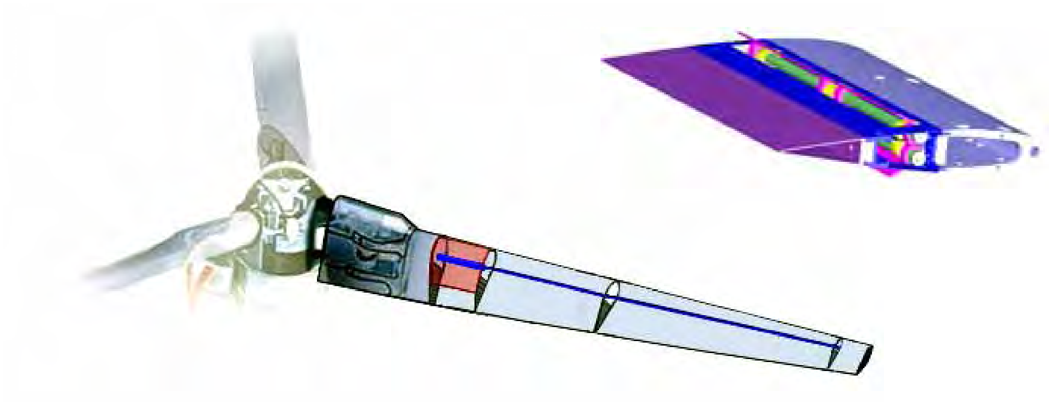
Boeing's Morphing Aerostructures

F. Tad Calkins
Boeing Commercial Airplanes
Enabling Technology and Research
Aeroacoustics
425 237-2831
frederick.t.calkins@boeing.com

Outline

Morphing structures
Actuation capability
Potential applications
The Future



Morphing Overview

- Morphing Technologies **increase a system's performance by manipulating characteristics to better match the system state to the operating conditions (environment and task)**
- Aerospace applications
  - **Landing gear**
  - **Flaps**
  - **Swing wing F-14, B1B**
  - **Concorde nose tilt**
  - **V22 Rotors rotate down**
  - **Active Aeroelastic Wing**
  - **Mission Adaptive Wing**

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC86-33385-002 Date: February 27, 1986

AFTI F-111 Mission Adaptive Wing (MAW) in flight

What's New

- **Current "morphing" has disadvantages**
  - **Even small structural changes are difficult**
  - **Requires heavy motors, hydraulics, structural reinforcement**
  - **Complexity**
  - **Expensive**
- **"Smart" materials lead to new morphing concepts**
  - **Fully integrated, distributed actuation**
  - **Conventional components given additional capability**
  - **Does NOT add weight**
  - **Simple mechanisms**
  - **Add additional capability to current structure: "multi-functional element"**
  - **Smart materials applicable to morphing structures**
    - **Piezoelectrics, electrostrictives, piezopolymers (electro elastic)**
    - **Magnetostrictives, ferromagnetic SMA (magneto elastic)**
    - **Shape memory alloys, polymers (thermal elastic)**
- **Applicability to real airplanes in the near term**

Integration of Shape Memory Alloys into aerospace materials, such as composites

Advantages To Boeing

- Lighter Weight Aircraft
- Aircraft that Adapt to Changing Flight Conditions
- Low Part Count
- Long Shelf Live
- Increased Range
- Increased Payload
- Reduced Noise
- Reduced Operating Cost
- Reduced Time to Repair or Reconfigure

Simultaneous (Increased Range, Increased Payload)

Shape Memory Alloy Actuators

- **Nickel Titanium based (60-Nitinol, 55-Nitinol, High temp)**
- **High efficiency, low weight, high energy density**
- **Shape Memory Effect**
  - **Thermally activated**
  - **Microstructural phase change produces shape change under load**
  - **Shape change**
    - **Austenite (C) fully immersed**
    - **Martensite (A) retracted**

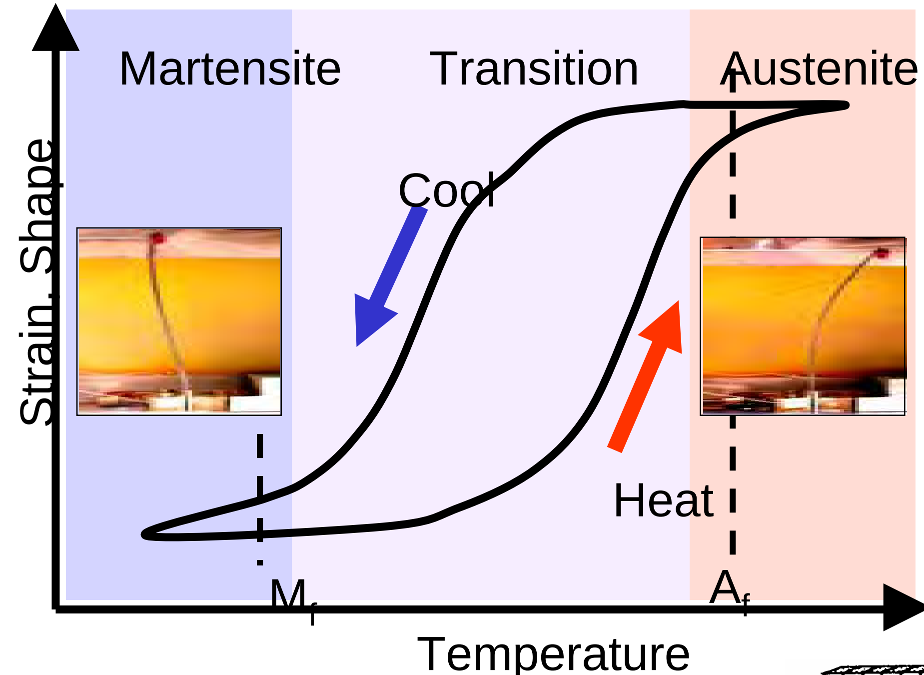
–Thermal management key to actuator operation

