Personal thoughts on the occasion of
the Xth QIRT Conference

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www.onera.fr
I have been asked to present this keynote lecture relatively late. In these conditions I was unable to prepare a text to be included in the book of proceedings.

In counterpart, the PowerPoint transparencies of this presentation will be included with the rest of the proceedings in the QIRT Open Archives of the QIRT Website.
### Content of the presentation

- **How all this started – QIRT’92**
- **A short history of the conference**
- **QIRT is not only a conference**
- **A look at the QIRT Community**
- **Present situation of NDE techniques**
- **Comparison of techniques**
- **Flashbacks on pulse thermography**
- **Proposal for the organization of round-robins**

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**Souvenirs and history**

**Information on QIRT activities**

**Personal remarks concerning the NDE field**

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http://dx.doi.org/10.21611/qirt.2010.161
The first conference, QIRT’92, started from several ideas based on my own thermographic experience:

- Thermography is a really powerful tool if sustained by a heat transfer knowledge and a theoretical background linked to the physics of the studied phenomena whatever be the application domain;
- Importance of the adjective “qualitative”
- Thermography is not a simple technique. The investment required for achieving a good practice is not only a question of apparatus but also of well-trained experimenters. Furthermore, the experience adquired in one field can be applied in another field, often with novelty.
- Interest of mixing practitioners from very varied fields of application in the same conference, with sessions on common basic topics and specialized applicative sessions

I had two models in mind:

- QNDE which was, and is still, the leading conference in the NDE field, the conference where new ideas are presented. This conference insists on the term “quantitative”,
- Thermosense conference which was the annual thermographic key event.

In parallel to these technical motivations, and in the context of the beginning nineties (strengthening and possible enlargement of the European Community and end of the “cold war”), there was also “political” aims:

- to give to Europe (Eastern and Western Europe) a great conference comparable to what existed in USA,
- to help the establishment of friendly and scientific links between the different national thermographic communities of Europe
- Make the conference travelling from one country to the other and not staying at the same place.
A short history of the conference

First QIRT Conference

This idea of a QIRT Conference was submitted to colleagues from other European countries and we constituted a Scientific Committee composed of 8 members from 8 countries.

The first announcement of the conference was sent in Septembre 1991.

The first meeting of the committee, which took place in Paris on March 16, 1992, must be considered as the foundation of QIRT.

Ecole Centrale de Paris, Châtenay-Malabry (Paris), July 7-9, 1992

Opening of QIRT'92

Souvenirs and history
A short history of the conference
The QIRT Conference series

Stuttgart (Germany)  Lodz (Poland)


Reims (France)  Dubrovnick (Croatia)


Brussels (Belgium)  Padova (Italy)

2010  2008

Quebec (Canada)  Krakow (Poland)

Souvenirs and history
QIRT is not only a conference.
QIRT Web site – QIRT Open Archives

QIRT Web site

http://qirt.gel.ulaval.ca

Created in 2004

Upgrade of the site: 2006

QIRT Open archives

http://qirt.gel.ulaval.ca/dynamique/index.php?idM=39&Lang=1

Started in 2007

With the QIRT 2010 papers, there will be soon near 600 papers freely laodable (pdf)

Information on QIRT activities
QIRT Journal

First issue: June 2004

Acceptance of the Journal in the ISI Web of Science: 2010

Thomson Reuters Master Journal List JOURNAL LIST

Search terms: QIRT
Total journals found: 1

1. QIRT JOURNAL
Semiannual ISSN: 1768-6733

LAVOISIER, 14, RUE DE PROVIGNY, CACHAN, FRANCE, 94236

1. Science Citation Index Expanded
2. Current Contents - Physical, Chemical & Earth Sciences
3. Current Contents - Engineering, Computing & Technology

Information on QIRT activities
QIRT is not only a conference
How all this works?

