Mechanical Systems Roadmap

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- **Areas of Interest:** Computational Mechanics, Impact and Blast Response of Laminated Plates and Shells, Sensors, Optimization of complex multi-disciplinary systems using probabilistic methods, Multi-objective Optimization, Structural Health Monitoring and Energy Harvesting
- **Education:** Ph.D Purdue, M.S. Indian Institute of Science, Bangalore; B. S. Punjab Engineering College, Chandigarh
- **Research Funding:** 75 projects from such sources as AFOSR, NASA, ARO, AFRL, DARPA, ONR, NSF, Aurora, Boeing, GDAMS, Luna Innovations, Adoptec, NIA, and ZONA
- **Key Accomplishments:** 7 Post-Docs, 27 Ph.D., 36 MS. 120+ Archival Journal papers, 220+ Conference Proceedings, 1100+ citations of Journal papers, 2000 & 2010 Dean's Award for Excellence in Research, Associate Editor, AIAA Journal.
- **Teaching:** Intro to Aerospace, Thin-walled structures, Aerospace structures, Vibration and control, Rigid-body dynamics, Finite element analysis, Numerical methods, Vehicle structures, Vibration and flutter

Space Trusses

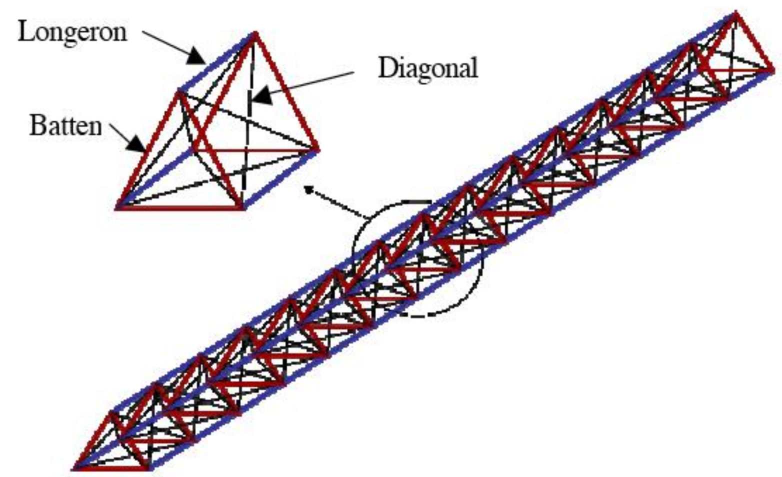
Lattice Structures Using Continuum Modeling

- Obtain continuum Timoshenko beam model for periodic trusses using energy equivalence
- Compare continuum model with FEM for deterministic and random member stiffness properties
- Use anti-optimization to identify maximum errors in continuum model for all types of responses
- Identify best continuum model kinematics to study coupling and warping
- Study reliability using continuum models

Inflatable Viscoelastic Tubes Modal-Damping Analysis

- To study responses of thin pressurized viscoelastic tubular members under various loads using FEM
- Investigate more complex phenomenon of contact, bending and impact loading

Sponsor: DARPA/LANGLEY/NIA to ICAM



Space Truss Visco-elastic Tubular Member Experimentation

End Cap

Boom

Piezo-Patch

Heavy Foundation on Damping Pads

Parameter	Value
Length	1.2255 m.
Radius	0.0508 m.
Thickness	0.00038 m.

Specimen

Picture Source:CIMSS

Optimal Placement of Piezoelectric Actuators on a Space Mirror

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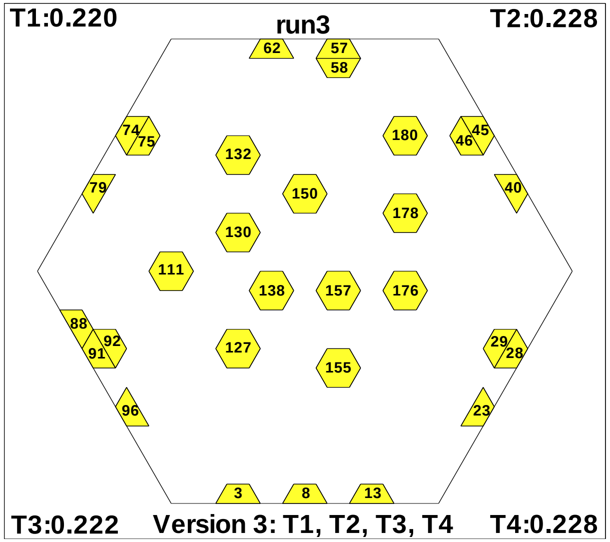
AOE