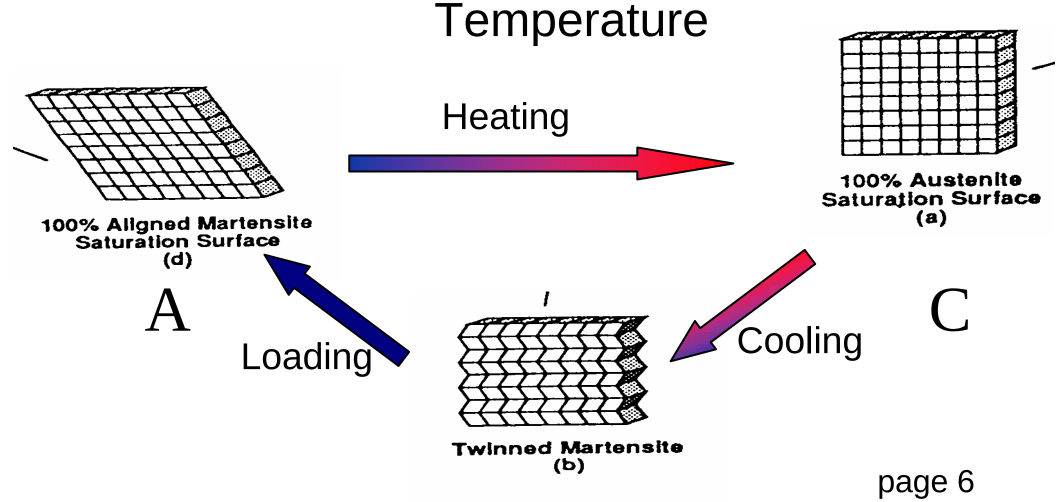
–Other properties of interest

- **–Damping**
- **–Superelasticity**
- **–Hardness**

–Forms

- **–Wire**
- **–Flexure**
- **–Tube**
- **–Other**





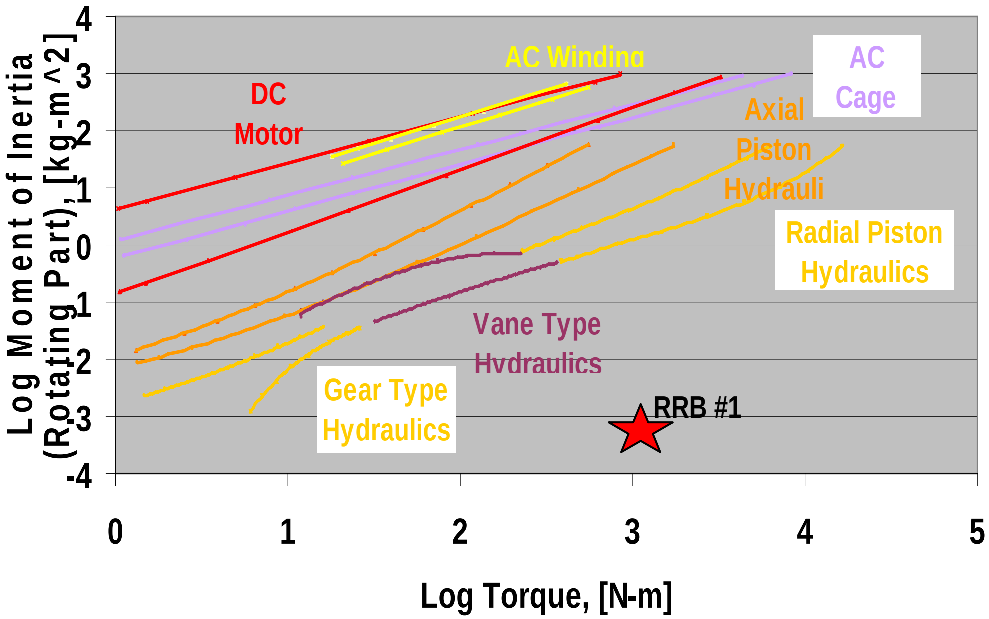
Benefits of SMA Based Design

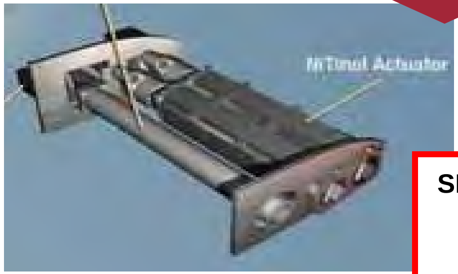
- **SMA Actuator Technology benefits**
  - **Robust Technology**
  - **Lightweight**
  - **Integrates well**
  - **Simple system design**
  - **Flight tested system**
- **Boeing is world leaders in this technology**

Motor:
Torque 66 in-lbs
25 lbs

Gear box :
190 in-lbs
16 lbs

Rotary Actuator Characteristics





SMA Rotary Actuator :
150 in-lbs
1 lbs

Conclusion:

