NASA Aeronautics Research Institute

Active Truss for Fast Response Tip Clearance Modulation

Fanping Sun, Zaffir Chaudhry, Hailing Wu,
Lee Hoffman and Huan Zhang

United Technologies Research Center

NASA Aeronautics Research Mission Directorate (ARMD)

FY12 LEARN Phase I Technical Seminar

Nov 13-15, 2013

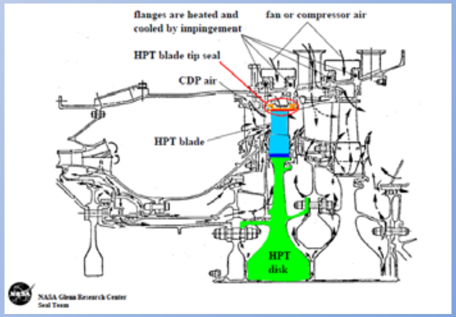
Outlines

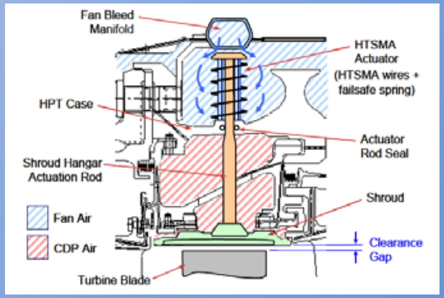
- The innovation
- Technical approach
- Impact of the innovation
- LEARN Phase I Results
- Summary
- Next steps

Need for Innovation

NASA Aeronautics Research Institute

- Current State of Technology
  - Thermal expansion and contraction of entire shroud/case (Active Case Cooling)
  - Slow response and scheduled modulation
    - huge thermal mass with seal segments directly mounted on engine casing,
    - ineffective heating or cooling of the shroud via convection between shroud surfaces and air.
    - No asymmetry modulation
- Prior Research
  - Mechanical/Smart materials/Hydraulic/Pneumatic
  - External to engine case/shrouds and moving parts
  - Incompatibility with environment for HPT
- Need for Innovation
  - Fast Response Tip Clearance Modulation Mechanism
  - Light weight, compact and environmental compatible to HPT
  - Integral to shroud-case structure w/o moving parts





DeCastro, etc, 2005

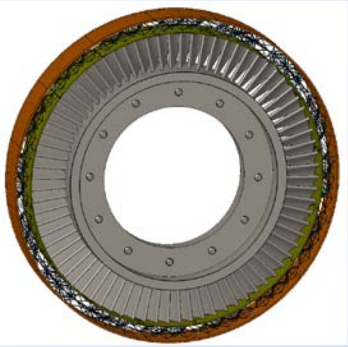
Impact of Innovation

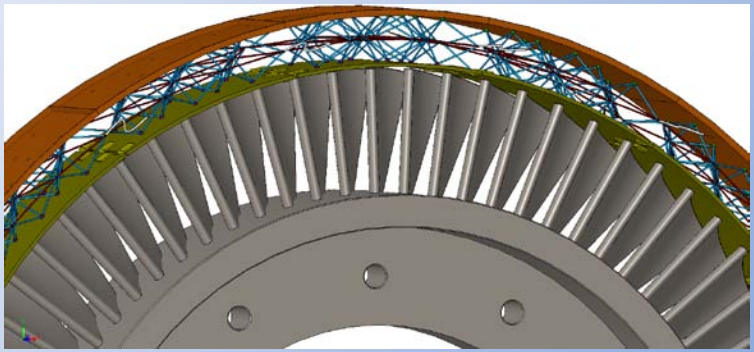
NASA Aeronautics Research Institute

A Fast Response Tip Clearance Modulation

- Enable turbine tip clearance set to "optimal" during longest flight segment (cruise)
- Reduce specific fuel burn (SFC) and exhaust gas temperature (EGT)
  - 0.01" in turbine blade tip clearance equals:
    - 1 % in SFC
    - 10° C in EGT
- Low CO_2 emission
- More time on wing

Innovation-Active Truss Modulation





Approach:

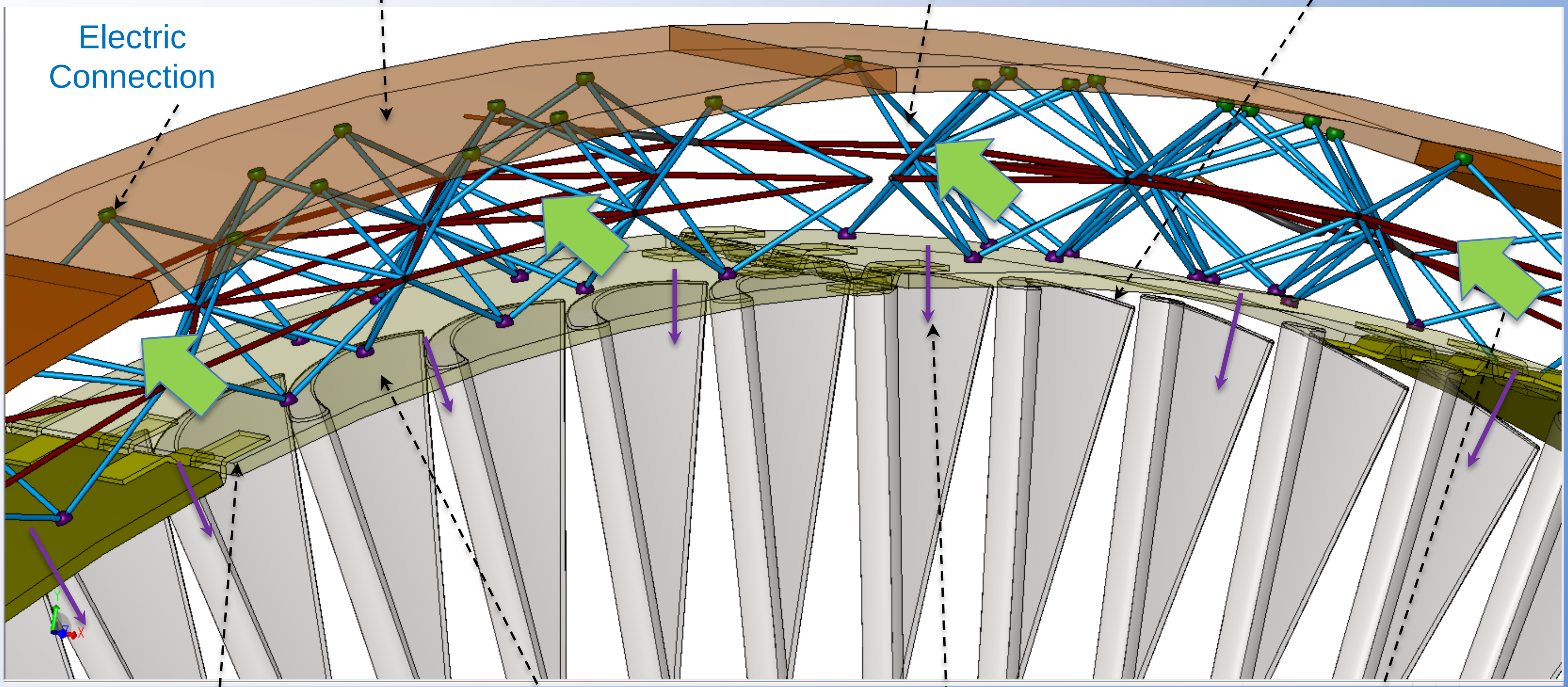
- Variable geometry active truss for tip clearance modulation
- Truss actuation by thermally induced strains
- Low thermal mass and large surface area for heat exchange