RMS Error and Optimal Location of 30 Actuators

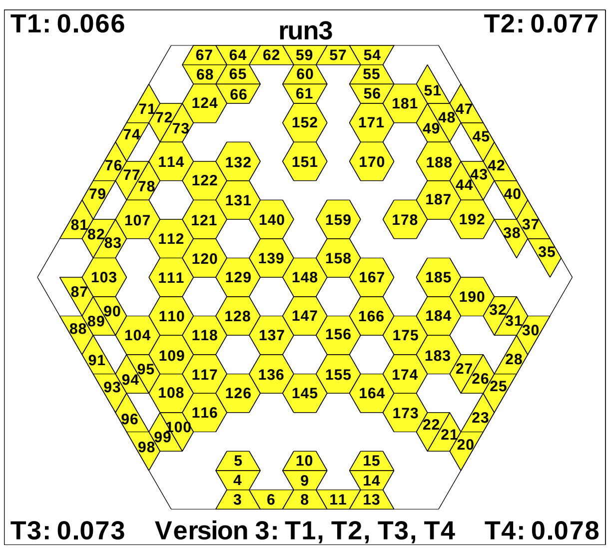
Optimization Problem: Optimal Placement of Actuators on the mirror of astronomical telescope.

The scale of the Problem:

$$ {}^{193}C_n = \binom{193}{n} = \frac{193!}{n!(193-n)!} $$

$$ {}^{193}C_{30} = 1.28866*10^{35} $$

$$ {}^{193}C_{121} = 1.38231*10^{54} $$



RMS Error and Optimal Location of 121 Actuators

Research Objectives:

- Perform Multi-disciplinary Design Optimization of Smart Structures.
- Develop Genetic Algorithms to Obtain Optimal Designs.

Approach:

- Use High Performance Computing to Design Smart Structures.
- Extensive use of FEM and Genetic Algorithms.

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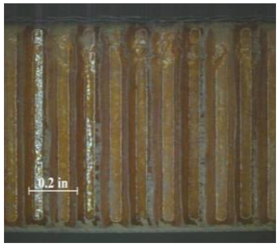
Compression After Impact (CAI) of Thin Facesheet Honeycomb Core Sandwich Panels

AOE

RESEARCH OVERVIEW

- Experiments and analysis which highlight new results for the damage tolerance characteristics of composite, sandwich construction plates
- Experiments at NASA Langley Research Center in Hampton, VA in partnership with the National Institute of Aerospace (NIA)
  - Work done under the direction of Dr. Stephen Scotti and Dr. Sandra Walker

DAMAGE FORMATION



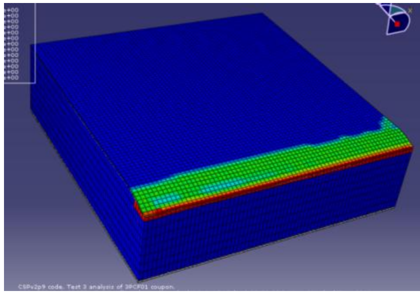
- Damage formation studied for low energy impacts for three unique material systems with heavy lift space vehicle applications
- Impact formation evaluated using destructive and non-destructive evaluation (NDE) techniques

