, shaped in an annulus and linking the engine shrouds to the engine inner case, consists of multiple segments, each individually controllable to its radial height, shown in Figure 1. By selectively heating and cooling its member elements the actuator moves the shroud inward and outward modulating the tip clearance in linear or binary manner. Air is blown on the truss matrix to cool it to ambient temperature rapidly when the active members are powered off.

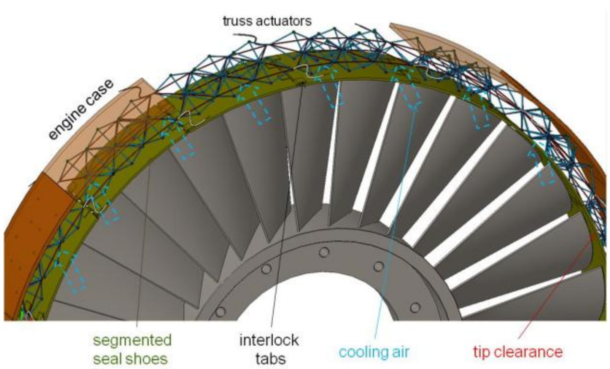


Figure 1 Tip clearance modulation by thermal truss actuation around engine shroud

The core element of the active truss actuators is a dual-tetrahedron truss structure, shown in Figure 2. Any truss member in the tetrahedron pyramid can modulate the height *DE* by its axial elongation or contraction. The top vertex of the dual tetrahedron *D* is attached to the engine case while the bottom vertex *E* to the segmented shroud. Each segment is suspended by an array of these pyramid truss cells along the circumferential and axial directions of the engine, as seen in Figures 1 and 2. By heating/cooling the diagonal or base members respectively, one is able to move the vertex *E* upward or downward.

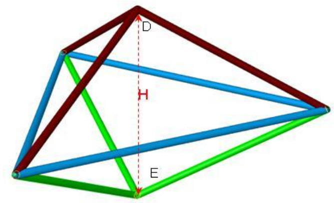


Figure 2 Tetrahedron truss actuators

The variable geometry truss actuator needs to be designed to possess several distinctive features for tip clearance modulation in gas turbine engine environment:

- Fast response modulation due to its extremely low volume (mass) density. Resistive heating is instantaneous. One order of magnitude response time improvement during air cooling is desirable over the shroud contraction method (ACC).
- Structural amplification of the truss configuration. Each truss member can generate a very little thermal expansion by its own. It must be amplified to a large modulation for typical transportation engines (0.02 to 0.05 inches).
- Compact design that fits in typical engine shroud head room without moving parts while providing plenty of airflow channels for air cooling.
- Symmetric and asymmetric modulation by collective and/or individual actuation of shroud segments.
- Feasible for electric heating, wiring and air cooling.

System Control

The dual-tetrahedron can be in principle individually heated by applying current to each member. The thermal expansion of the diagonal members reduces the tip clearance and their contraction opens up the clearance. To reduce the complexity of wiring and to increase the resistance of heating circuit, it is preferred to connect a number of the truss cells electrically in series and structurally in parallel. Figure 3 illustrates the activation of the truss mechanism by selectively heating topologies. In this intelligent heating scheme, only the diagonal members are actively heated and the base member carries no current because of the Wheatstone bridge effect. As such, the thermal expansion/contraction of all the diagonal members contributes in phase to the aggregated actuation of the bottom vertex *E*. Control of the electric power into the truss cells would modulate the actuation as a linear function of the temperature elevation from their ambient. The control of the rates and the temperature of air flow in the engine axial direction maintains a thermal equilibrium of the truss cells in actuation mode, and rapidly cools them to ambient temperature after the heating power is turned off. The actuation operates fail safe as the tip clearance reaches a maximum in the event of electric power failure.

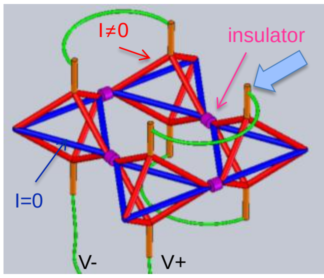


Figure 3 Actuation and electric control topologies of four active tetrahedron truss cell by resistive heating in series and structural support of the shroud in parallel

Kinematic Actuation

A kinematic model is developed to design the aggregated actuation of a tetrahedron truss element as well as its other structural characteristics, such as stiffness that reflects its load carrying capability, and the volume density that is directly related to its thermal response speed, as shown in Figure 4.