Benefits:

- Sustain beauties of thermal expansion approach
- Fast Response-one order of magnitude improvement
- Light weight and Integral to shroud-case structure
- Asymmetric and symmetry clearance modulation

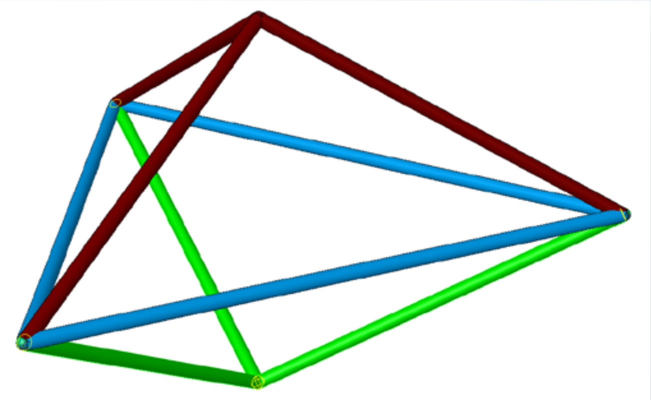
Active Truss Modulation (ATM)

NASA Aeronautics Research Institute

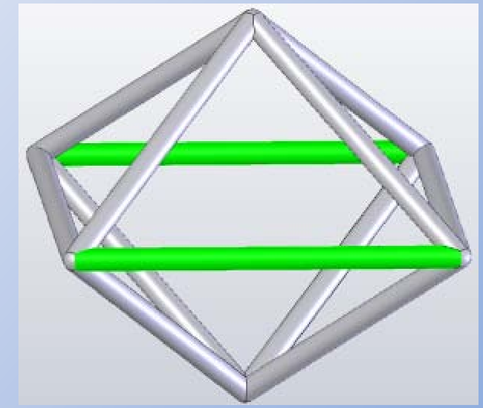


Core Elements of Truss Actuation

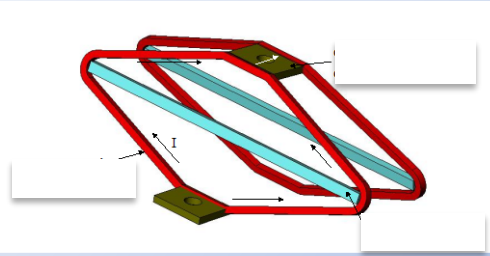
Prime Movers



Dual Tetrahedron



Dual Pyramid

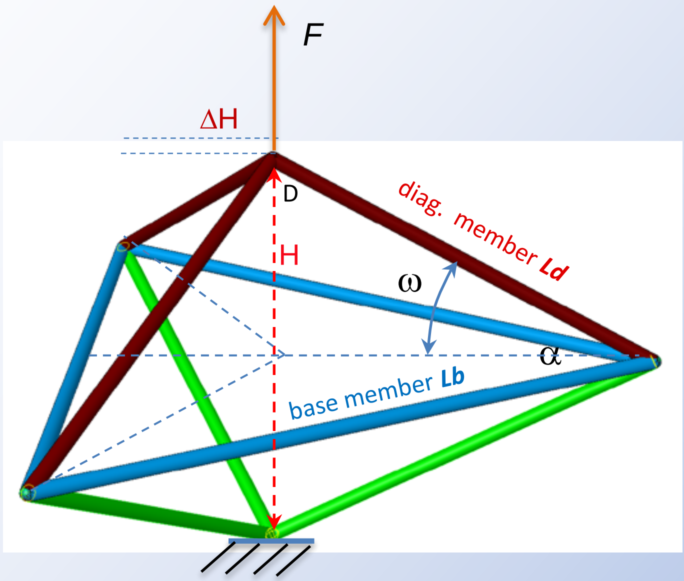


Parallel *Theta* Ring (2D)

- Actuation by linear thermal expansion
- Structural amplification of displacement
- Multiple inputs and single output actuation
- Low thermal mass and volume density (<0.1)
- One order of magnitude faster response than engine case cooling (ACC)

Principle of Truss Actuation

NASA Aeronautics Research Institute



For thermally induced actuation

- Displacement
- Stiffness
- Response
- Temperature

$$H = 2\sqrt{l_d^2 - \frac{l_b^2}{3}} = 2l_d\sqrt{1-\cos^2\omega}$$

Actuation displacement

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

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

Tip clearance modulation

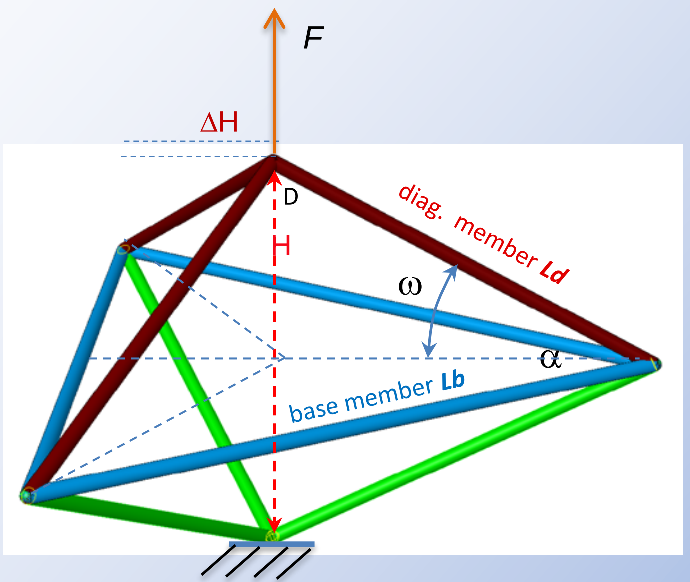
$$\Delta H_t = \sum_{j=1\sim 6}\frac{\partial H}{\partial l_d^j}dl_d^j - \sum_{i=7\sim 9}\frac{\partial H}{\partial l_b^i}dl_b^i$$