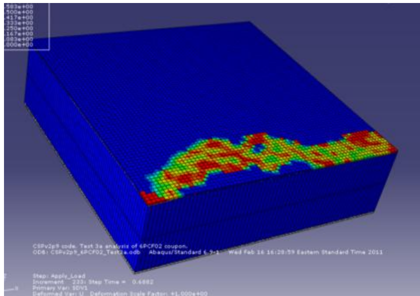
COMPRESSION AFTER IMPACT TESTING

- Test design based on ASTM test standards
- Impact damage levels selected for coupons based on damage formation tests to highlight barely visible impact damage
- Two failure modes encountered
  - Indentation propagation (top right), and crack propagation (bottom right)
- New results for dependency of failure mode on core density

FINITE ELEMENT ANALYSIS

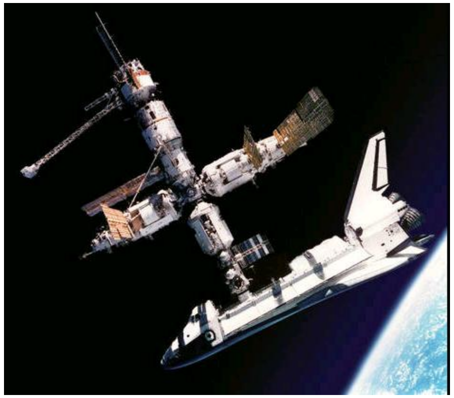
- A new finite element model (FEM) has been proposed for high fidelity representations of both failure modes found in experimental testing
- Increased fidelity of impact damage representation from current models





Mechanical Systems Roadmap: Summary

- Key Technology Areas:
  - Deployables, Docking and Interfaces
  - Mechanism Life Extension Systems
  - Electro-mechanical Systems
  - Design and Analysis Tools and Methods
  - Reliability/Life Assessment/Health Monitoring
  - Certification Methods



Docking Space Shuttle with Space Station
(http://wapedia.mobi/en/International_Space_Station)

Inflatable Space Habitat
(http://students.egfi-k12.org/inflatable-space-stations)

Deployables, Docking and Interfaces: Summary

- *Motivation*
  - *Meet Constraints on Fairing Size, Spacecraft and Spacecraft Separation*
  - *Reliable, Less Costly Interfaces for Connectivity*
- *Needs*
  - *Common Universal Interchangeable Reliable, Verifiable Interfacing*
  - *Generation, Scalable, Revolutionary Deployables with very High Precision*
  - *Extensibility*
  - *Automatic Precision Landing with Hazard Avoidance*
- *Challenges*
  - *Integration of Various Technologies for the System*
  - *Better Modeling of Pyrotechnic Operations*
  - *Correlation Between Scaled and Full models*
  - *Model simulation and Ground Testing of Large Systems*
  - *Develop Tests and Model Correlation to Show very Low Tolerance*
- *Technology Developed*
  - *Common Universal Inter-Changeable Interfaces, Restraint/Release devices, Deployment of Flexible Material, Large Lightweight Stiff Deployable, Mechanism for Auto Precision Landing Hazard Avoidance, an Precision Structure Deploy Mechanisms*

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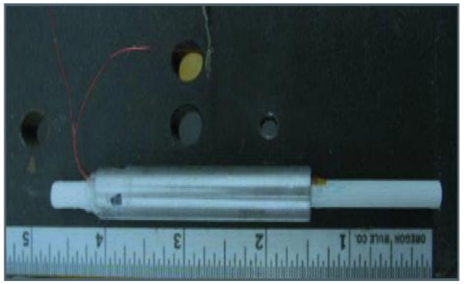
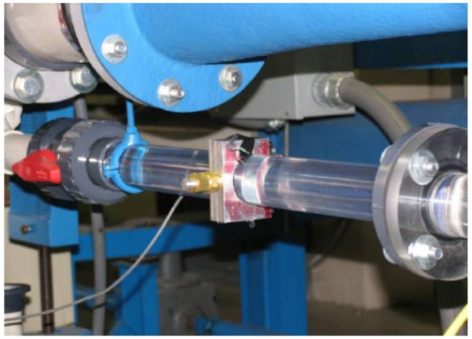
Mechanism Life Extension Systems