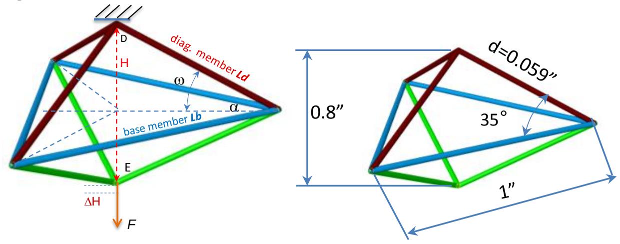


Figure 4 Tetrahedron truss actuator, design parameters and a case study

The actuation output of the tetrehadron truss elements is the displacement of the vertex *E*, or change of its height *ΔH*. The kinematic amplification of the truss cell is a simple function of design angle ω and the member lengths *lb* and *ld,* when each vertex is considered as an articulated joint and the bending stiffness of the truss is neglected. The rates of the height change with respect to the member length changes can be described as:

$$\frac{\partial H}{\partial l_b} = \frac{-\frac{2}{3}l_b}{\sqrt{l_d^2 - l_b^2/3}} = \frac{-\frac{2\sqrt{3}}{3}\cos(\omega)}{\sqrt{1-\cos^2(\omega)}} \qquad (1)$$

$$\frac{\partial H}{\partial l_b} = \frac{-2l_b}{\sqrt{l_d^2 - l_b^2/3}} = \frac{2}{\sqrt{1-\cos^2(\omega)}} \qquad (2)$$

The aggregated actuation of vertex *E* can be expressed as a sum of the thermal expansion by each contributing member amplified by the truss strutural configuration:

$$\Delta H_t = \sum_{j=1\sim 6} \frac{\partial H}{\partial l_d^j} dl_d^j - \sum_{i=7\sim 9} \frac{\partial H}{\partial l_b^i} dl_b^i \qquad (3)$$

Where dl_b^i and dl_d^i are the effective thermal elongation or contraction of each truss member with a temperature elevation *ΔF*, respectively.

The thermal expansion/contraction of the truss members is assumed to be linear with the temperature rise from its ambient (except for SMA, nonlinear near the phase transformation)

$$dl_d = l^j{}_d C_{ted} \Delta T_{l_d} \qquad (4)$$

$$dl_b = l^i{}_b C_{teb} \Delta T_{l_b} \qquad (5)$$

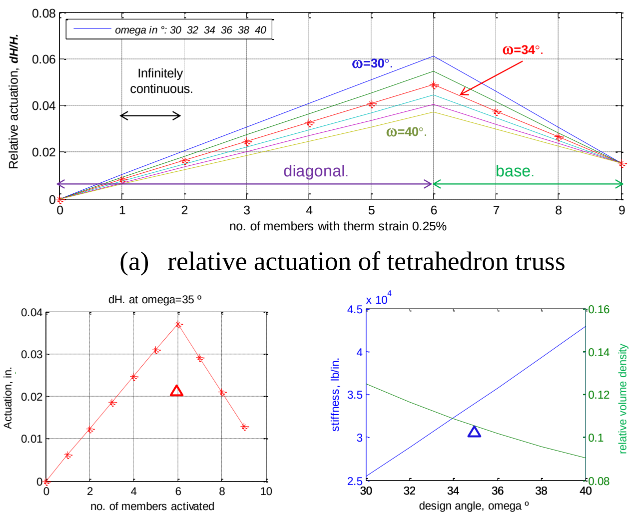
Its equivalent structural stiffness at the point of load vertex *E* is a function of the stiffness of each member and the design angle ω:

$$K_D = \frac{9k_d k_b \sin^2\omega}{4k_d\cos^2\omega + 6k_b} \qquad (6)$$

The relative volume density of a hallow tetrahedron truss vs. a solid tetrahedron is dictated by the slenderness ratio (*d/lb*) of the members (*d* is the member diameter) and the design angle:

$$\bar{\rho} = \frac{\pi(3+2\sqrt{3}/\cos^2\omega)}{\tan(\omega)}(d/l_b)^2 \qquad (7)$$