Thermal expansion in each members

$$dl_d = l^j{}_d C_{ted} \Delta T_{l_d}$$

$$dl_b = l^i{}_b C_{teb} \Delta T_{l_b}$$

Principle of Truss Actuation



Structural stiffness

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

Total displacement modulation

$$\Delta H = \Delta H_t + F / K_D$$

Member buckling (*L*/*r* slenderness)

$$\sigma_{cr} = \frac{4\pi^2 E}{(L_b / d)^2}$$

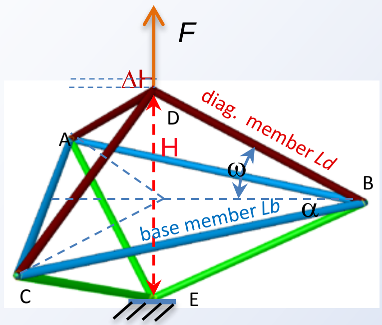
Volume density (weight)

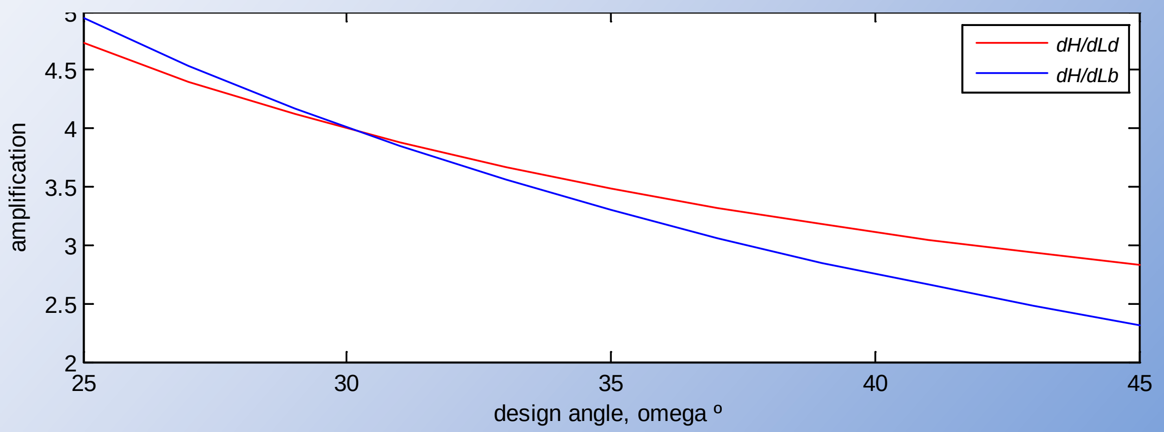
$$\bar{\rho} = \frac{\pi(3+2\sqrt{3}/\cos^2\omega)}{\tan(\omega)}(d/l_b)^2$$