AOE

- ***Motivation***
  - *Long Duration Missions Requiring Safety and Reliability in Harsh Environment (Dusty, Cryogenic)*
- ***Needs***
  - *Long Life Bearing/Lubricating Systems for Propellant Depot Type Vehicles*
  - *Long Life Actuators for Scientific Missions in Cryogenic Temperatures*
- ***Challenges***
  - *Life Testing of Complete Systems in Harsh Environments (Non-stationary Random Excitations)*
- ***Technology Products***
  - *Nitinol-60, Silicon Carbide, Titanium carbide, Magnetic bearings, Low-temperature Piezoelectric Materials, Magnetostrictive Devices*



a. PVC Probe in Aluminum Bushing



b. Test Section Installed in Channel

Experimental Setup to Validate Our Modified Code for Flow Induced Vibration Prediction with Allowance for Shear Stress and Mean Response

Electro-Mechanical Systems

- *Motivation*
  - *Successful, Safe, Reliable Operation of and Resupply to Spacecraft, Spacecraft Systems and Space Habitats*
  - *Precision Landing Systems with Attenuated Impact Loads*

- *Needs*
  - *Robotic Assembly*
  - *Servicing of Spacecraft and Spacecraft Components*
  - *Fluid Transfer from Carrier to Storage Depots*
  - *Exploration Vehicles*
  - *Lightweight, reliable Active Landing Attenuation Systems for Safe Landing*
  - *Innovative Sensors, Actuators and Controllers to Avoid Gears*

- *Challenges*
  - *Lightweight Systems*
  - *Sensing, and Actuation Materials Capable of Operation in Cryogenic Environment*
  - *Simulation of Realistic Operating Environment During Testing*
  - *Understanding of System Behavior from Subsystem Behavior*
  - *Lightweight, reliable Active Landing Attenuation Systems for Safe Landing*
  - *Innovative Sensors, Actuators and Controllers to Avoid Gears*

- *Technology Products*
  - *Robotic Assembly Tools*
  - *Ability to Transfer Fluids in Cryogenic Environment*
  - *Active Landing Systems*
  - *Ability to Test in Cryogenic Environment*

Design and Analysis Tools and Methods

- ***Motivation***
  - *Analysis of Complex Systems Using High-Fidelity, Accurate Methods for Design, Certification and Health Management*
  - *Lack of Models for Emerging Materials and Multi-functional Sub-systems (e.g. Landing Systems, Deployment mechanisms, Turbomachinery)*

- ***Needs***
  - *Computational Modeling of the Complete System as Opposed to Iterative Analysis of Subsystems in Series*

- ***Challenges***
  - *Computational Power Needed*
  - *Numerical ILL-Conditioning*
  - *Uncertainty Quantification*
  - *Nonlinear Effects*
  - *Constitutive Law for Multifunctional Materials, Damage Modeling*
  - *Data Transfer*

- ***Technology Product***
  - *Innovative Approaches to Solve Large, ILL-Conditioned Problems*
  - *Analysis Based Health Management*
  - *Analysis-Based Certification*

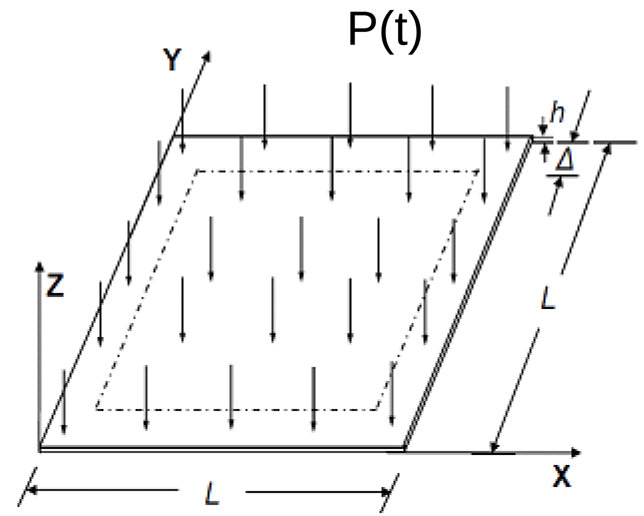
Reliability/Life Assessment/Health Monitoring