The height of tetrahedron truss *ΔH* can be modulated by individual or collective activation of each truss member. Figure 5 shows a parametric analysis and a case study of an ideal actuation output as function of design angle ω and the progressive contribution from each member. Figure 5(a) reveals several features about the tetrahedron truss as an actuation mechanism. The aggregated modulation increases linearly with the numbers of the members activated simultaneously. The structural amplification of the thermal actuation grows heavily with decrease of the design angle ω. Elongation of the diagonal members, *ld* 1~6, actuates the vertex *E* in phase (clearance out of phase) while that of the base members, *lb* 7~9, actuates out of phase (clearance in phase). This differential actuation (the negative sign in Equation (1) and positive in Equation (2)) can be explored to eliminate partially the drift of the modulation with ambient temperature variation. As the thermal elongation and contraction of each member is linear with its temperature elevation, the tetrahedron truss is capable of an infinitely continuous actuation when the temperature elevation is precisely controllable. Furthermore, the multiple input and single output summation mechanism enables a step-wise continuous modulation with easy-to-implement binary strain input (or temperature rise) to each member (through phase transformation of SMA, for instance). As such, use of combination of the phase difference, linear and binary input can in principle achieve an arbitrary modulation profile in any desired resolution and precision.



(a) relative actuation of tetrahedron truss

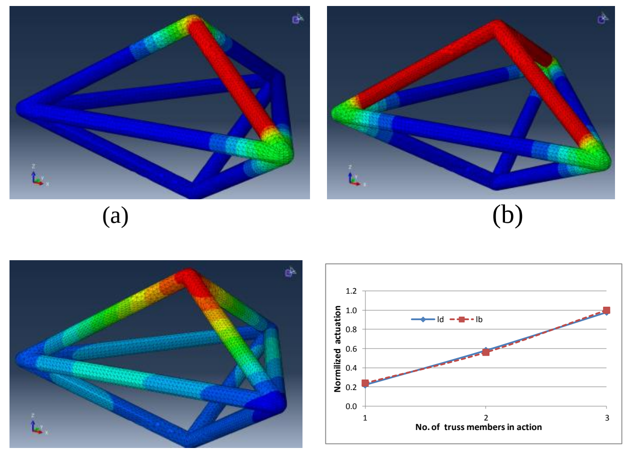
(b) absolute actuation (c) stiffness and volume density

Figure 5 Actuation of articulated tetrahedron by kinemics models. Δ and Δ are the FEM model predictions with welded joints and member with shortened effective length.

With the kinematic models, we have conducted a design case study on a tetrahedron truss actuator with one inch nominal dimension (Figure 4) made of Inconel 718 alloy. The case study results, Figures 5 (b) and (c), show that with 350°F temperature rise in all six diagonal members, the tetrahedron is able to modulate the height *H* by 3.5~6.1%. The six diagonal members ($l_{d1\text{-}6}$) can progressively displace vertex *E* toward the engine center and other three base members ($l_{b7\text{-}9}$) can linearly do in the opposite direction. The actuator structural stiffness (critical for carrying static pressure differential load *F* on the shroud) and volume density of the truss (critical for the cooling speed during the deactivation) vary by the design angle in an opposite trend with the structural amplification. An angle of 35° illustrates a near optimal design among the three key variables, the amplification (3.5), volume density (0.12) and structural stiffness (34000*lb*/in) that could meet a nominal mechanical requirement of the clearance modulation. The design results in a 0.035" net displacement by 350°F temperature rise in its all six diagonal members.

Structural Validation

The performance analysis of the tetrehadron truss by the kinematic model is then verified by a finite element model (FEM in ABAQUS) with more realistical joint constraint and more designable truss configuration. Welded joints and shortened member length are used to include the effects of the member bending and the reduced effective length due to the heat transfer to and from the joints, as shown in Figure 6. The structural FEM model without air cooling and heat transfer thermal equilibrium has verified that the thermal actuation of each member is linearly superimposable to the aggregated modulation of vertex *E* as predicted by the kinematic model. It also illustrates that, due to the joint rotational constraints at each vertex (vs. hinged joint in the kinematic model) and the reduced effective member length (practically designable), the structural modulation can achieve approximately 65% of the analytical prediction without pressure differential load.