QIRT Steering Committee

- QIRT Conferences
  - International Scientific Committee
- QIRT Web site
  - Local Organising Committee
- QIRT Journal
  - Scientific Advisory Board
  - Board of editors

Information on QIRT activities
A look at the QIRT Community
Evolution of the number of communications at QIRT conferences

Number of papers

Year

Information on QIRT activities

http://dx.doi.org/10.21611/qirt.2010.161
A look at the QIRT Community
Papers and participants at QIRT Conferences

Information on QIRT activities

http://dx.doi.org/10.21611/qirt.2010.161
Domains of interest of the QIRT community

Comparison between the first and the present conferences

Year 1992
- Solid mechanics, experimental mechanics 15%
- Fluid dynamics, Combustion 12%
- Civil Eng., Art Works 3%
- Environment 6%
- Thermophysics 6%
- Monitoring & maintenance 1%
- END 19%

Year 2010
- Thermographic techn., (equipments, calibration, emissivity, pyrometry...) 28%
- Solid mechanics, experimental mechanics 4%
- Fluid dynamics, Combustion 10%
- Image & data processing, IR signature & recognition, TSR method 3%
- Photothermal techn., Thermal waves 7%
- Civil Eng., Art Works 19%
- Environment 4%
- Thermophysics 7%
- Monitoring & maintenance 8%
- END 16%

38% Common basic topics
62% Particular application domains
31% 69%

Information on QIRT activities
Domains of interest of the QIRT community
Time-evolution of the respective importance of the topics

Information on QIRT activities
Reflections on NDE applications

Present situation of the main thermographic NDE techniques

Comparison between the main thermographic techniques

Flashbacks on pulsed thermography

Need of round-robins

Personal remarks concerning the NDE field
In the field of non-destructive evaluation, every year, new refinements in image and data processing of thermographic experiments are proposed.

Nevertheless, often these works,
- do not take into consideration some basic thermal phenomena involved in real experiments,
- forget the abundant literature existing on the subject in the 80’s and 90’s,
- establish **non-objective comparisons** of techniques,
- and **finally lead to very view quantitative results** concerning the defect parameters: depth, extent, severity.

Most of the papers can be sorted into three categories: Pulse Thermography (PT), Pulse Phase Thermography (PPT), and Lock-in Thermography (LT). There is like a competition between these techniques. For his keynote lecture given in Cracow, this situation has inspired Steve Shepard to present the following transparency:
Lock-in vs. Pulse: A Matter of Geography?

PPT first!

Go Flash!

Lock-in Forever!

Thermography Olympic Event - London 2012?

Personal remarks concerning the NDE field

http://dx.doi.org/10.21611/qirt.2010.161
Comparison of the respective merits of the three thermographic techniques

<table>
<thead>
<tr>
<th>Pulsed thermography</th>
<th>Lock-in thermography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude based (PT)</td>
<td>Phase based (PPT)</td>
</tr>
<tr>
<td>Heat source</td>
<td>Heat pulse</td>
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<td></td>
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<tr>
<td>Regime</td>
<td>Periodic heating</td>
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<td>Permanent</td>
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<tr>
<td>Advantages</td>
<td></td>
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<td></td>
<td>Possibility of rectification by log-log plot</td>
</tr>
<tr>
<td></td>
<td>Non uniform heating easily corrected by normalization</td>
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<tr>
<td></td>
<td>Depth inversion technique simple</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
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<tr>
<td></td>
<td>Multifrequency</td>
</tr>
<tr>
<td></td>
<td>Signal-to-noise decreases with time but this is compensated by the increased number of acquired points per time scales</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>Little impact of non uniform heating</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Disadvantages</td>
<td>For the inversion, adequate sampling and truncation parameters (functions of material thermal properties and defect depth) must be chosen interactively during the signal discretization.</td>
</tr>
<tr>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Method is slow because:</td>
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<td></td>
<td>- as many tests required as defect depths</td>
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<tr>
<td></td>
<td>- permanent regime has to be reached</td>
</tr>
<tr>
<td></td>
<td>Due to the need of a permanent regime:</td>
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<tr>
<td></td>
<td>non uniform heating and 3-D conduction effects may take importance</td>
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</tbody>
</table>