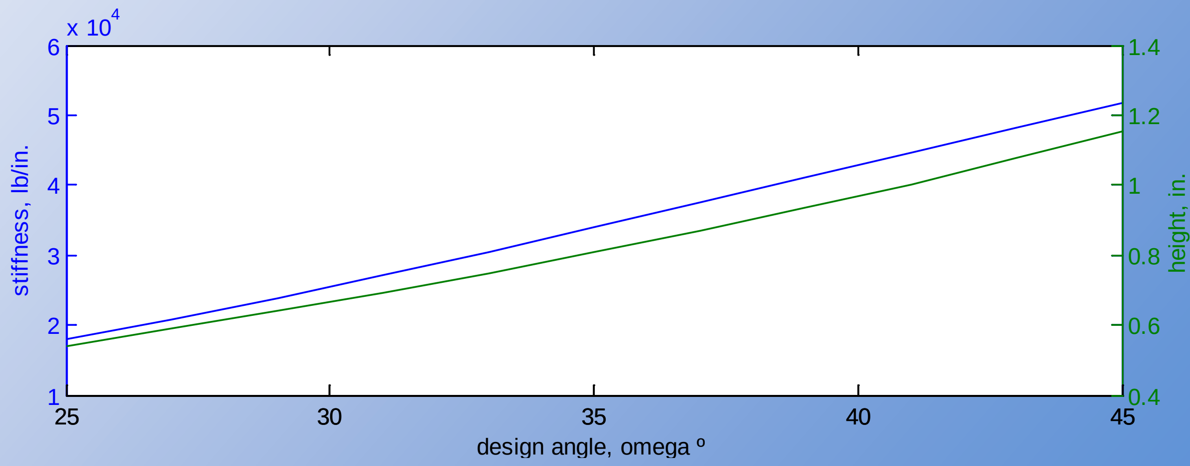
Design of Tetrahedron Truss

NASA Aeronautics Research Institute

Kinematic and Structural Design Envelope

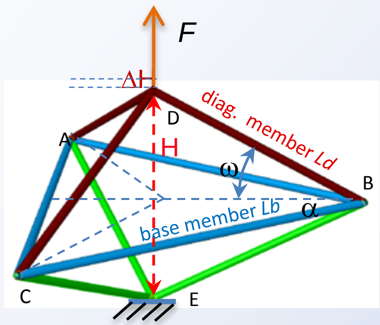


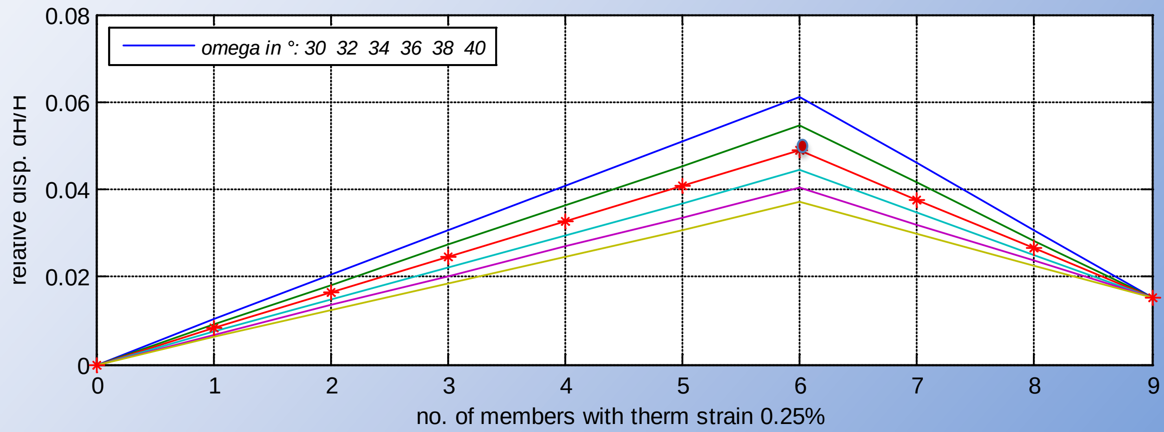


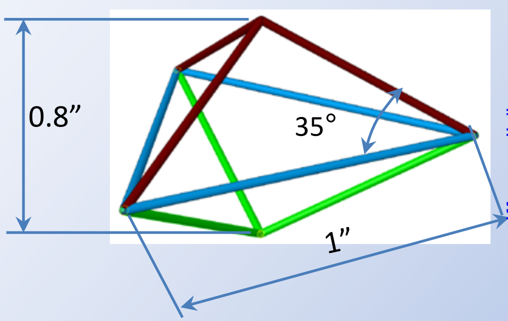


Design of Tetrahedron Truss

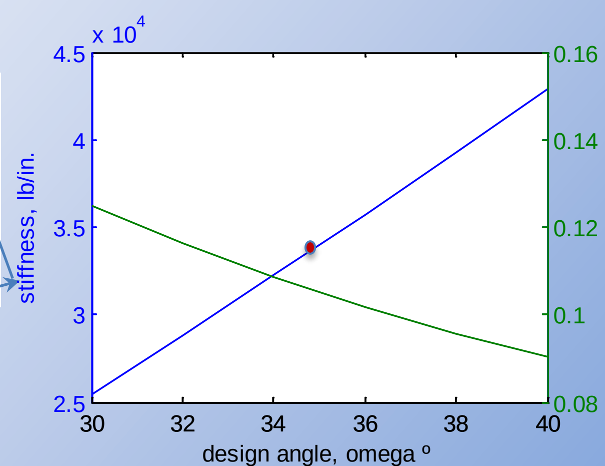
Kinematic and Structural Design Envelope