(a) (b)

(c) (d)

Figure 6 Thermal actuation of welded tetrehadron truss with shortened effective member length,
(a) and (b) temperature elevated in single and three diagonal members, respectively, (c) aggregated thermal actuation, (d) linear contribution by each member.

Integrated Thermal and Fluid Model

A heat transfer and computational fluid dynamic (CFD) model (in Fluent/ANSYS) was developed to analyze the coupled performance of the tetrehadron truss as tip clearance modulation in response time, power dissipation and available modulation output. Figure 7 shows the FEM model coupled with CFD model and its thermal fluid boundary conditions in an ideally controlled volume. The top wall represents the engine case inner wall, and the bottom wall represents the shroud outer wall. The cooling air comes in, performs heat exchange with the truss members and then exits on the outlet of the control volume in a uniform flow distribution. The model uses the same dimensions as defined in Figure 4.

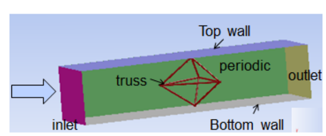


Figure 7: Computational domain and boundary conditions of FEM/CFD model

The model captures the steady state and dynamic processes of a single cell tetrehadron truss during the activation/deactivation of its six diagonal members: 1) steady state modulation output in response to a nominal temperature rise of 350°F in its six members interacting with airflow; 2) rapid cooling to the ambient by the airflow when the electric power is turned off, and 3) the heat dissipation during the activation and deactivation. Figure 8 shows the diagonal members temperature change with time, and the steady state and transient heat dissipation rates. Upon resistive heating of the six members (t = -5s), the vertex *E* displaces by ΔH=0.0128" instantaneously (Figure 9(a)). Then to sustain its activated steady state position, a minimal airflow (0.328 ft/s) and electric power (20 BTU/hr, or, 6.7 Watts) must be supplied continuously to the truss cell to maintain a power flux equilibrium between the truss and the airflow and the temperature difference between the active member and non-active members. The de-actuation starts when the electric heating is turned off and the air flow increases to 32.8 ft/s to carry the heat away rapidly from the hot truss members.

The time required to reach the fully deactivated state of the truss, or to cool all members to a uniform temperature close to the ambient is the key objective in design. For given truss design and temperature rise, increasing the speed and lowing temperature of the cooling air would shorten the required time. In this study, air flow of 32.8 ft/s and 1300°F is employed and the deactivation status is practically defined as when the average temperature (there is large variation along the length of each member due to the air cooling and heat transfer to/from the joints) of the diagonal members settles to the ambient 1350ºF. Figure 8 shows that the time to cool the entire truss to the ambient is approximately 16 seconds.

During the activation, the heat dissipation of the truss cell by airflow in a thermal equilibrium state is assumed to equal the electric power input. Keeping the truss cell activated to 1650ºF requires much less power than the heat dissipation capacity of the full speed airflow (143 BTU/hr, or, 43 Watts). Therefore, only a small airflow and electric heating power (0.328 ft/s and 6.7Watts) is required for cooling during the activation.

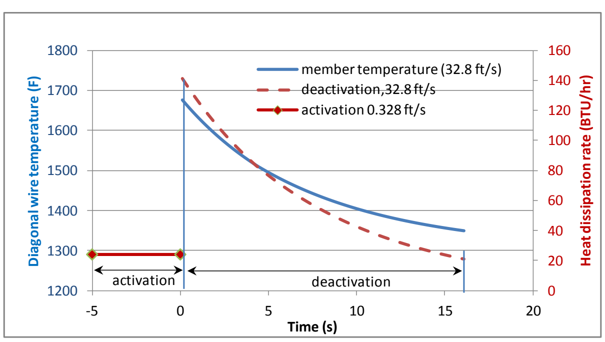
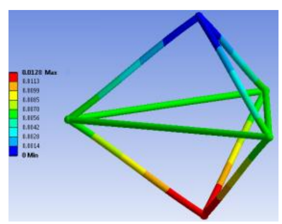


