National Aeronautics and Space Administration

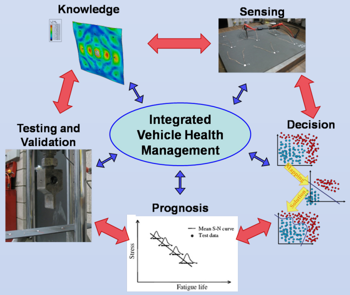
An Integrated Vehicle Health Management approach to Heterogeneous Structural Systems

Aditi Chattopadhyay, Antonia Papandreou-Suppappola, John Rajadas (Arizona State University)

Objectives:

- **Physics based modeling of impact damage & wave based interrogation for virtual sensing**
- **Data reduction and damage classification for state awareness**
- **Damage localization using sensor arrays in composite systems**
- **Sensor scheduling for robust damage assessment**

Research supported by NASA's Integrated Vehicle Health Management Program

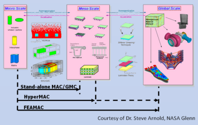


Damage Modeling

IMPACT ON COMPOSITE BEAM

MOTIVATION

- Physics based multiscale modeling necessary to get insight into damaged state of material
- Identification of damage parameters that can be used as effective damage indicators for state awareness
- Essential link between state awareness and damage prognosis
- Existing off-the shelf sensors are not capable of detecting small damage; physics based models can be used to provide virtual sensor data for damage characterization in SHM
- Provides database for life model in prognosis



Courtesy of Dr. Steve Arnold, NASA Glenn

OBJECTIVE

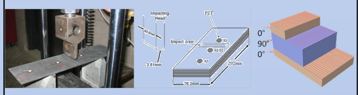
- Develop an explicit multiscale model for damage characterization of continuous graphite epoxy laminates under low speed impacts
- Experimental study to validate impact model for damage progression
- Piezoelectric sensing and Non-destructive evaluation (NDE) to characterize damage for Structural Health Monitoring

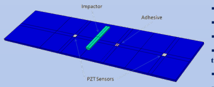
PROGRESSIVE FAILURE

- Apply loading progressively
- When subcell reaches failure criterion, reduce stiffness to specified percentage of original

- Global stiffness reduced
- Continue loading until global (unit cell) failure criterion satisfied

EXPERIMENTAL AND SIMULATION SETUP

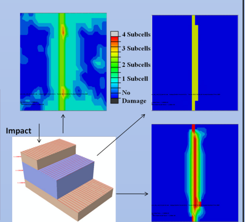




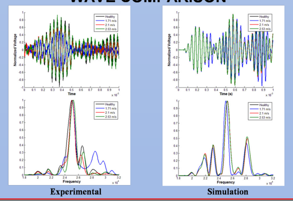
- $[(0/90)]_{4s}$ CFRP composite experiment
- $[(0/90)]_{s}$ CFRP composite simulation
- 15.9 Kg impact head
- Impact velocities 1.71, 2.1, and 2.53 m/s
- Bonded APC 850 piezoelectric transducers
- Three point bending BC's
- Used continuum shell elements and used MAC material within the impact zone

DAMAGE COMPARISON AFTER 2.53 m/s IMPACT

- Experimental shows impact distributed throughout beam
- Simulation has distributed damage & correlates well with experiment



WAVE COMPARISON

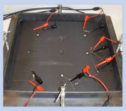


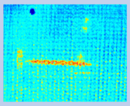
Time domain waveforms show good correlation but it is hard to tell the differences between the signals. FFTs show the damage progression and signal changes better than time response

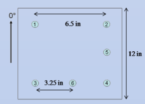
Data Reduction and Classification

EXPERIMENTAL SETUP

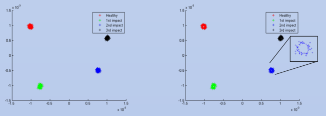
- $[0,90]_s$ composite laminate
- Charpy style impactor
- Hemispherical tup (35mm dia.)
- 20 Joule impact
- Clamped boundary condition



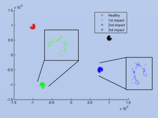




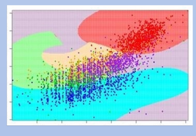
FEATURE EXTRACTION/DATA REDUCTION



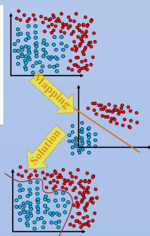
- Feature Extraction using Relevance Weighted Linear Discriminant Analysis (RWLDA)
- Data reduced by
  - Eliminating interior points in each cluster
  - Removing exterior points that do not affect decision plane



SUPPORT VECTOR MACHINES



- Data not easily separable or nonlinearly separable in input space
- Possible to map to high dimensional space for easier separation.