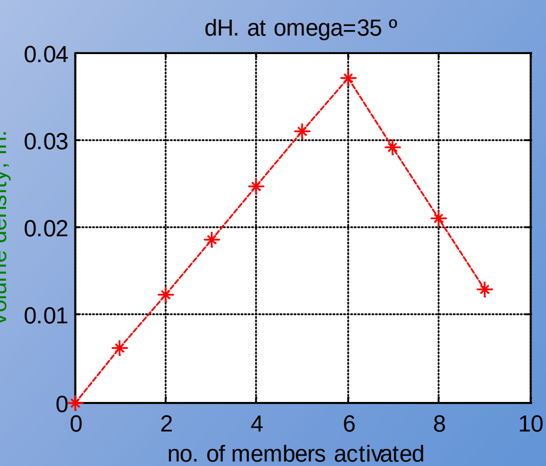






case design

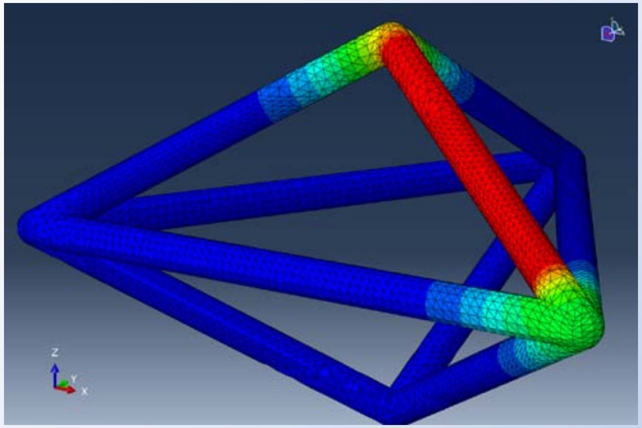


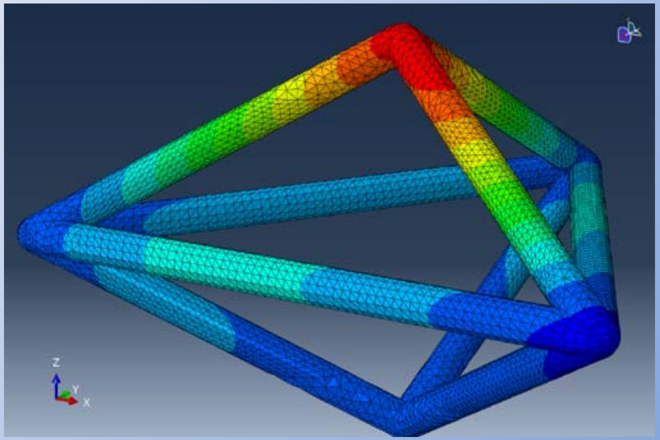


Design of Tetrahedron Truss

NASA Aeronautics Research Institute

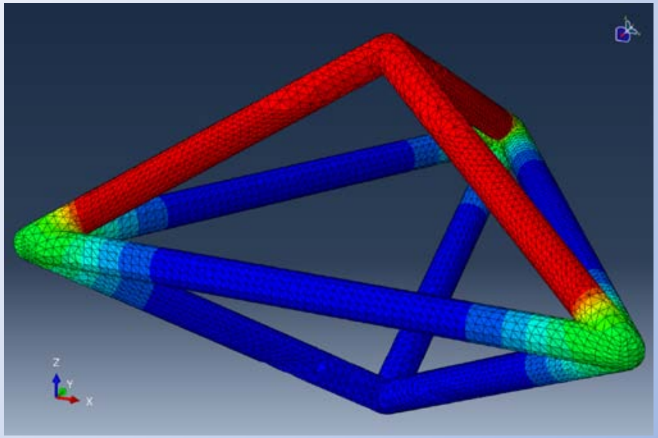
FEM Model

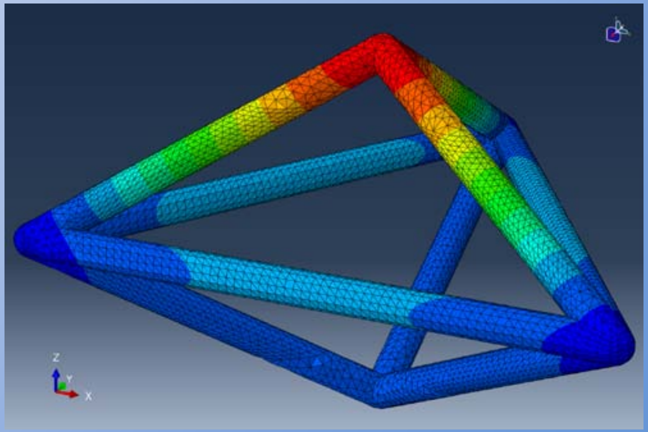




Δ T=300 °F applied to 1 diag. member

Thermal expansion field



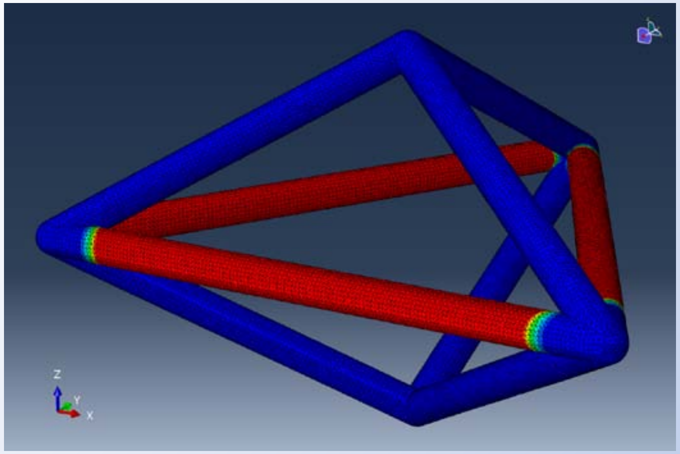


Δ T=300 °F applied to 3 diag. members

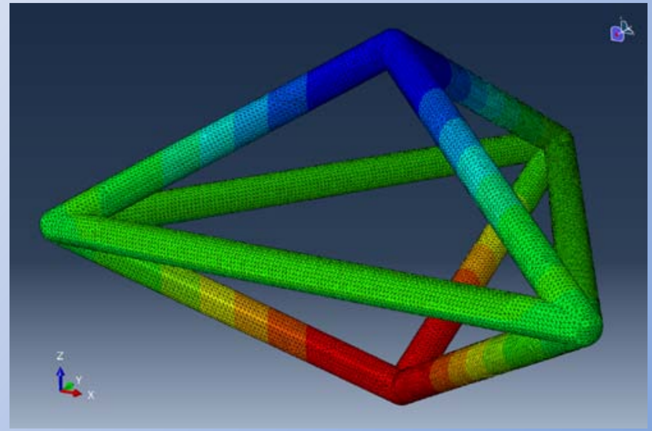
Thermal expansion field

Design of Tetrahedron Truss

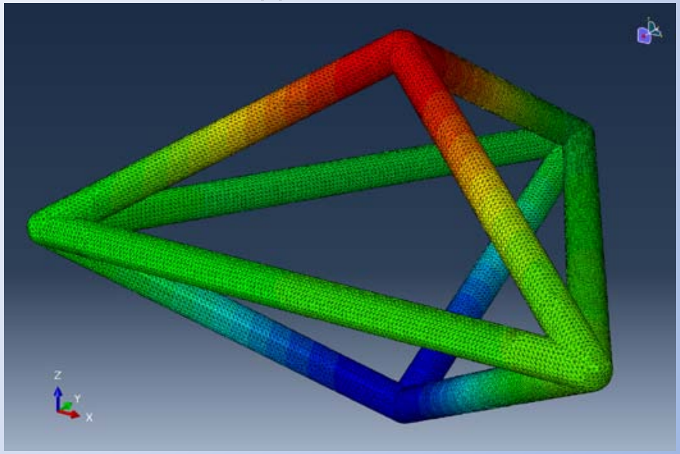
FEM Model (cont'd)



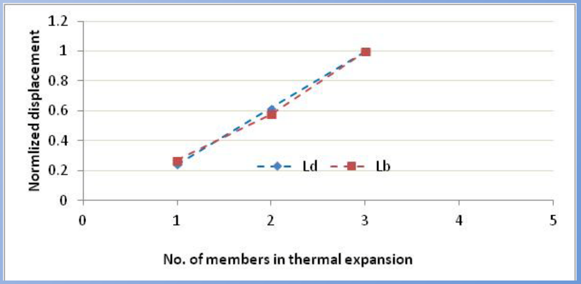
∆ T=300 °F applied to 3 horizontal members



Thermal Expansion

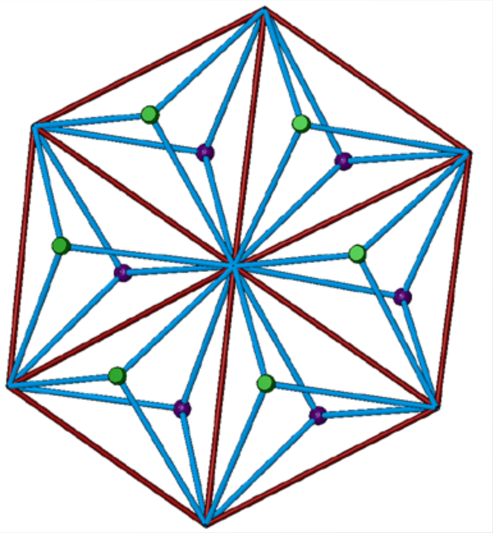


Deformation field under load



- Linear summation of thermal expansion by each member
- Max principal stress $\sigma_{max} << \sigma_{yield}$ & σ_{cr} under ΔP= 180 psi

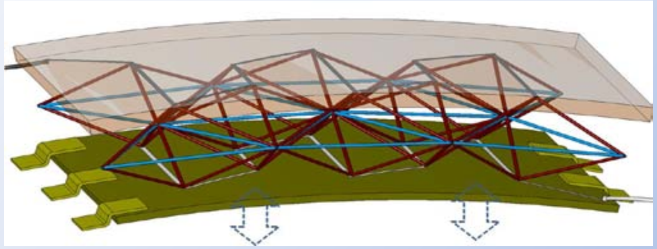
Electric Activation of Truss Matrix

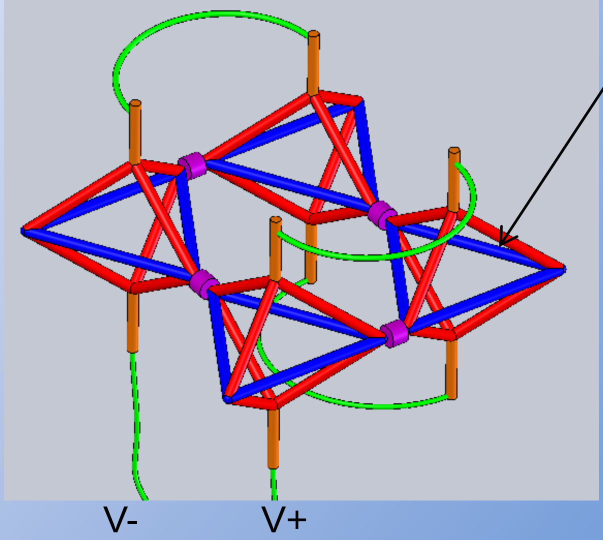


Direct resistive heating topologies

- Heating each member individually
- Group collective heating (base and diagonal)
- Combination of series and parallel heating
- Intelligent heating-Wheatstone bridge effect