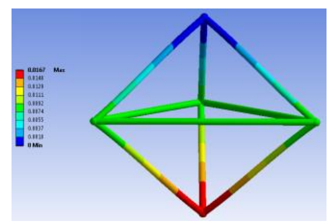
Figure 8 Thermal response time of tetrahedron actuation and power dissipation during activation/deactivation

The fast response is attributed to the fact that the tetrahedron truss structure of this design possesses 88% less material mass and 55% more of heat exchange surface area than a solid device with the same volume. The CFD modeling illustrates two important thermal features of slender truss element as an actuator: 1) in deactivation mode, cooling a slender truss structure by 350°F to its air ambient temperature in a matter of ten seconds is quite feasible; 2) maintaining temperature difference between active and non-active truss members for sustainable actuation requires an active air cooling and consumes a small amount of electric power.

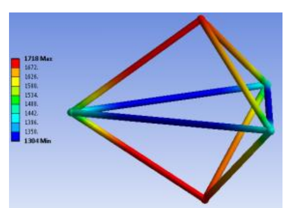
The coupled CFD model also reveals that the temperature distribution along the truss member is fairly uneven (Figure 9(c)) due to the heat transfer from the active members to the joints, rendering an effective net actuation further down from the structural FEM prediction by 44% (Figure 9(a)). The aggregated deformation of the truss cell due to the pressure differential and the structure compliance change at elevated temperature is consistent with the uncoupled FEM model and is relative minor (ΔH=0.002" at 70 *lb* load and 1650ºF, Figure 9 (b)), indicating the slender truss cell is sufficiently stiff to actuate independent of the static pressure load. The maximal stress in the pressure loaded truss member is well below the yield strength of the material (150 ksi), as shown in Figure 9 (d).



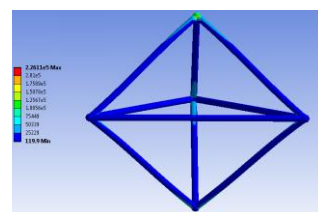
(a) free actuation = 0.0128"



(b) loaded actuation = 0.0148"



(c) temperature distribution



(d) von Mises stress

Figure 9 Effective modulation by 350ºF temperature rise: (a) w/o pressure load, (b) with 70 lb pressure load, (c) temperature distribution and (d) stress in truss members

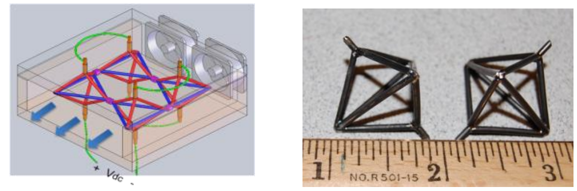
The coupled CFD/FEM model has so far illustrated that a sparse truss actuation mechanism can respond to a snap throttle transient demand 4 ~ 5 times faster than the current prevalent active case cooling approach. The magnitude of the modulation practically achievable, with the air cooling, internal heat transfer and uneven temperature distribution factored in, is approximate 40% of the what the analytical model indicates. Therefore, by use of the tiny linear thermal expansion of high temperature alloys (typically in 6~8e-6/°F) as the primary mover, a truss actuator can be designed to meet the requirement for small aero engines using 0.01inch clearance per inch shroud head room criterion.

Obviously, application of this modulation mechanism to large commercial transport engines will be unleashed if materials of phase transform strain 2~3% and with high temperature capability, such as HTSMA, are employed.

Experimental Demonstration

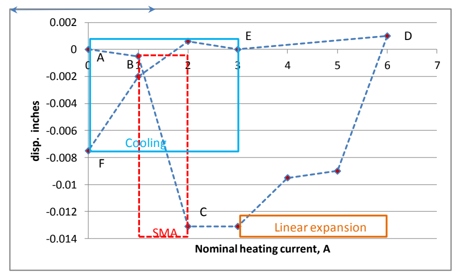
An experiment was conducted to demonstrate the concept of the active tetrahedron truss for tip clearance modulation. The experiment is designed to qualitatively assess modulation obtained by both induced strain of material phase transformation and linear thermal expansion of shape memory alloy during the heating and cooling. The four truss cells are sandwiched between two parallel plates, heated by electric current (via large current power supply) and cooled by the fan airflow, as shown in Figure 10(a). The truss cells are preloaded in tension by four springs as means of restoring mechanism from the phase transformation strain. The movement of the top plate is monitored by a laser displacement sensor during the heating and cooling of the truss cells. The tetrahedron truss cell is made of spot welding SMA (Nitinol) wire with nominal austenite transformation temperature of ~194°F and thermal expansion coefficient of 6.1×10^{-6} /°F (Figure 10 (b)).