CLASSIFICATION RESULTS

CR using S2		Predicted Damage State C0	C1	C2	C3
Actual Damage State	C0	1	0	0	0
	C1	0	1	0	0
	C2	0	0	1	0
	C3	0	0	0	1

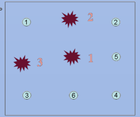
C0: Healthy plate

C1: 1st impact

C2: 2nd impact

C3: 3rd impact

- 40% computational time reduction
- 79% data reduction
- Time required for data reduction : 0.18s
- Training time with reduced set : 4.61s



Damage Localization

ACTIVE DAMAGE LOCALIZATION USING GUIDED WAVES

Motivation

- Composite components used more frequently in critical aerospace applications
- Wave based methods provide large sensing distance with minimal sensors
- Localization in composites needs to be expanded

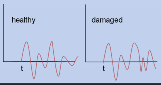
Objectives

- Develop active localization method for composite materials
- Verify functionality of localization code
- Calculate damage position

Key Issues

- Wave propagation complicated in composites
- Dispersion and wave velocity must be carefully studied
- SHM methods must be adapted for composites

Signals from active method

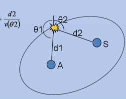


ELLIPTICAL LOCALIZATION DEVELOPMENT

Velocity as function of theta

- Difference between healthy and damaged signals at time t after actuation
- Results in a scaling of the ellipse due to wave velocity
- d1+d2 not constant because velocity is dependent on wave mode and orientation

$$t = \frac{d1}{v(\theta 1)} + \frac{d2}{v(\theta 2)}$$



Time contour map creation

- Time for wave interaction calculated for each point in a discrete grid representing the structure

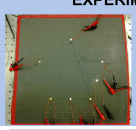
$$t_i^{1,2} = \frac{\sqrt{(x_i - x_1)^2 + (y_i - y_1)^2}}{v(\theta 1)} + \frac{\sqrt{(x_i - x_2)^2 + (y_i - y_2)^2}}{v(\theta 2)}$$

- Time contour map transformed into damage map using extracted damage time

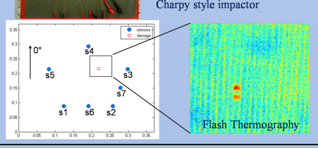
$$E_i^{1,2} = \begin{cases} t_i^{1,2}/t_{damage1} & t_{damage1} > t_i^{1,2} \\ t_{damage1}/t_i^{1,2} & t_i^{1,2} > t_{damage1} \end{cases}$$

Guided wave velocity dependent on wave mode and ply orientation

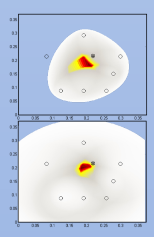
EXPERIMENTAL SETUP



- (0/90)s carbon fiber laminate test sample
- APC 850 piezoelectric transducers (diameter = 0.25in)
- 20 Joule impact using modified Charpy style impactor



DAMAGE LOCALIZATION



25 kHz Interrogation

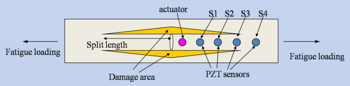
	x position (m)	y position (m)
Calculated damage position	0.208	0.183
Actual damage position	0.218	0.217
Absolute Error	0.0354 m	

50 kHz Interrogation

	x position (m)	y position (m)
Calculated damage position	0.186	0.201
Actual damage position	0.218	0.217
Absolute Error	0.0358 m	

Sensor Optimization

SENSOR OPTIMIZATION FOR NOTCHED LAMINATE IN FATIGUE



Objective:

- Estimate damage growth given sensor measurements
- Select an optimized sensor configuration to reduce damage estimation error

PROBLEM FORMULATION

- Damage parameter model

  Physics based damage progression model [S. M. Spearing et.al., 1992]

$$x_n = x_{n-1} + \chi \cdot \lambda\left(\frac{\frac{1}{2}(\Delta P)^2 \,\partial C/\partial x}{G_s t + G_d x_{n-1} \tan\alpha}\right)^{m/2}$$

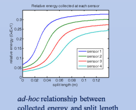
split length

we introduced a variable with a log-normal probability density distribution in the model in order to to compensate for any modeling errors ==> parameter model is now stochastic

- Two proposed measurement models $p(y_n|l_n, z_n)$:
  - Apply a different hidden Markov model (HMM) for each split length based on different time-frequency features
  - Assume a different energy variation with respect to split length for each sensor
- Assuming S independent sensors, then:

$$p(y_n \mid x_n, z_n) = \prod_{s=1}^{S} p(y_{n,s} \mid x_n)^{z_n^s}$$

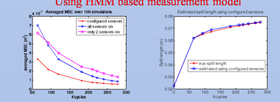
where y_n^s is the measurement from the sth sensor.



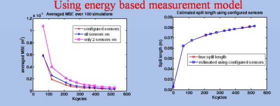
ad-hoc relationship between collected energy and split length

SIMULATION RESULTS USING 4 SENSORS

Using HMM based measurement model



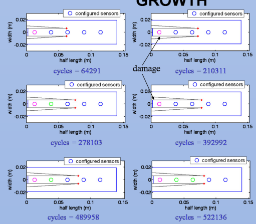
Using energy based measurement model



Averaged MSE

Estimated split length

CONFIGURED SENSORS WITH DAMAGE GROWTH



actuator

sensors not selected

sensors selected

- Demonstrate only half of the sample with sensors.
- We demonstrate the sensors selected by the optimization algorithm (blue sensors) as the damage increases with the number of cycles.