Challenge: Large current and low voltage



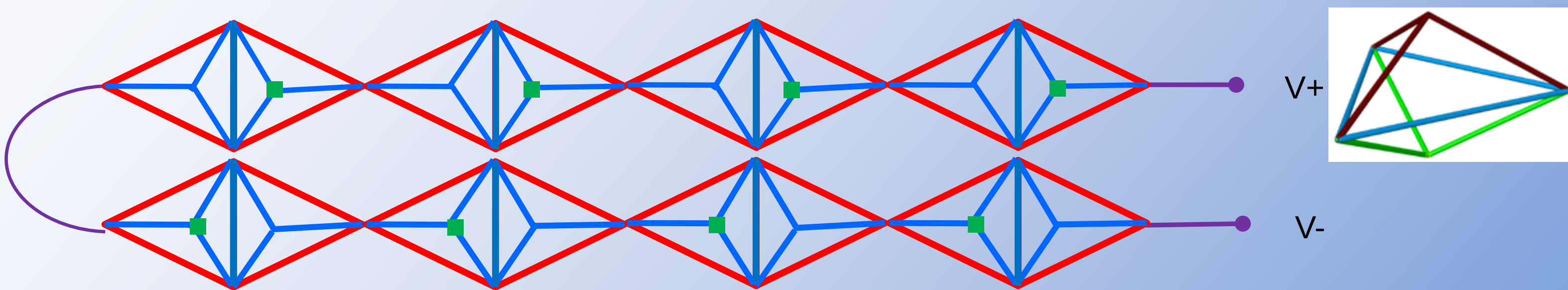


I=0

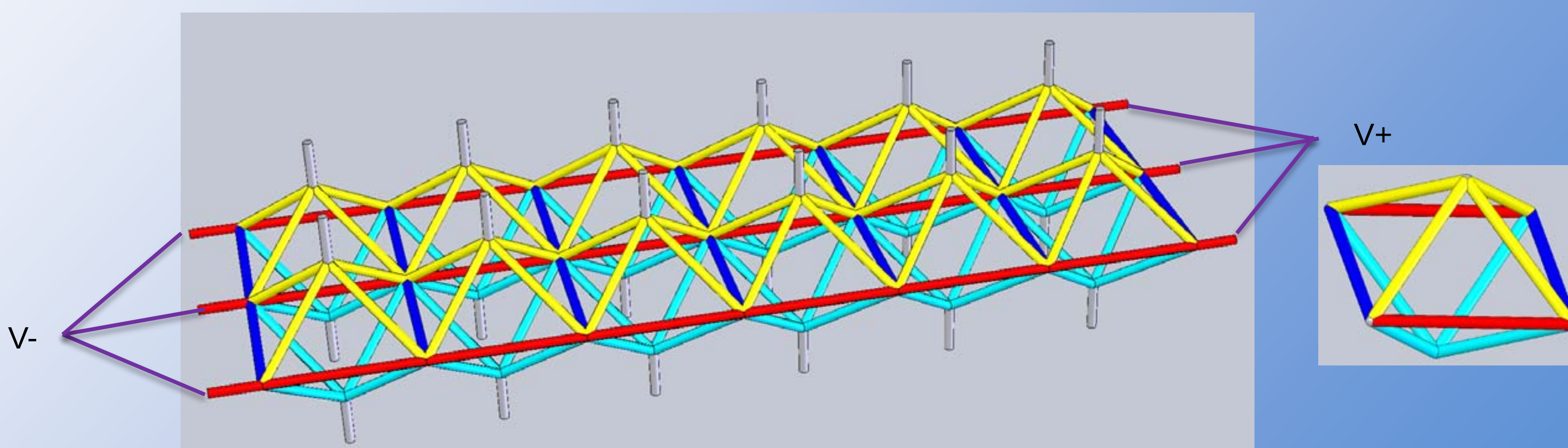
- Cell to cell series connection
- Full actuation
- Fail safe
- Embedded wiring in case

Electric Activation of Truss Matrix

Series connection and partial grouping (2/3 activation)



Parallel/series connection and partial grouping (1/2 activation)

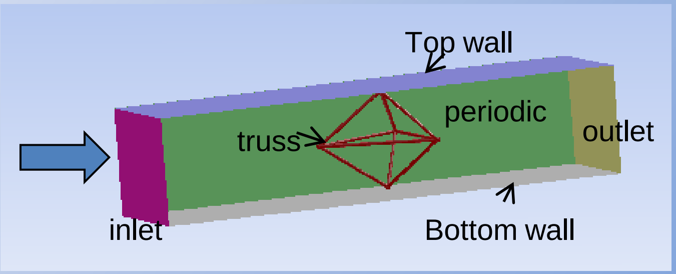


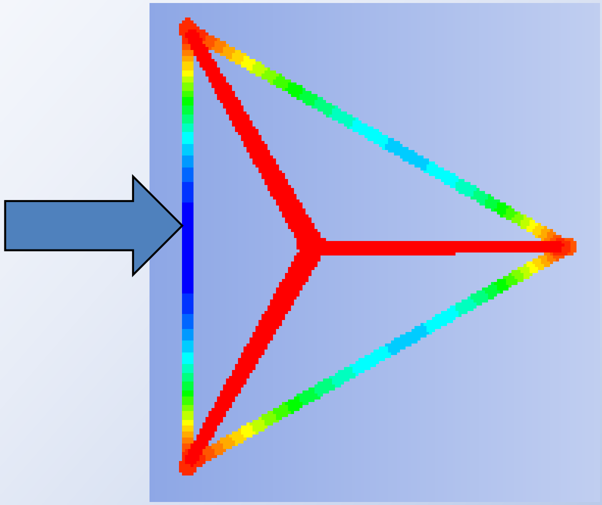
Air Cooling- Activation and Deactivation

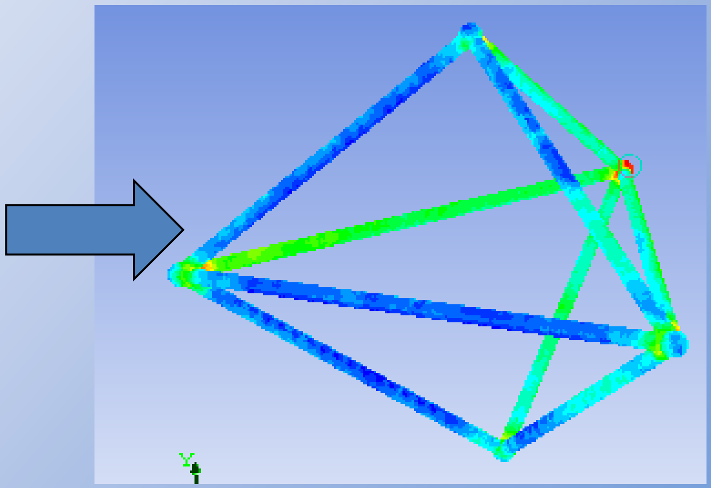
NASA Aeronautics Research Institute

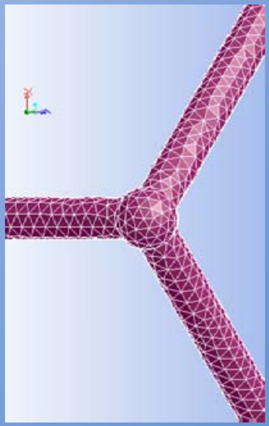
Air Cooling Modeling

- Steady state heating/cooling
- Transient cooling









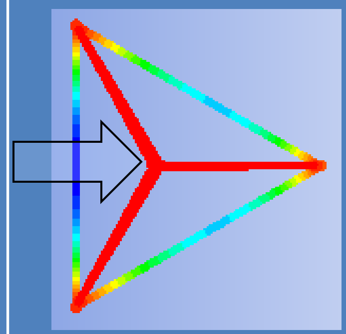
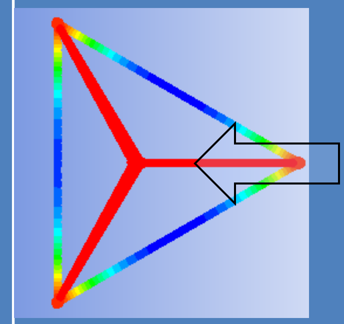
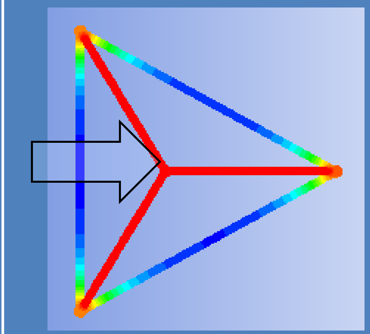
Remain activated, electric power on