- *Motivation*
  - *Reduce the Weight of a Mechanical System and Enhance its Life by Using Structural Health Monitoring*
- *Needs*
  - *Mechanisms' Durability Testing in Mission Environments*
  - *Predictive Damage Methods to Predict as-manufactured and Residual Strength of Mechanical Systems*
  - *Embedded Systems to Provide Predictive and Condition-based Monitoring*
  - *Prediction Tools To Extend Life, Avoid Failures and Assist System Operations*
- *Challenges*
  - *Reproduction of Relevant Environments. Model Correlation of Mechanisms to Effects of Environments*
  - *Miniaturizing and Incorporating Sensor Technology as an Integral part of Mechanical Systems and Accurate Correlation of System Feedback*
  - *Determination of Actual Cumulative Damage, as well as, Establishment of Accurate Life Predictions*
  - *Standardization of Interfaces for Embedded-Technology*
- *Technology Products*
  - *Integrated Structural Health Monitoring System*
  - *Virtual Digital Fleet Leader*
  - *Leakage Detection*

Gossamer Structure SHM using Polymer Nanocomposite Sensor

- Calibration of Nanocomposite for large strain sensing and development of a structural health monitoring system for a prestressed membrane using these sensors

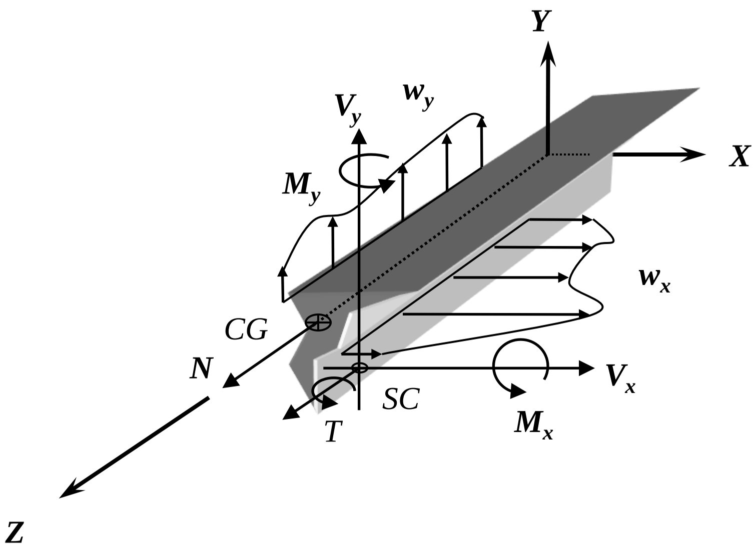
- Calibration of the Nanocomposites
  - Modeling the hysteresis and relaxation in the resistance vs. strain data using modified fractional calculus and Preisach approaches
  - A hysteresis and relaxation compensator to get back strain from resistance data and calibrate the sensor



Prestressed Membrane
Under Dynamic Pressure

- Neuro-fuzzy Based Damaged Detection
  - A prestressed membrane as an example
  - Wavelet packet analysis of the strain history at the sensor locations under a transverse dynamic pressure to define a damage index vector
  - A neuro-fuzzy system to detect damage from the wavelet based damage index vector

Reliability-Based Structural Optimization



Research Objectives:

- Design Optimization under Uncertainties in Loads and Material Properties.
- Comparing between Deterministic and Non-deterministic Methods
- Comparing Different Reliability Approaches
- Comparing Different Response Approximation Techniques
- Comparing Different Optimization Algorithms

Investigators:

Dr. R. Kapania,
M. Ba-abbad
Aerospace & Ocean Engineering

Sponsors:

General Dynamics Amphibious Systems,
Office of Naval Research.