Figure 10(c) shows how the displacement of the top plate with respect to the base plate (averaged actuation output from vertex *E* of all the truss cells) is correlated to the heating current in trend in both SMA and linear thermal expansion modes. In SMA mode (A~C), the material undergoes a transformation from martensite to austenite. The tetrahedron trusses contract rapidly in their height *ΔH* in a binary manner when the electric current across the each truss cells increases beyond approximately two amperes. As the current continues to increase, the linear thermal expansion of the alloy material starts dominating the actuation(C~D) and the plate moves in the opposite direction. When the electric current reduces and cooling fan is turned on, the truss cells begin their contraction again(D,E and F). Point A to F in Figure 10(c) illustrates a complete acuation cycle by the tetrahedron truss with combined phase transformation and linear thermal expansion strains. The trend in each actuation phase demonstrates overall positive correlation to the control current and cooling flow. The displacement does not return to zero at the end of the cycle *F* as a result of material hyteresis and insufficient restoration force inserted by the bias spring to the truss cells. The net displacement measured in the cycle is also less than expected by the numerical models. The phase transformation of the material (A ~D) delivers less than 30% of the anticipated displacement. The combined responses by linear contraction and phase transformation (restoring) on the air cooling (E~F) is also shown much reduced in a similar scale.



(a) experiment setup (b) truss cells, l_b=1.0”,ω=35°

(b) experimental test setup



(c) displacement actuation vs. nominal control current.

□, □ and □ binary heating, linear heating and combined cooling zones, respectively.

Figure 10 Experimentally demonstrated actuation cycle

The experiment has revealed several major deficiencies in implementing thermal actuation by direct resistive heating (shown in Figure 3) of welded wire truss. First, the low electric resistance of the truss cell made of metallic alloys makes a precision and linear control of the thermal expansion a significant challenge. The heating circuit typically operates on a large current and a low voltage such that the heating is extremely sensitive to the contact resistance in the circuit. The contact resistance of each wiring node to the truss cells also constitutes a great portion of the total circuit resistance. It varies with the wire connectivity and welding quality of the truss vertex joints. As a result, the actual heating power to the truss members becomes largely uncertain. With a voltage applied to a group of four truss cells in series connection, the actual power on each truss cell can vary by as much as 50%. Second, the electric contact resistance at each vertex joint is comparable to that of the truss members. It causes a large and unpredictable local heating, heat transfer to the adjacent members and temperature redistribution among the truss members. As a result, some joints become the hottest spots in the truss cell (rather than the center of the member) and largely distort the anticipated actuation output. In addition, the over-heating of the nodes may have resulted in a partial loss of the truss’ trained strain generation and recovery capability. Although hard to characterize quantitatively, it is believed these are major causes of the observed poor correlation and further reduced effective actuation from the CFD/FEM prediction. The direct resistive heating of the truss actuator appears less engineering feasible unless alloy materials of large resistivity are employed.

Summary

The research has developed a conceptual design of turbine blade tip clearance modulation by an active truss structure. It also demonstrates by analytical and numerical models that such a thermally active truss with very low mass density is able to respond rapidly to the demand of sudden clearance change. The kinematic and structural analysis show that design of such active truss structure is viable at key components level and they can meet the challenging actuation requirement of gas turbine environment. A conceptual system control scheme is presented and evaluated experimentally. It demonstrates the overall controllability of such active thermal truss actuation and also identifies the challenges of implementing the proposed direct resistive heating.

Patent Application

An invention disclosure “Fast Response Blade Tip Clearance Control by Variable Geometry Structure” has been submitted for filing with USPTO.

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