Deactivated, electric power off

Air Cooling- Activation Mode

NASA Aeronautics Research Institute

To maintain temperature difference while electrically heated

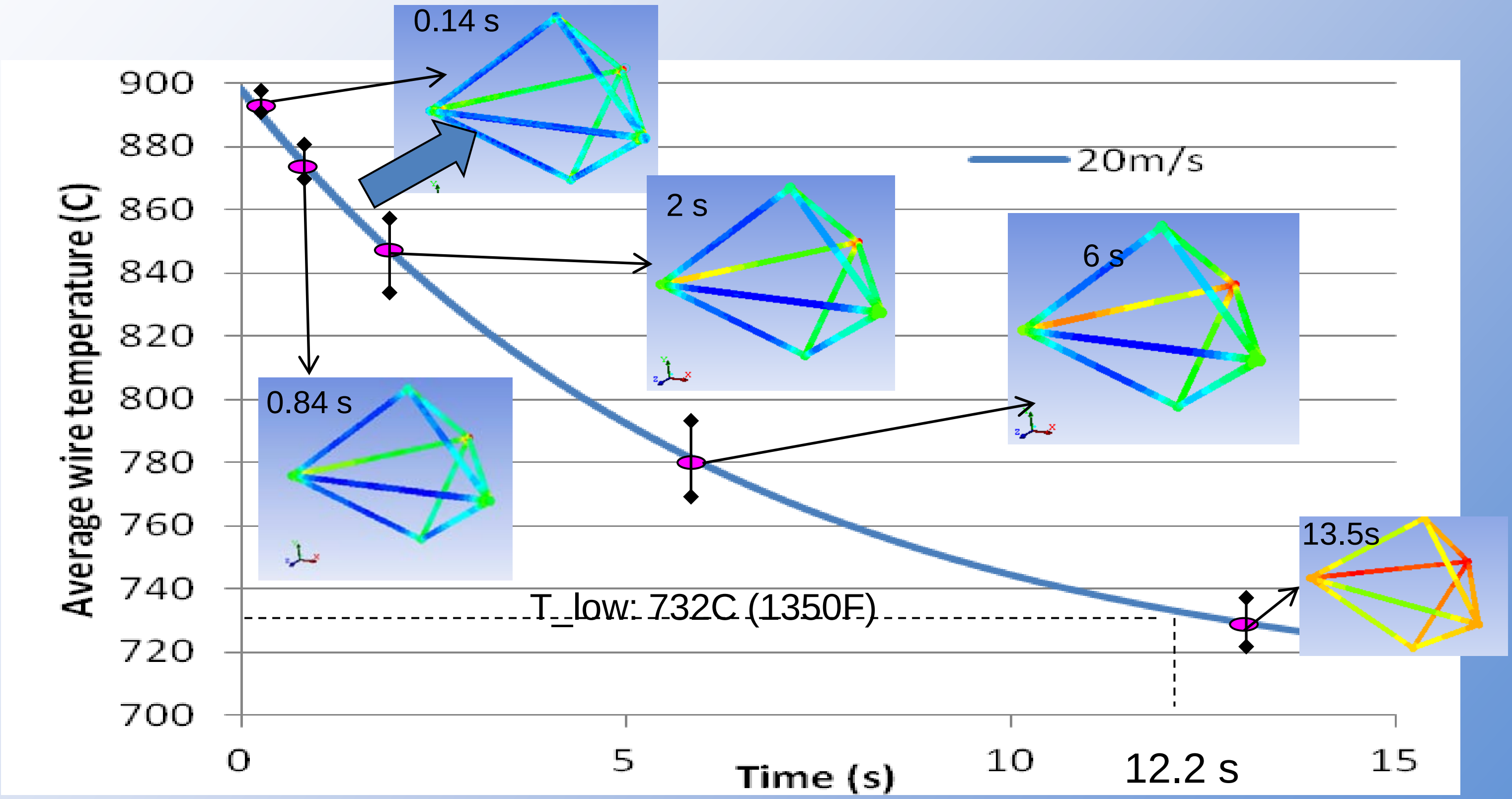
Member temperature contours			
Air flow (m/s)	0.1	0.1	10
Temperature difference between heated and unheated wires (°C)	100	110	180
Heat dissipation rate (W)	7.04	6.9	42.2

- Six members being electrically heated at 899 ºC (1650°F) while being air cooled
- Three members being air cooled to 732ºC (1350°F)

Air Cooling-Deactivation Mode

NASA Aeronautics Research Institute

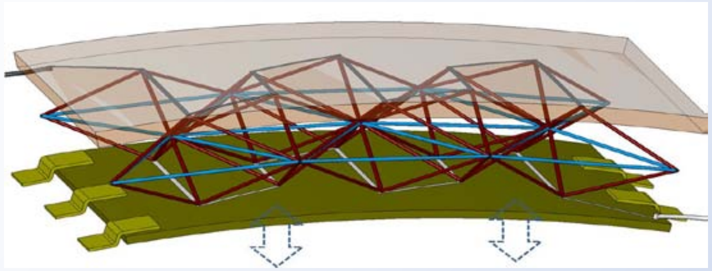
To cool to ambient temperature after electrical power turn off

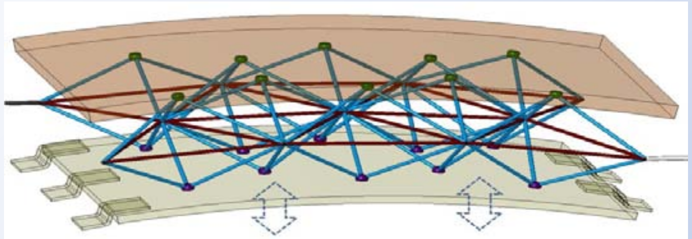


Member temperature change during cool-down with air velocity of 20 m/s

System Design Case

NASA Aeronautics Research Institute





Design Parameters	
20 truss cells per shroud	structurally in parallel
	electrically in series
	two actuation modes
Truss cell material	Inconel 718
Therm. expansion coef.	8.5e-6/ °F
Elastic modulus	*24* Mpsi
Cell dimensions	*Lb*=1", *d*=0.059"
Volume density	ρ=0.11
Design angle ω	35 °

