CRYO-COOLING THERMOGRAPHY:
Health Monitoring of Composite Cryogenic Fuel Tanks

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INTRODUCTION

- Composite fuel tanks for RLV’s
  - crucial for weight reduction
  - structural load path
  - cryogenic hypergolic fuel

- Health monitoring system necessary
  - safety
  - longevity of vehicle, investment
HEALTH MONITORING

- Visual inspection and Ultrasonic ground testing
  - expensive labor costs
  - long down times
  - pre/post flight
  - difficult with TPS and insulation or high damping ratio

- Embedded gauges
  - strain, thermocouples, crack gauge, piezo
  - high manufacturing costs
  - complicated manufacturing issues
  - difficult interpretation
SOLUTION

- Infrared Thermographic Imaging
- Non-destructive, non-contact, simple

Processing Unit ➔ IR Camera

Heating/Cooling Source
Theory

Thermal conductivity and density dependant
Phase Lag w/Fourier analysis

\[ \frac{\partial T}{\partial t} - \frac{\partial^2 T}{\partial x^2} \]

Thermal Diffusivity

\[ T(x, t) = \frac{I_0}{\omega} e^{\omega x} e^{j\omega t} \]

Thermal Wave

\[ \frac{1}{\sqrt{\frac{2 \pi}{\frac{\partial}{\partial x}}} \frac{\partial}{\partial c}} \]

Thermal Length

Thermal conductivity and density dependant
Phase Lag w/Fourier analysis
THERMOGRAPHY

- **Pulse Thermography**
  - flash lamps for excitation on surface
  - local temperature variation produced on surface
  - thermal waves very damped, short travel, limited energy

- **Lock-in Thermography**
  - modulated heat source
  - reflection of thermal wave, amplitude & phase detected
  - surface reflections or outside sources eliminated
  - depth dependent on how low modulating frequency; slow!
Cooling Down Thermography

- CDT new approach
  - samples are pre-heated to a uniform temperature
  - infrared camera used to monitor temperature decay
  - quality control in thermally treated products originally

- Differences
  - Thermal perturbation travels half the distance
  - quicker results, better resolution
  - less flexible, suited to specific problems

- Applications
  - deep defects and delaminations
  - insulating and coated materials
Fig. 7 - Phase image with lock-in thermography at 0.0037 Hz.

Fig. 8 - Images with cooling down thermography on same sample as in fig. 8.
(left: after 1.5 minutes; right: after 4 minutes)

“Cooling Down Thermography: principle and results for NDE” -- Danesi, Salerno, Wu, Busse
CRYOGENIC APPLICATION

- Cryo-Cooling Thermography (CCT)
- Adaptation of CDT to suit cryo-tank applications
- Generally improves detection of flaws in composites
  - High conductivity of CFRP
  - High insulative properties of GFRP
- Faster, Cheaper and more Efficient
  - Cryogens appear distinctly, quickly because of extreme \( T \)
  - No heating source required, can use energy of system often
  - Less post processing then with heat waves
EXPERIMENTAL SETUP

- Stainless steel tray on foam insulation to contain LN2
- 150L dewar of LN2, refill tray every 10 minutes
- 20 mil AL plate to provide uniformly cooled flat surface
- Inframetrics Thermocam™ 1000 with focused lens
- Images monitored and captured on laptop computer
- Samples placed on cooling surface, immediate results
TEST MATRIX

- **Embedded** Teflon, epoxy joints and sensors in CFRP
- **Cracks** due to thermal loading in untoughened epoxy
- **Voids** in airfoil sections
- **Disbonds** in rotor blades
- **Impact** damage in insulating sandwich panel
- **Leak** detection through insulation
- **Damage** due to thermal shock in pressurized cylinder
EMBEDDED
CRACKING
DISBOND
VOIDS
IMPACT
LEAKS
DAMAGED CYLINDER

- Composite cylinder, 1” diameter, 1’ long
- One end sealed with steel plate and epoxy
- Open end sealed with vacuum bag and tape

- Filled with LN2, sealed to allow gas to pressurize
- Could not cause cracks, so tank appeared uniform
CONCLUSION

- CCT very successful method of NDE for composites
- One of few techniques that can investigate insulation
- Practical for many aerospace applications
  - quick and simple
  - economical and portable
  - accurate and reproducible
- Procedure depends on application, can be specific
- Viable option for in flight fuel tank monitoring
FUTURE WORK

- Same line of tests with more controlled specimens
- Small scale pressurized fuel tank
- Time constant characterization of various insulation

Ultimate goal
- utilize digital analyzer to try to remotely detect damage
- computer characterization; take human out of loop