Personal views open to contradictory discussions

Personal remarks concerning the NDE field
## Flashbacks on pulse thermography

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<tr>
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<th>Lock-in thermography</th>
</tr>
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<td>Heat pulse</td>
<td>Periodic heating</td>
</tr>
<tr>
<td><strong>Regime</strong></td>
<td>Transient</td>
<td>Permanent</td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Fast</td>
<td>• Low power injected in the sample</td>
</tr>
<tr>
<td></td>
<td>• Multifrequency</td>
<td>• Good signal-to-noise ratio possible</td>
</tr>
<tr>
<td></td>
<td>• Signal-to-noise decreases with time but this is compensated by the increased number of acquired points per time scales</td>
<td></td>
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<tr>
<td></td>
<td>• Possibility of rectification by log-log plot</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Non uniform heating easily corrected by normalisation</td>
<td></td>
</tr>
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<td></td>
</tr>
</tbody>
</table>
Signal to noise ratio is compensated by the increase of the number of points per time scale.

Typical pulse thermogram (here 10 mm-thick plate of duraluminum without black coating, fram rate 200 Hz)
Thermogram rectification

The smart patch with an artificial defect

The usual cartesian coordinates
The wrong way!

Normalized temperature increase

Thermographic image of the patch during cooling

Normalized temperature increase

Personal remarks concerning the NDE field
Thermogram rectification by log-log plot

The log-log plot

Normalized temperature increase

The usual cartesian coordinates
The wrong way!

Normalized temperature increase

Personal remarks concerning the NDE field
The log-log plot is a means of rectification. Rectification is important, since a curve having even a portion of its range plotting in a linear manner is far more revealing than one that curves over its entirety. It divides that data into zones or regions anticipated by theoretical expectations, and provides confirmation by slope measurements that theory and experiments are in fair agreement.

In pulse heat transfer log-log plot is a tool for multiscale analysis of the phenomena occurring. This is based on the notion of heat diffusion length $d \sim \sqrt{\alpha t}$, relating the time and the space.

Polynomial regression in log-log leads to a better fit than in cartesian coordinates. Practically with polynomials of degree <10, fitting is satisfactory on the full domain of the thermogram, leading to $R^2$ coefficients very near 1 (i.e. 0.9999). The TSR technique is based on that.
Non-uniform heating suppression by normalization

Personal remarks concerning the NDE field

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Personal remarks concerning the NDE field
Depth determination of a defect from the time analysis of the thermal contrast

Based on the intuitive reasoning consisting in optimizing the signal-to-noise ratio of the contrast, since the 1980’s, to identify the depth of defects, most of the experimenters use the occurrence time of the maximum contrast, or sometimes on the occurrence time of half this maximum.

This is an error due to a lack of consideration of the thermal phenomena occurring in a real sample.
In 1994, Krapez and colleagues proposed the use of an early detection and characterization of the defect to avoid 3-D internal conduction effect producing blurring of the images, and sensitivity of the identification to multiple parameters.

Emerging contrast (early detection) $t_{\text{emerge}}$

Maximum contrast $t_{\text{max}}$

Log($\Delta T$)

Sound zone

Defective zone

$\Delta(\Delta T)_{\text{max}}$

$\Delta(\Delta T)_{\text{max}}/2$


The double advantage of the early detection

The earlier the identification of $z_d$, the less the result is sensitive to the thermal resistance of the defect.

Identification from the emerging contrast: highly sensitive to $z_d$, insensitive to $R_d$.

Identification from the maximum contrast: highly sensitive to both $z_d$ and $R_d$.

Relative contrast $= \frac{(\Delta T_d - \Delta T)}{\Delta T} \, (%)$

Sensitivity

$Fo = a_z t / z_d^2$

Relative contrast for $R_d = z_d / k_z$ ($R^* = 1$)

$z_d / L = 0.91$ (1-D model)

Personal remarks concerning the NDE field
Principle of the identification of defect depth and thermal resistance using the emerging thermal contrast

A time \( t_{\text{emerge}} \) is chosen at which the absolute contrast emerges from noise (± \( \delta T \)), as earlier as possible.