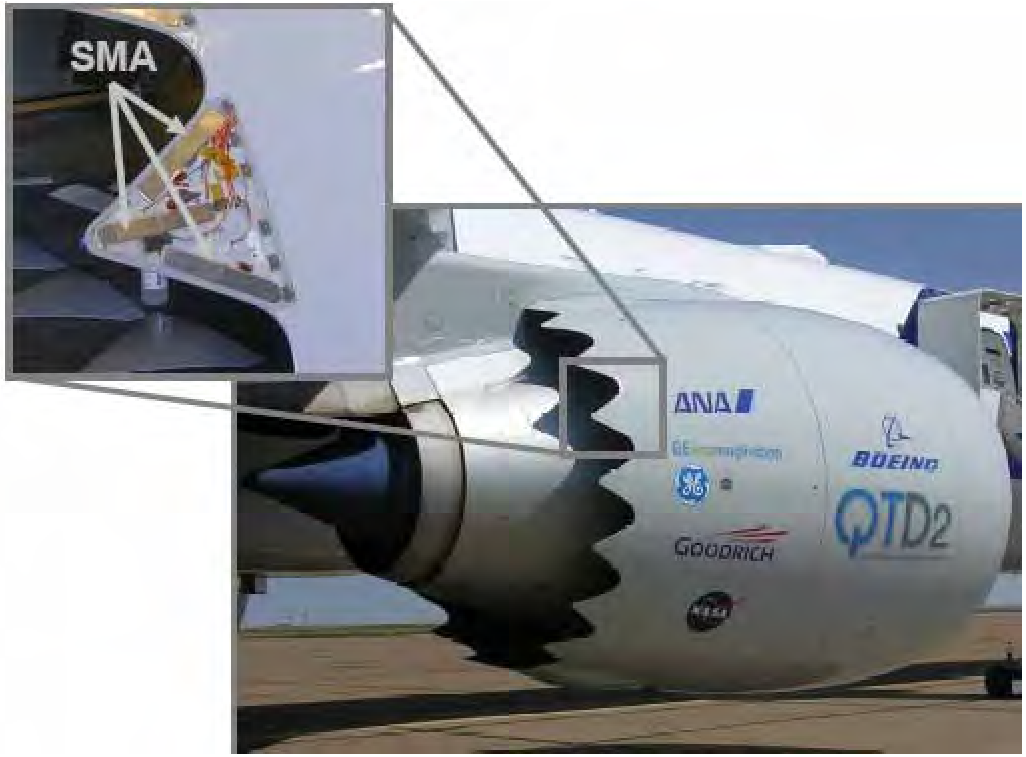
- **NiTinol is ideal for torque high stroke, low duty cycle applications where weight is a premium**
- **Technology can provide major benefits for aerospace applications**

Applications

- **Variable Geometry Chevron**
- **Reconfigurable Rotor Blade**
- **Deployable Rotor Tab**
- **Variable Engine Inlet**

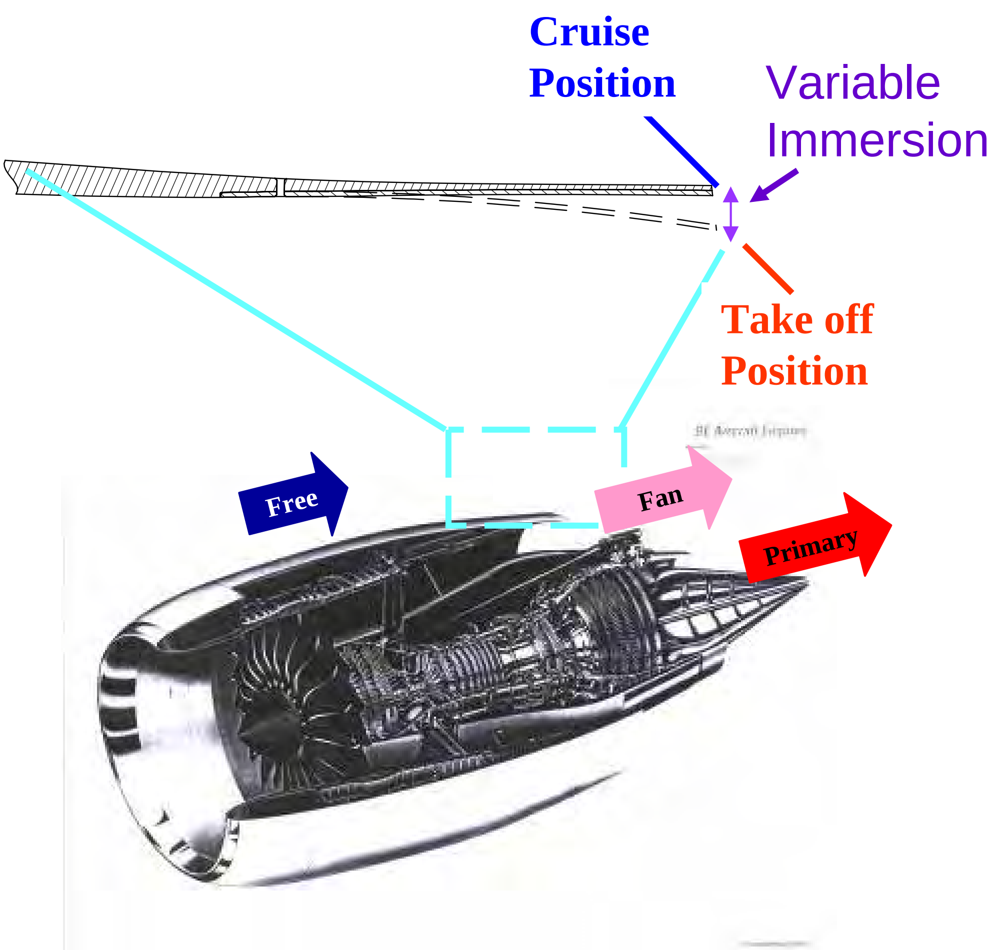
Variable Geometry Chevrons

- **Reconfigurable engine nozzle fan chevron**
- **Apply morphing structures technology to enable efficient chevron shape change**
- **Shape Memory Alloy is key technology**
- **Example of new testing capability**
- **Mature technology TRL level 6-7**