	Clearance modulation, in	Max. Deflection @ 2200, lbf	No of actuators per shroud	No. of shroud segments	Shroud surface area, in^2	Headroom between case and shroud, in	Air temp. between case and shroud °F	Deactivation time, s	Power to maintain activated, w
Nominal requirement*	0.05~0.1	N/A	1	20	12	2	1300	N/A	N/A
Tetrahedron truss cell	**0.035**	**0.005**	**28**	**20**	**12**	**1.5**	**1650**	**13**	**1344**

*DeCastro, 2005

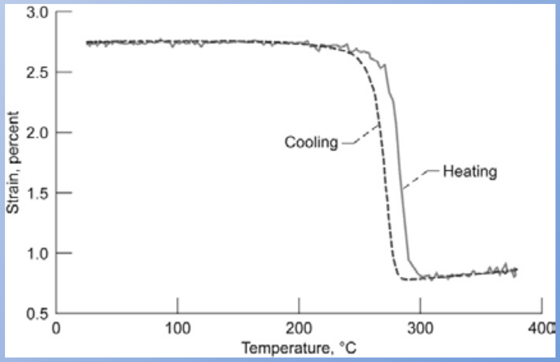
Perspective on Materials

•Baseline materials: High temperature alloys
  •Marginal CTE for large tip clearance modulation
  •Use of material phase transformation induced strain: 10x in stroke

•Commercially available Shape Memory Alloy (Nitinol SMA): 2~4% recovery and Af <100 °C
  •Applicable to Fan clearance modulation

•High temperature SMA in development
  •Ni30Pt20Ti50 by NASA GRC,
  •Recovery >2% and Af>250°C
  •High TRL and in useful form (NASA)
  •Applicable to HPC clearance modulation

•Ru-50 Nb and RuTa based high temperature SMA :
  •Martenstic transformation temperature > 800 °C
  •In early stage development
  •Potentially applicable to HTP clearance modulation

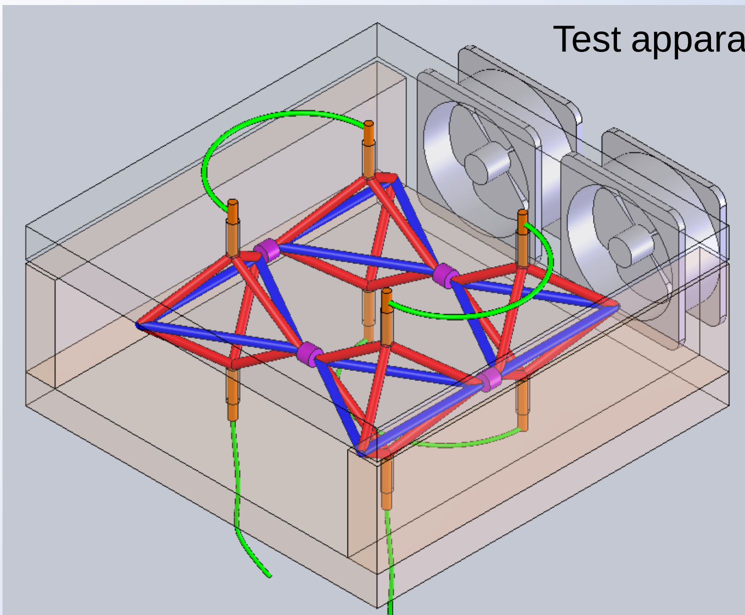


Thermo-mechanical test of N30Pt20Ti50 at 198 Mpa, Courtesy of NASA, M. Nathal, etc 2013

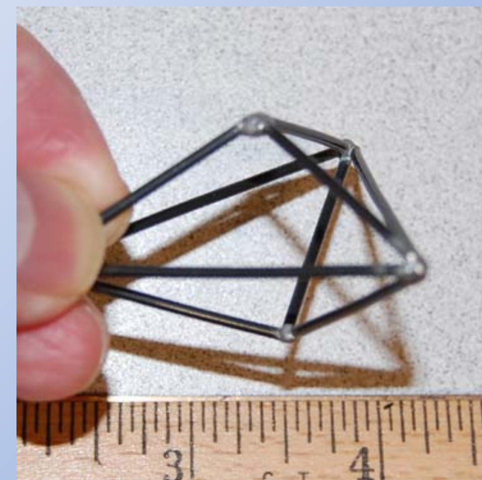
Proof of Concept Experiment

NASA Aeronautics Research Institute

In progress

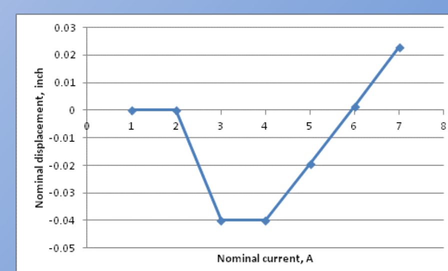


Test apparatus



Nitinol Tetrahedron Actuator
•Thermal expansion : 6.1e-6 /°F
•Electrical resistivity : 39 mΩ-in

Qualitatively Evaluation of
- Displacement output
  - Linear and binary thermal expansion
- Response time in cooling
- Structural stiffness



Anticipated results

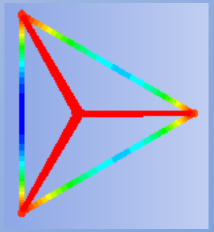
Summary

- Active truss tip clearance modulation by thermal expansion is conceptually viable
  - kinematically, structurally and thermally
- Fast response is analytically verified to be within tens of seconds at HPT environment
- Modulation by material linear thermal expansion is adequate for small and mi-size engines
- Experimental validation of tetrahedron truss actuation in progress

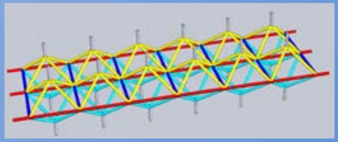
- Challenges identified in materials
  - High induced strain for large transport engine
  - High temperature to enable HPT
  - High resistivity to ease direct electric heating

Next Steps

- LEARN Phase I
- Enhance modeling fidelity of single cell-truss actuation
    - Structural FEM model close loop with air cooling models
    - Air cooling models close loop with electric heating
- Experimental validation of Tetrahedron Actuation in room temperature.



- LEARN Phase II
- Expanding structural and air cooling models to large scale repetitive Active Truss Matrix structure
- Notional design and analysis of tip modulation on a notional engine
- Electric heating and control of truss modulation
- High temperature shape memory alloy (HTSMA)



Distribution/Dissemination

In 2012, NARI awarded ARMD LEARN Fund grants to make deliberate investments in early-stage and potentially revolutionary aviation concepts and technologies that are aligned with NASA's mission. These grants went to teams external to NASA. The objectives of this three-day seminar are to increase awareness of LEARN activities within NASA projects, to provide technical feedback to LEARN principal investigators, and educate/inform the public. This will help facilitate transfer of LEARN-developed technologies within NASA and disseminate LEARN findings to the external aeronautics community, including academia, industry, and the general public.

Distribution and dissemination are unlimited