The emergence criterium is: \( (\Delta T_d - \Delta T_s)_{\text{emerge}} > \delta T \)

The defect depth is given by the simple formula*:

\[
R \quad \text{identification} \\

z_d = \sqrt{\frac{\kappa_{zd} \cdot t_{\text{emerge}} \cdot \ln(2/Cr_{\text{emerge}})}}{\Delta T_s}
\]

\( Cr_{\text{emerge}} \) being the relative contrast at time \( t_{\text{emerge}} \):

\[
Cr_{\text{emerge}} = \frac{(\Delta T_d - \Delta T_s)_{\text{emerge}}}{\Delta T_{\text{emerge}}}
\]

The depth can be calculated for several different relative contrasts, depending on the experimental noise and possibly extrapolated to a quasi null contrast.

Then, \( z_d \) being identified, the thermal resistance of the defect, \( R_d \), can be evaluated through an implicit inversion process using the equation (*) simplified by replacing the erfc function by its development:

\[
Cr_{\text{emerge}} = 2 \exp(-1/Fo_d) \left[ 1 - 2 Fo_d/(R_d + 2Fo_d) \right]
\]

\( R_d \)

* This expression is the asymptotic behaviour for an infinite thermal resistance of the approximate expression of the relative contrast in the emergence zone:

\[
Cr_{\text{emerge}} = \left[ (\Delta T_d - \Delta T_s)/\Delta T_s \right]_{\text{emerge}} = 2 \exp(-1/Fo_d) - 4 \sqrt{\pi} \left( Fo_d/R_d \right) \exp[4(1+Fo_d/R_d)/R_d] \cdot \text{erfc}(1/\sqrt{Fo_d} + 2\sqrt{Fo_d}/R_d)
\]

(*)

with: \( Fo_d = \kappa_{zd} t/z_d^2 \) and \( R_d = \mathcal{R}_d k_{zd}/z_d \)


Personal remarks concerning the NDE field
Validation of the early detection method by numerical simulation \((z_d/r_d = 0.66)\)

\[
\frac{z}{z_d}
\]

Emerging contrast threshold
- 0.5 %
- 1 %

Half maximum contrast
- 2 %
- 4 %
- 6 %

Maximum contrast

0 % (extrapolation)

Studied case:

\[
\left( \frac{r}{z_d} \right) \left( \frac{\sqrt{k_r}}{\sqrt{k_z}} \right) = 1.5
\]

\[
R^* = Rk_z/z_d = 1, \quad z_d / e = 0.5
\]

Personal remarks concerning the NDE field
Experimental validation of the early detection method

Black Plexiglas® sample containing an axisymmetric rear-face open cavity

D = 200 mm

Pulse heat flux on the front-face

Personal remarks concerning the NDE field
Experimental validation of the early detection method

Black Plexiglas® sample containing a 3-D axisymmetric void
Depth profile deduced from a pulse heating

The early detection is clearly better than the one using the maximum contrast.
The optimum contrast threshold seems to be between 3 and 5 %.

Personal remarks concerning the NDE field
The detection of the emerging contrast in Pulsed Thermography and of the blind frequency in Pulsed Phase Thermography are equivalent approaches.

Nevertheless, more works is needed for making the depth identification from the blind frequency rigourously quantitative. A comparative study starting from same thermograms would be highly interesting to judge of the respective merits of the two approaches.
PT is the best thermographic tool for multi scale analysis of material and structure

Resin semi-transparency and heterogeneity at ply-scale

Semi infinite regime in the composite layers + bond layer

Transition to air (hole)

Over-thickness of bond layer (lower effusivity) in the PZT region and thermal resistance of the PZT and its interfaces

Transition between the patch and the Al substrate

Beginning of the quasi adiabatic plateau of the Al layer

Heat losses and 3-D heat transfer

Region 3 tends to homogeneize with the rest of the sample due to the heat sink constituted by the Al plate

Transition due to Al/air interface delayed by the PZT inclusions

Scatter of the thermograms due to the variability of the heat losses at the boundary