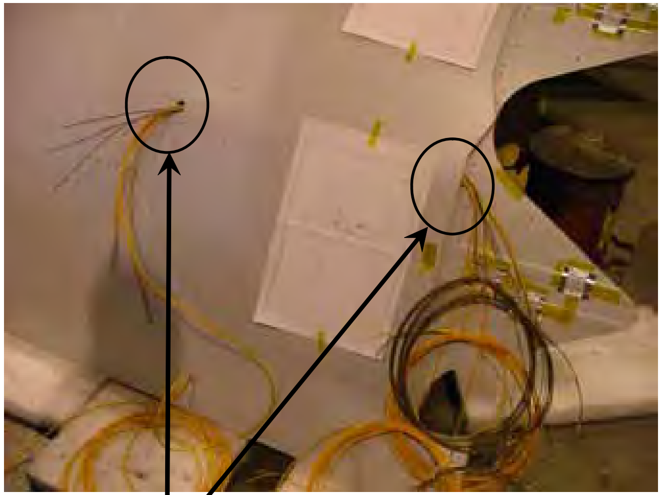
Calkins, 2006

Variable Geometry Chevron Overview



- **Goal: morph chevron shape to optimize engine performance**
  - Community noise reduction
  - Shockcell noise reduction
  - Cruise performance

Improved System Integration



Wires routed through conduit in honeycomb core of inner sleeve.

Inner Sleeve

Outer Sleeve Joined to Inner Sleeve, wiring routed in space between sleeves

VGC was integrated into production design and fabrication processes. Future applications also need look ahead to system level integration issues and wherever possible also use a multi-function approach.

Mabe, 2006

VGC Flight Test/Static Engine Test Overview

BCA Noise Engineering

Flight Tests

- Instrumentation, power, gages, and controller worked without failure
- Demonstrated autonomous (non-powered) operation
- Demonstrate and tested individual VGC control of 9 Chevron configurations.

Flight Test used for development of 787 static fan chevrons

Calkins, 2006, 2007

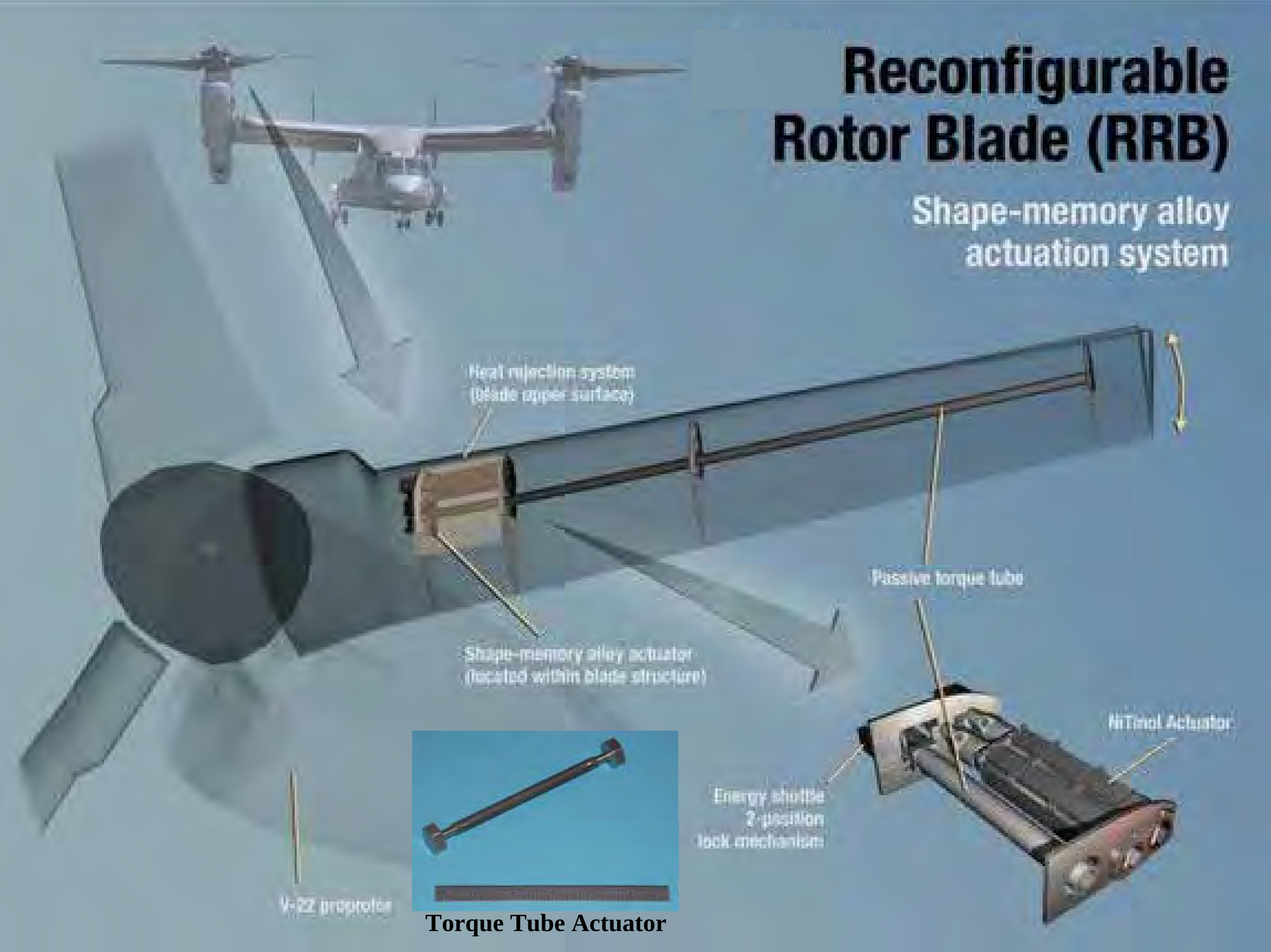
Static Engine Test

- Noise performance evaluated
- Demonstrated full autonomous operation

SMA Actuators Re-engineered for ground based operation.