Approach:

- Use Reliability and Statistical Concepts to Improve Safety of Vehicles and Minimize their Life-Cycle Cost.
- Approximation Techniques to Minimize the Computational Costs using Efficient Methods to Calculate Reliability and to Perform Optimization

Benefits:

- More reliable design for the same weight
- Most nuclear power-plants are designed using probabilistic approach

Certification Methods

- *Motivation*
  - *Reduce the Certification Cost of Futuristic Space Systems Using High-fidelity Simulation*
  - *and Minimizing Testing for V&V*
  - *Inability to Simulate the Environment on the Ground*
  - *Include Uncertainties*
- *Needs*
  - *Structural Health Monitoring*
  - *Modeling of Various Failure Modes*
  - *Test Data and Information to develop Various Probabilistic Models*
  - *Test Verified Physics and Modeling*
  - *Efficient Software including Reduced-Order Modeling*
- *Challenges*
  - *Lack of Information about the Loads and Environment*
  - *Not all Failure Modes are known for Novel Synthesized Materials*
  - *Reliability of Computers, Software, Telemetry used in Data Transfer*
- *Technology Products*
  - *A Knowledge of Loads and Environment*
  - *Reliability-Based or Probabilistic Design as Opposed to Ad-hoc Factor of Safety Based Design*
  - *Digital Certification*

Response to Specific Questions

- *What are the top technical challenges in the area of your presentation topic?*
  - *Miniaturization to Reduce the Weight*
  - *Lack of Information about the Loading Environment*
  - *Effect of Radiation on Material Properties*
  - *Analysis and Design of Multidisciplinary Systems (Information Management) Reliable Software*

- *What are technology gaps that the roadmap did not cover?*
  - *Energy Requirements for all the subsystems and systems, computers, sensors, actuator*
  - *Is Energy Harvesting the Answer?*
  - *Fiber-Optics based Sensors*
  - *Distributed Sensing*

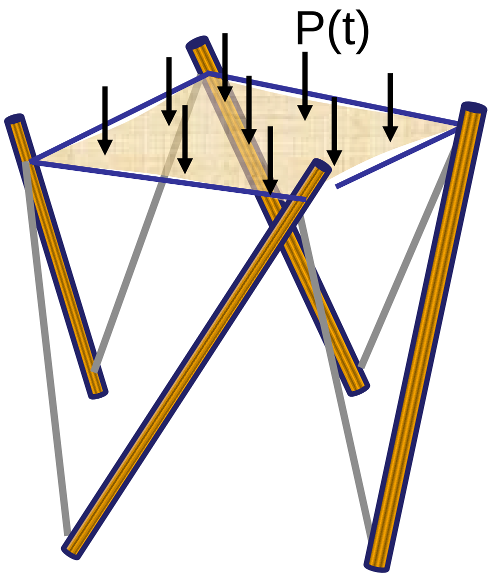
- *What are some of the high priority technology areas that NASA should take?*
  - *Miniaturization and Optimization of Various Systems*
  - *Development of Reliable Software for Multi-system Analysis*
  - *Failure Modes of Multifunctional Materials*

- *Do the high priority areas align well with the NASA's expertise, capabilities, facilities and the nature of the NASA's role in developing the specified technology?*
  - *Yes. NASA had been a leader in multi-disciplinary analysis and design, damage progression in composites, has extensive facilities for systems large and small*

Tensegrity Structure's Energy Harvesting

- Harvesting energy from the vibration of a membrane attached to a tensegrity structure using electro-mechanical transducer

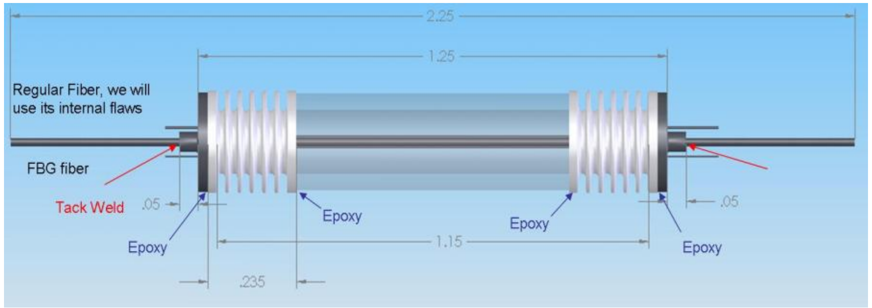
- Accomplishments
  - Adomian decomposition method to estimate the energy harvested from a membrane (without the tensegrity structure) restrained at the four edges
  - Harvested energy maximization
  - Found out the stable equilibrium of a tensegrity structure with a membrane
  - Estimation of the harvested energy