<table>
<thead>
<tr>
<th>t (s)</th>
<th>Duralumin $\alpha=6.4\times10^{-6}$</th>
<th>C/epoxy $\alpha=4.9\times10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 µs</td>
<td>14 µm</td>
<td>3.5 µm</td>
</tr>
<tr>
<td>10 µs</td>
<td>45 µm</td>
<td>11 µm</td>
</tr>
<tr>
<td>100 µs</td>
<td>140 µm</td>
<td>35 µm</td>
</tr>
<tr>
<td>1 ms</td>
<td>450 µm</td>
<td>110 µm</td>
</tr>
<tr>
<td>10 ms</td>
<td>1.4 mm</td>
<td>350 µm</td>
</tr>
<tr>
<td>100 ms</td>
<td>4.5 mm</td>
<td>1.1 mm</td>
</tr>
<tr>
<td>1 s</td>
<td>1.4 cm</td>
<td>3.5 mm</td>
</tr>
<tr>
<td>10 s</td>
<td>4.5 cm</td>
<td>1.1 cm</td>
</tr>
<tr>
<td>100 s</td>
<td>1.4 dm</td>
<td>3.5 cm</td>
</tr>
</tbody>
</table>

Beginning of the heat losses

Personal remarks concerning the NDE field
Conclusions

Time-resolved pulsed thermography is the best tool for quantitative multi-scale thermal analysis of materials/structures, if using:

- Normalisation,
- Log-Log plot for rectification,
- Early detection/characterisation based on the emerging contrast,
- TSR (thermographic signal reconstruction) approach for denoising and the related log derivatives for earlier information.

In these conditions, and in the case of composite materials, thermography can compete with ultrasonics.

Personal remarks concerning the NDE field
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In these conditions, and in the case of composite materials, thermography can compete with ultrasonics.

There is a severe lack of really objective and quantitative comparisons between the existing thermographic methods applied to realistic and representative samples.

Need for a general round-robin comparing PT, PPT and LT.

Future QIRT conferences are the ideal place for organizing such a round-robin on this thematic and disseminating the information.
The QIRT community is perfectly able to organize such a round-robin, by constituting a group of experts in charge of:
- Defining the type of coupons to test, the thermographic techniques to involve, the criteria to use for objective comparison of the various techniques,
- Finding the best laboratories to generate well-documented experimental data,
- Finding the laboratories able to apply the various techniques for defect and/or thermal properties identification from the experimental data,
- Compiling the results and elaborating a synthesis,
- Writing a report which could be presented at the next QIRT Conference under the form of a plenary lecture.

By the past, this type of collective work has been achieved and presented at QIRT’98 and QIRT’2000

By D.P. Almond*, R.J. Ball*, A. Dillenz**, G. Busse** J.-C. Krapez***, F. Galmiche**** and X. Maldague****

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**IKP, Universitat Stuttgart, Pfaffenwelding 32, D-70569 Stuttgart, Germany
***Structure and Damage Mechanics Department, ONERA, BP 72, 92322 Châtillon cedex, France
****Université Laval, Cité Universitaire, Quebec, Canada, GIK 7P4

Abstract:
Four samples of carbon fibre reinforced composite which contained impact damage sites, verified by ultrasonic C-scans, have been studied independently by the groups participating in this second QIRT Round Robin exercise. The samples were selected from a much larger collection because long pulse heating transient thermography (Bath) had failed to detect the presence of the defects at the front (impact) faces. The other techniques employed were: optical lock-in thermography and ultrasound lock-in thermography (Stuttgart); pulsed thermography using the emerging contrast technique (ONERA) and pulsed phase thermography (Laval). Only ultrasound lock-in thermography was successful in detecting the defects at the front faces.

1. Introduction

This second QIRT Round Robin exercise, devoted to investigating the relative merits of different thermographic techniques in detecting and characterising impact damage in carbon fibre composites, arose from a presentation at QIRT 98 on the detection of impact damage in thin carbon fibre composites [1]. At this presentation it was reported that a total of 88 samples, with thicknesses ranging from 3.44mm to 16mm, had been examined using the long pulse heating transient thermography techniques and that impact damage in 19 samples had not been detected at the impact face. As in practice it is only the front face (impact face) that is accessible to an inspector, of an aircraft structure for example, these failures cast doubt about the reliability of thermography in this important application. It was decided to circulate a number of these 19 samples amongst the participants of this round robin exercise as a challenging test of their particular thermographic techniques for defect detection.
Lock-in vs. Pulse (or Phase vs Amplitude): Need for round-robins

PPT first!
Go Flash!

Lock-in Forever!

Thermographic NDE round-robin: QIRT 2012?

Personal remarks concerning the NDE field
Thank you for your attention