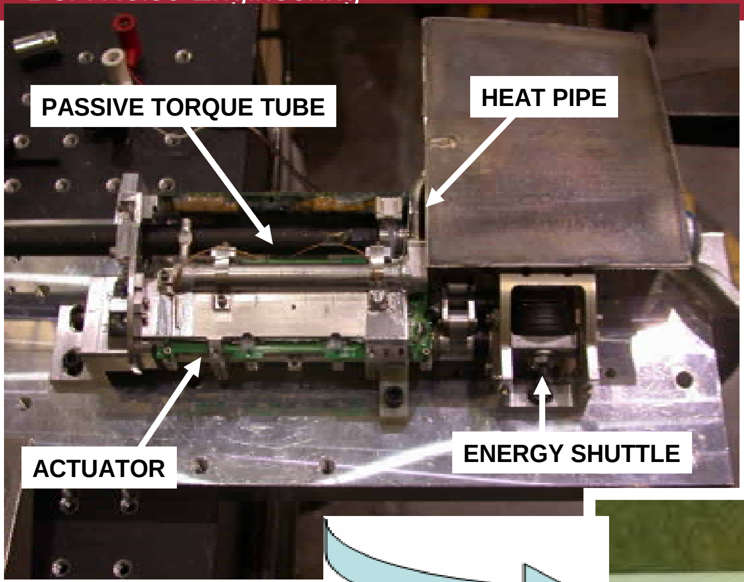
- Higher Transition Temperature
- Increased Authority

787-8

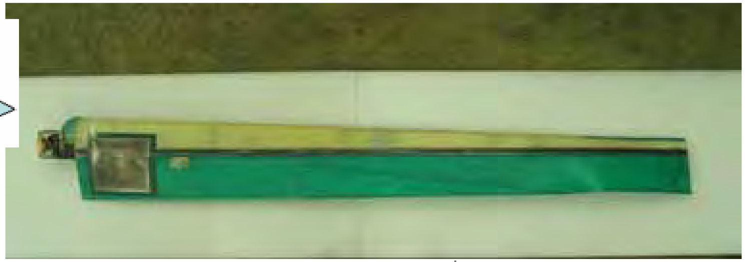


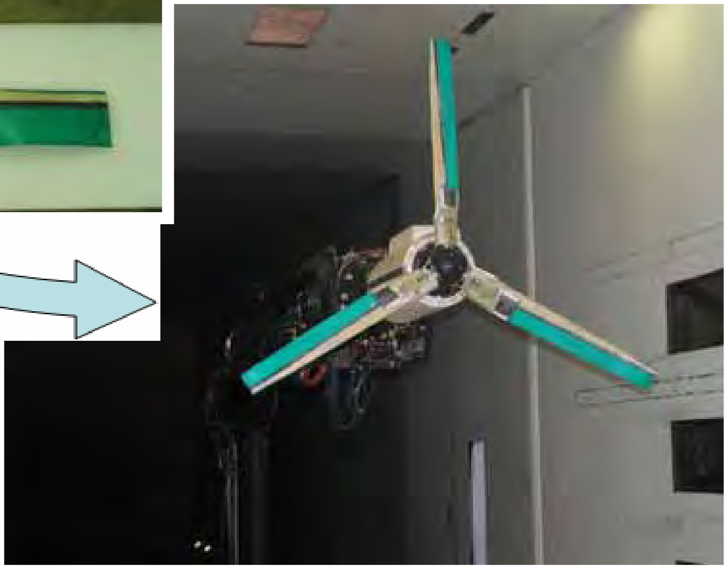
Torque Tube Actuator

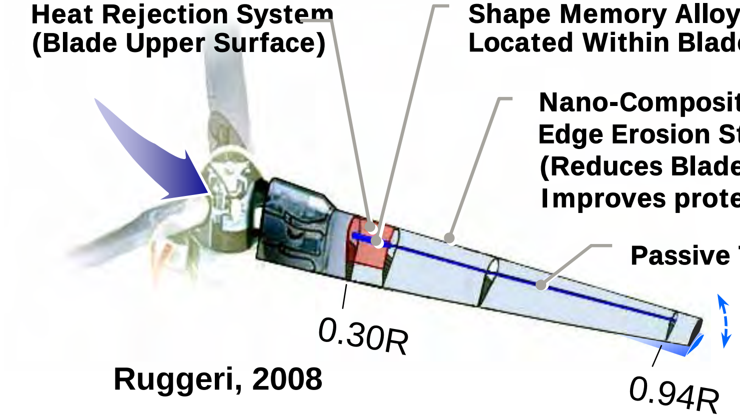
Reconfigurable Rotor Blade (RRB)



- **Blade Twist Change Enhances Aircraft Performance**
  - Entire System weighs < 20 lbs
  - 5000 in-lbs twists blade 2 deg
- **¼ Scale Wind Tunnel Tests Completed**
  - Integrated 3 actuators into CDI-V8 Blades
  - Tested blades in several hovering and axial flight configurations
  - Demonstrated ability of RRB actuation system to morph blade
  - Twist in a rotating environment

