NEW TECHNIQUES IN THERMAL NONDESTRUCTIVE TESTING

Introduction: Basics of Infrared

Technical diagnostics

Active NDT of materials

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Thermal NDT
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Basics of Infrared Thermography
The grand five in nondestructive testing:

ultrasonics, X rays, liquid penetrants, magnetic particles & eddy currents

Infrared Thermography № 6
What makes IR thermography so useful?

There are, at least, five things which make IR thermography so uniquely useful.

• It is non-contact – uses remote sensing
• It is two-dimensional – produces images
• It is accomplished in real time
• It senses heat losses which irreversibly accompany human activity
• It is applicable to both metals and non-metals
Thermal NDT

- Image analysis
- Camera handling
- Thermal science
- Applications
- Radiation science
- Inspection routines and reporting
Thermal NDT

What is an Infrared System?

- Night Vision
- Search & Rescue
- Surveillance
- Alarm systems

Technical Diagnostics
- Predictive Maintenance
- Condition Monitoring

Nondestructive Testing (NDT) of Materials (thermal stimulation is required)

Processing software

Infrared imager

Atmosphere

Test target

Computer
**Thermal NDT**

Visible light

- Gamma (0.1 Å - 1 Å)
- X-ray (1 Å - 10 Å)
- UV (10 Å - 0.1 μm)
- Infrared (0.1 μm - 10 μm)
- Microwave (10 μm - 1 mm)
- Radiowaves (1 mm - 1 km)

Visible: 0.4-0.7 μm
Near IR: 0.8-1.7 μm
Short wave IR: 1-2.5 μm
Mid wave IR: 2-5 μm
Long wave IR: 8-14 μm

3-5 μm (Middle Wave) and 7-13 μm (Long Wave) wavelength bands are typically used in IR thermography.
Thermal NDT

Infrared Imagers
Thermal NDT

Opto-mechanical scanning

High-precision mechanics

A typical array consists of tens thousand of sensitive elements

Two Types of IR Imagers
Thermal NDT

Infrared Image

- Dark areas: cold, bright areas: hot
- What does this IR image tell about?

Standard IR images reflect distribution of “radiation” ("apparent", "effective") temperature across a building facade. Special data processing may provide versatile information on issues of interest.
Night vision
Thermal NDT

Night Vision (Police Operations)
IR Thermography Exotics: Counting Deer in an Open Field at Night (at 400 m distance)
Technical diagnostics
Applications: Technical Diagnostics in Industry

In Russia, IR Thermographic diagnostics of tanks with liquid ammonia is obligatory by law.

At Tomsk Polytechnic University, the federal guidelines on the evaluation of industrial chimneys have been developed.
Thermal NDT

Technical Diagnostics in Industry

Defective rod insulator: $\Delta T = 10^\circ C$

Defective rod insulator: $\Delta T = 4^\circ C$

Porcelain and Polymer Insulators

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A typical defect in bolt joints is the absence of washers when connecting copper wires with a flat outlet made of copper or aluminum. It is recommended to perform the IR thermographic inspection of bolt joints once a year because defects appear continuously depending on load, impact of chemical reagents, grade of tightening, etc.
Thermal NDT

Steam Line Surveys

Manhole Cover

Leak Underground

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Thermal NDT

Inspection of Trains with Radioactive Wastes
(Germany, 2010)
Active NDT of Materials
Active Thermal NDT of Materials (Pulsed & Thermal Wave, or Lockin Techniques): Optical Heating
Basic Inspection Procedure

Step 1:
- Test modeling & optimization, or
- Having the NDT standard, or
- Having the experience with the object to be tested

Software

Step 2:

Choosing hardware

Step 3:

Performing the test and recording data

Step 4:

Processing and documenting results

Characterizing defects

Detecting defects

Producing the map of defects

Key element of the strategy is a specialized software ThermoCalc-6L, ThermoFit Pro

Cylindrical and conical objects made of composite materials

Software customers: Boeing, NASA
Thermal NDT

Heating Procedures

I – Optical Heating

II – Inductive Heating

III – Electric Current Heating

IV – Microwave Heating

V – Heating with Gas (Liquid)

VI – Air Flux Heating

VII – Sonic IR Imaging (Thermosonics, Ultrasonic Lockin Thermography, Vibrothermography)

VIII – Natural Heating

Gas, liquid

Turbine blade

Area heater

IR imager

Inductive heat source

Metal

Non-metal

AC

Metal

Crack

AC/DC

Moisture

Microwave heat source

Sun

Mine

Air Flux Heating

Optical Heating

Inductive Heating

Electric Current Heating

Microwave Heating

Natural Heating

Sun

Mine

Air Gun

Ultrasonic emitter

Ultrasonic emitter

Austenite

Ferrite

Graphite

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Advanced Data Treatment in Thermal NDT

- **Processing Single Image**
  - Filtration (smoothing, sharpening, morphological treatment etc.)
  - Histogram Analysis & Modification (stretching, binarization etc.)
  - Choosing Palette
  - Data Fusion