Prestressed Membrane on a Tensegrity Structure

- Future Goals
  - Optimization of the transducer locations, rest lengths of the tendons and membrane to maximize the harvested energy
  - Experimental validation

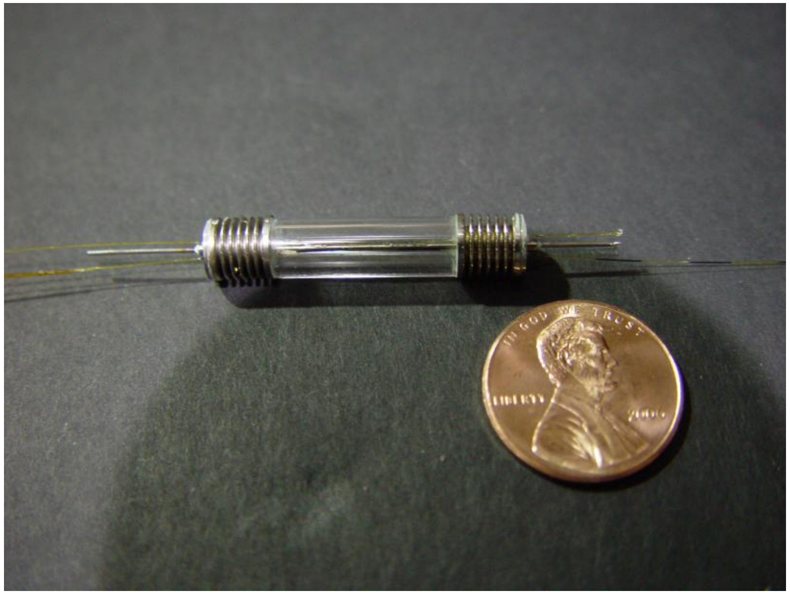
Pressure Sensor for Harsh Environment



R. K. Kapania & J. A. Schetz in collaboration with Luna Innovations,
Funded by NASA STTR

BENEFITS:

- For use in Nuclear Power-plant simulators
- Oil Wells
- 800^{o}C, 350 psi



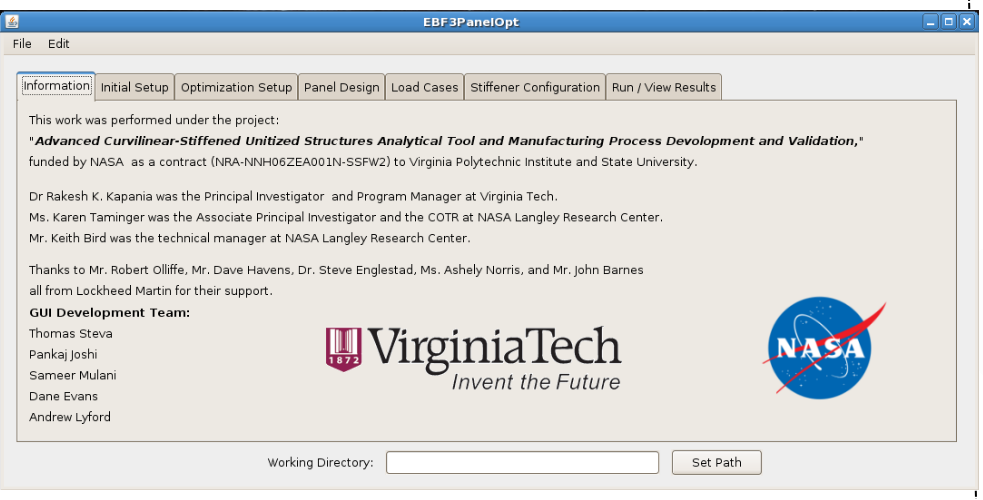
Response to Specific Questions (Contd.)