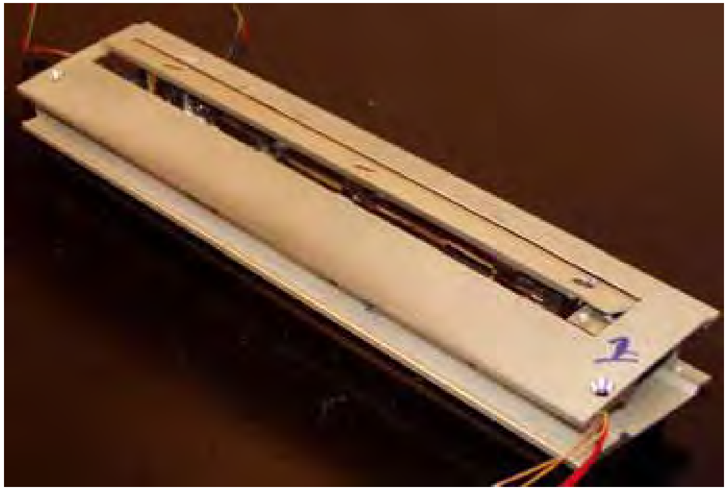






Ruggeri, 2008

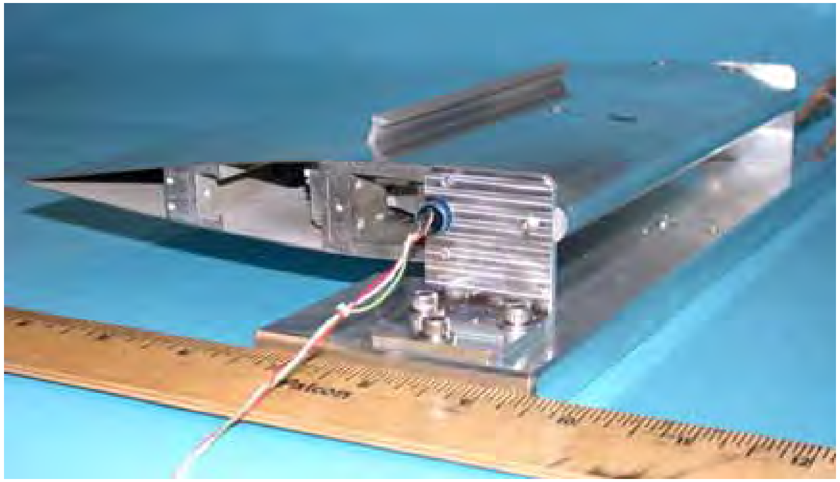
Deployable Tabs for Blade Vortex Interaction Noises Reduction



- **Blade Vortex Interaction (BVI) noise caused by trailing rotor blades impacting vortices created by leading blade during descent.**
- **Deployable tabs or flaps break up vortices and significantly reduce noise.**
- **Conventional actuators too large and heavy.**

<u>Active Hinge Pin Actuator (AHPA)</u>

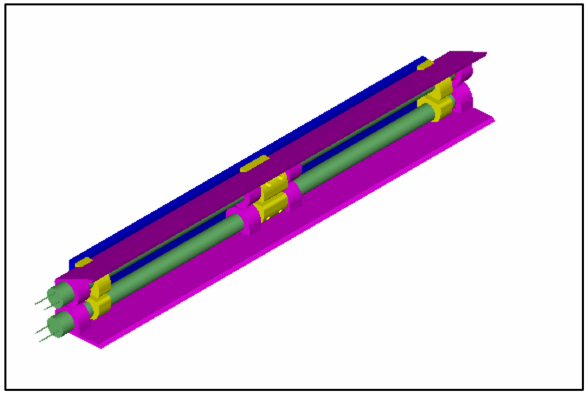
- **Order of magnitude reduction in weight than conventional actuation devices**
- **Compact size to fit rotor blade profile**
- **Ruggedized for harsh rotor blade environment**
- **Fails closed on loss of power**