- **General Temporal Analysis**
  - Fourier Analysis (Pulse Phase Thermography)
  - Fitting (polynomial, exponential etc.)
  - Neural Networks
  - Wavelet Analysis
  - Principal Component Analysis

- **Using Heat Conduction Models**
  - Normalization (subtraction, division, 3D filtration)
  - Non-Linear Fitting
  - Optimum observation
  - Early Detection
  - Thermal Tomography
  - Derivative Analysis
  - Defect Characterization

- **Processing Image Sequence**
Solving Inverse Problems and Defect Characterization in Thermal NDT

There are three defect parameters to be typically evaluated by surface temperature distributions:

• Defect lateral size $h$ (visual analysis or the Full Width Half Maximum (FWHM) technique)
• Defect depth $l$ (by an inversion technique)
• Defect thickness $d$, or thermal resistance $R_d$ (by an inversion technique)

Source image (CFRP)

Depthgram

Thicknessgram

Typical accuracy:
- few percent by $h$, $l$,
- tens percent by $d$
Applications: Detection of Hidden Corrosion in Metals

Aircraft aluminum panel (2 mm), front and rear surface

A developed algorithm allows both corrosion detection and quantitative evaluation of material loss

Steel thickness >10 mm

20% material loss – detection limit
Ultrasonic IR Thermography
(Sonic IR Imaging, Thermosonics, VibroIR)

Ultrasonic stimulation (22 kHz, 300 W)

Impact damage in graphite epoxy composite
Ultrasonic IR Thermography

Delamination in graphite/epoxy

Crack in composite

Optical stimulation

Ultrasonic stimulation

22 kHz
0.2-1 kW

Optical stimulation

Ultrasonic stimulation

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Ultrasonic IR Thermography

Crack in Turbine Blade
Inspecting 4 mm-thick graphite epoxy composite

Defects that are located close to the inner surface cannot be detected in a one-sided test.

In some cases, one-sided test can be substituted with a more sensitive two-sided test.
Ultrasonic IR Thermography

Defects in aluminum car cylinder block
Eddy Current IR Thermography

for electrically conductive materials (compressor blades, toothed gear wheels etc.).

Eddy currents are excited by inductors with power up to few kW. The carrier frequency of few hundred kHz is modulated with a frequency of 0.01-1 Hz.

Penetration depth of 100 kHz eddy currents in:
- steel - 0.07 mm
- aluminum honeycombs – 5 mm
- graphite/epoxy composite - 50 mm

Steel Bar Inspection in Automotive Industry

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Eddy Current IR Thermography

Steel Casting Samples
Eddy Current IR Thermography (Tomsk, 2012)

Section of a railway road car truck with a fatigue crack

Original image

After image processing

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Eddy Current IR Thermography (Tomsk, 2012)
The TSA technique is based on the equation of thermoelasticity that connects changes in mechanical stresses $\Delta\sigma$ that appear in materials under cyclic loading, with temperature changes $\Delta T$. This phenomenon is relatively weak: 1MPa change in stress causes only 1 mK temperature signal in steel. Therefore, IR cameras with very high temperature sensitivity are necessary.

When dealing with harmonic mechanical stimulation, peak values of stresses and temperatures are related by the Kelvin formula:

$$\Delta T = -\frac{\alpha}{\rho C_p} T \Delta \sigma$$

$\Delta T$ – temperature signal
$\alpha$ - coefficient of thermal expansion
$\rho$ - material density
$C_p$ - material heat capacity
$T$ - absolute temperature
$\Delta \sigma$ - change in the sum of principal mechanical stresses
IR Thermographic Stress Analysis

Stress distribution in a turbine blade

717 Hz

-100 MPa  +100 MPa

5911 Hz

-40 MPa  +40 MPa

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Thermoelastic stress analysis (TSA) provides the opportunity of crack depth and growth rate measurement.

In laboratory environment, TSA research has been conducted for a few decades. Recently, it was implemented outdoors (Sakagami et al., Japan): Mechanical cyclic stimulation of welded bridge joints was ensured by regular traffic of heavy trucks.
Analyzing damage of human bones under linearly growing load (Tomsk, 2005)
A definite trend is the further improvement of temperature and spatial resolution and increase of frame frequency of IR cameras. Such hardware will allow the inspection of high-conductive materials.

Development of novel stimulation techniques will be continued. In some special cases, ultrasonic stimulation of structural inhomogeneities seems to be very attractive. In the case of metals, inductive heating may be a solution. Perhaps, lasers which are rarely used in TNDT could experience revival as powerful and flexible heat sources.

Image processing will be, as before, forwarded to the better recognition of subsurface defects on the clutter background. The techniques of the Fourier transform, wavelet transform and the principal component analysis might be complemented with neural networks and data fusion.

Efficient defect characterization approaches will be developed. These algorithms should be essentially 3D to take into account a finite size of detected defects.

Thermal NDT will probably confirm its role as a screening technique, but, if the problems stated above, will be successfully solved, the thermal method may become unique in particular test cases.
THANK YOU