- *In your opinion how well NASA's proposed technology development effort is competitively placed.*
  - *I believe it would be quite competitive with any international entity. It should not seek to be competitive with any US entity; instead should be collaborative. For example, digital certification is something that is very important to the Air Force, the commercial aircraft manufacturers, the automobile industry, and the FAA as well.*
- *What specific technology we can call it as a "Game Changing Technology"?*
  - *Fabrication of a part from a CAD file to a 3-D object using additive manufacturing with sensing, actuation, computing, damage detection, and self-rapairing all built into a structure, in short an autonomous structure.*
  - *Reliable software that can do multi-system analysis accurately without conditioning problems*
- *Is there a technology component near the tipping point? (tipping point: technology insertion with small additional investment)?*
  - *Structural Health Monitoring (SHM)*
- *In your opinion what is the time horizon for technology to be ready for insertion (5-30 year)?*
  - *SHM in 5 years of metallic and more than 10 of composites, digital certification in 10 years, reliable autonomous structures in 25 years, digital certification of autonomous structures in 30 years.*

Curvilinearly Stiffened Panel Optimization

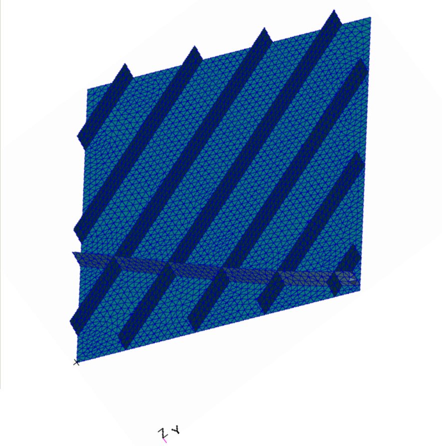
EBF3PanelOpt : Stiffened Panel Optimization with Curvilinear Stiffeners

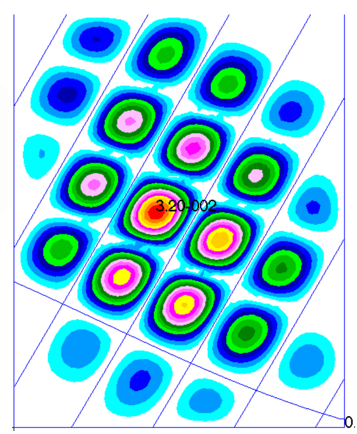
- Uniform/Non-Uniform Thickness for Flat/Curved Panel
- Blade-type Stiffeners (any number) and on Either Side of Panel or Both Sides
- Utility to Create Standard Panel Geometry (PATRAN), Supports Manually Created Complex Panel Geometries
- Multiple Load Cases Including Acoustics
- Coarse-Grained Parallel Processing
- Robustness for Optimization



Grid-Stiffened Panel Optimization with Curvilinear Stiffeners

- Grid of Blade Stiffeners based upon Applied In-plane Loads
- Curvilinear Orthogonal/Non-orthogonal Stiffeners
- Results in Mass Saving as Compared to *EBF3PanelOpt*
- Aligns Stiffeners along the Nodal-lines of the Buckling Mode Shape.
- Higher Order Buckling Mode Shape
- Optimal Design Has the Most Sub-pockets or Lobes





Response to Specific Questions (Contd.)

- *Provide a sense of value in terms of payoffs, risk, technical barriers and chance of success*
  - ***SHM has a tremendous pay-off*** *beyond space applications, technical barriers are embedded sensors, solution of inverse problems is still an art.*
    - ***Chances of Success Very High***
  - ***CAD to 3-D manufacturing of autonomous structures would be truly revolutionary****, risks include understanding complexity of structures made of synthetic materials, automatic repair would be the key technical barrier.*
    - ***Chances of Success High***
  - ***Probabilistic Design and Digital Certification also extremely important.*** *Significant Cost Savings. The Technical Barrier there is lack of information both in terms of failure modes and probabilistic models.*
    - *Chances of ``Success'',* ***Low to Moderate.***