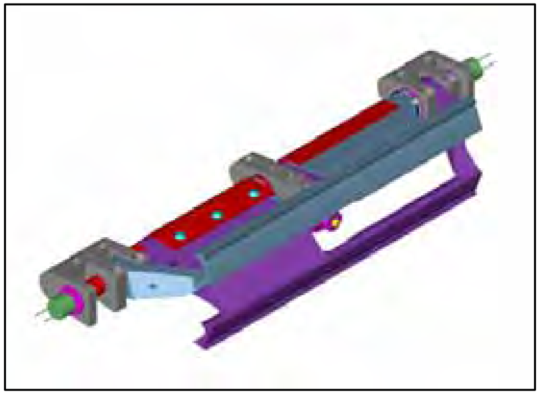
Mabe, 2008

Integration is Key to Application Success

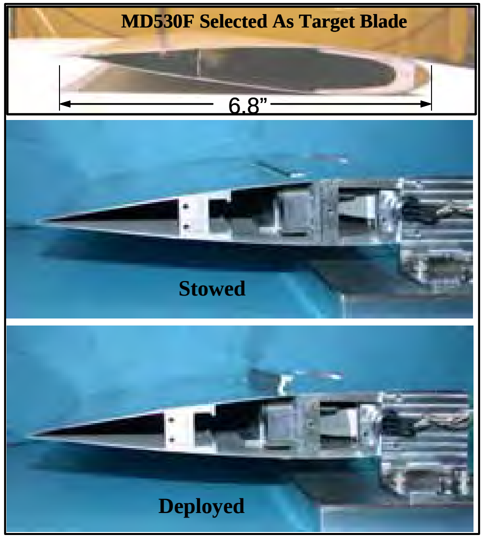
BCA Noise Engineering



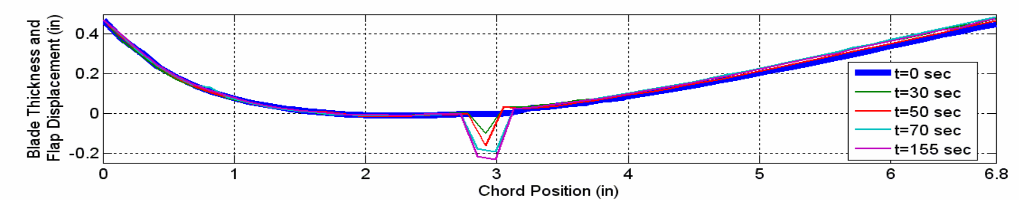
Conventional flap



Double Acting Hinge

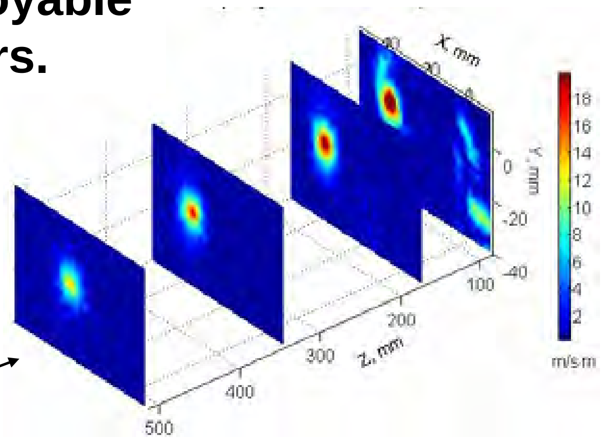


- **Centrifuge and wind tunnel testing of deployable rotor blade devices using SMA actuators.**

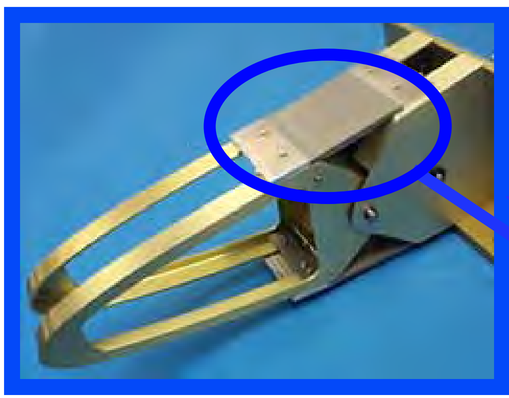


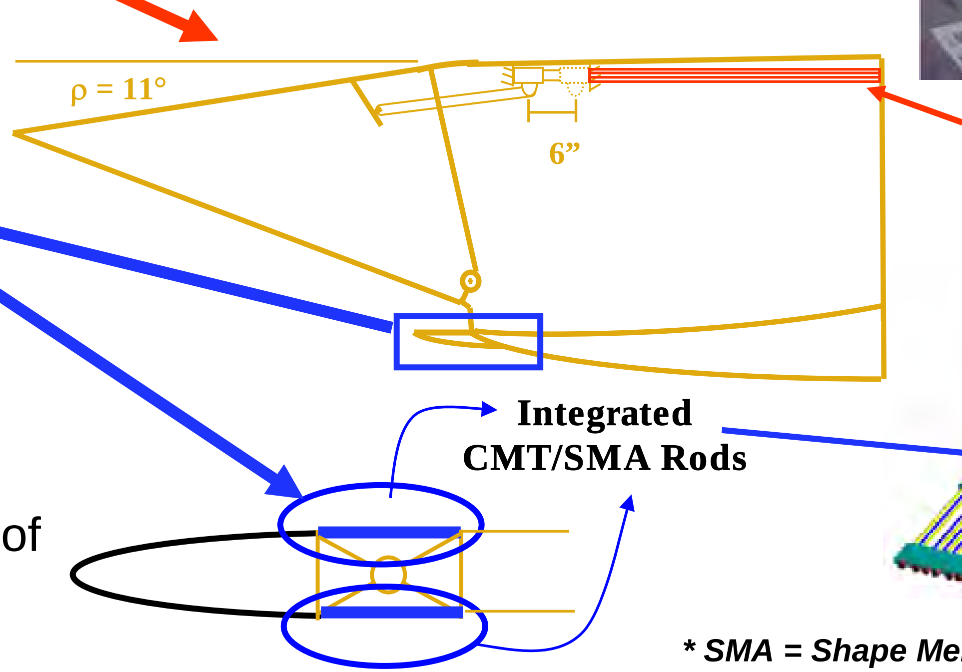
Centrifuge laser data

PIV data

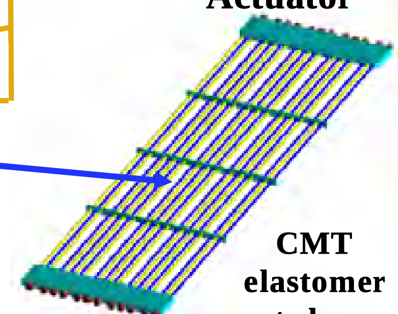


Engine Inlet Duct Shaping





High Force/Disp Antagonist SMA Tendon Cowl Actuator



Adaptive inlet improves performance over a range of flight conditions

**** SMA = Shape Memory Alloy,***
CMT = Conformal Moldline Technology
SAMPSON = Smart Aircraft and Marine Projects Demonstration

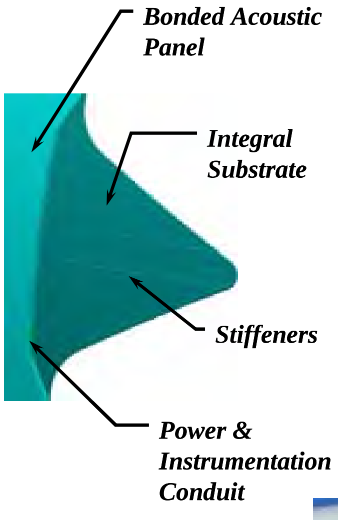
Pitt, 2001

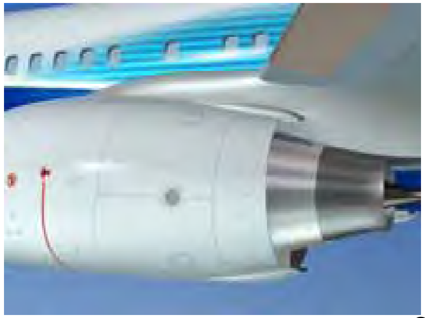
SMA Morphing Structures Design Map

- **SMA high energy density, low weight**
- **Simple design, low part count**
- **Fully integrate actuation into existing structure**
- **Add morphing to structural element: use morphing capability to optimize at multiple conditions**
- **Fast deployment, slower cycling**
- **Autonomous operation, thermal actuation, requires little or no power**

Composite Design Approaches

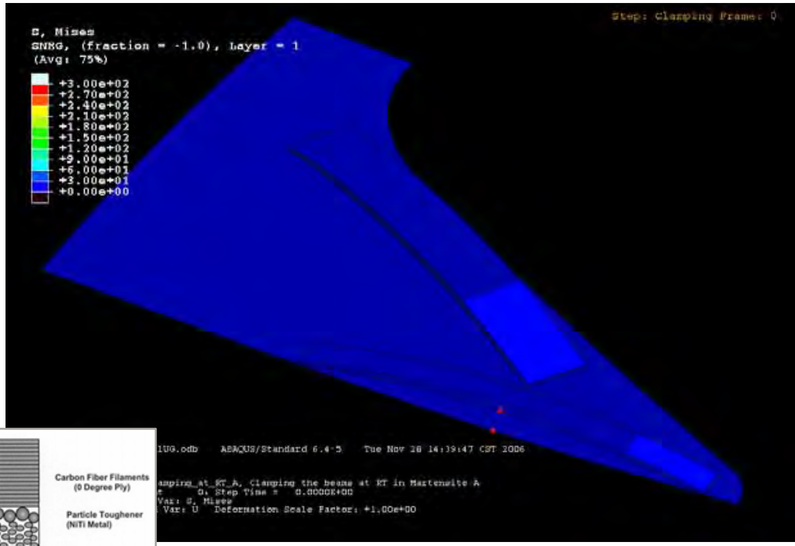
- **Traditional composite**
  - **Stiff, lightweight**
  - **Structural**
- **Multifunctional composite**
  - **Includes other capability (sensing, imbedded electronics)**
- **Morphing composite**
  - **Tailored composite enables motion/shape change**

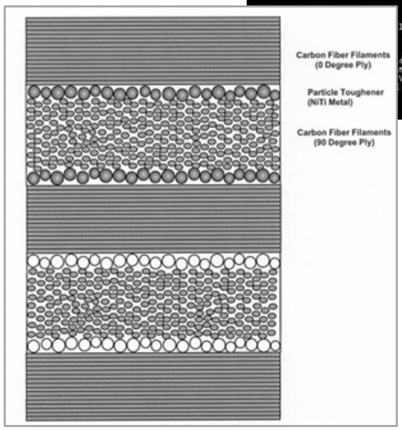




Morphing Structure Needs

- **Tools**
  - **Modeling of structure and actuator**
  - **Improved design and analysis tool (FEA based)**
  - **Optimization methods**
  - **State of the art testing methods**
- **Integration**
  - **Fully integrated: multi-functional elements**
  - **Active structural element design**
  - **Sensing**
  - **Fabrication methods**
- **Composites**
  - **High performance composites designed for morphing**
  - **Reliability**





SMA Based Morphing Structure Future Direction

- **Use technology to explore optimization of at multiple flight/operating conditions**
- **Incorporate more smart material capabilities into structure**
- **Realization of true morphing structures that provide distributed continuous optimization of aircraft performance**
- **Changes design philosophy: design for optimum performance at each condition of interest**
- **Autonomous operation**
- **Explore morphing technology use for future “active” design work**

- **SMA Technology direction**
  - **New Alloys (high temperature)**
  - **Connections**
  - **Fabrication technology**

Summary

- **Technologists goal is to exploit the right technology for an application to meet a Boeing need.**
- **Rapid cutting edge technology development**
- **Full scale flight test validates SMA technology, system approach, and technical readiness for morphing structures.**
- **Current applications provide roadmap for future development.**
- **Factors converging to make this the right time to exploit next generation morphing structures**
  - **SMA technology is ready**
  - **Resources are in place**
  - **Need is there**
- **Composites are needed to facilitate morphing aerostructures**

- **Questions, Comments ?**

References

1. **F. Calkins, G. Butler, and J. Mabe, "Variable Geometry Chevrons for Jet Noise Reduction",AIAA-2006-2546, 12th AIAA/CEAS Aeroacoustics Conference, Cambridge MA, May 2006.**
2. **J.H. Mabe, F.T. Calkins, G.W. Butler, "Boeing's Variable Geometry Chevron: Morphing aerostructure for jet noise reduction," 47nd AIAA Adaptive Structures Conference, AIAA-2006-2142, Newport RI, May 2006.**
3. **Robert T. Ruggeri, Richard C. Bussom, Darin J. Arbogast, "Development of a ¼-scale NiTinol actuator for reconfigurable structures" SPIE Smart Materials and Structures, 2008, paper 6930-21.**
4. **D. M. Pitt, J. P. Dunne, E. V. White, "SAMPSON smart inlet SMA powered adaptive lip design and static test", AIAA-2001-1359,AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, 42nd, Seattle, WA, Apr. 16-19, 2001.**
5. **Mabe, Gravatt Bushnell, Gutmark, Dimicco, Harris, "Shape Memory Alloy actuator for deployable rotor blade aerodynamic device," AIAA 2008-1451.**