The Use of Pulse Compression Technique in Non-Destructive Testing: A Review

Muhammad Khalid RIZWAN², Hamed MALEKMOHAMMADI¹, Stefano LAURETI¹, Pietro BURRASCANO², David A. HUTCHINS³, Gui Yun TIAN⁴, Junzhen ZHU⁴, Qiuji YI⁴, Marco RICCI¹

¹ University of Perugia, Perugia, Italy
² Universita degli Studi di Perugia, Terni, Italy
³ University of Warwick, Warwick Manufacturing Group (WMG), Coventry, UK
⁴ Newcastle University, Newcastle upon Tyne, UK

Contact e-mail: muhammadkhalid.rizwan@unipg.it

Abstract

Non-Destructive Testing (NDT) refers to an extended group of techniques used both in research and industry, which are exploited for inspecting, characterizing and evaluating various kinds of materials and goods. Eddy Current Testing (ECT), Ultrasonic Testing (UT) and InfraRed Thermography (IRT) are among the most employed NDT methods. In the said methods, a short duration delta-like signal provided by different types of transducers is typically employed to excite the sample under test (SUT) within an extended bandwidth. Features of interest, e.g. presence of flaws and inclusions inside the SUT, can be extracted by analyzing the system’s impulse response both in time and frequency domains. However, the maximum achievable Signal-to-Noise Ratio (SNR) is directly related to the source power. This limit can be overcome by using coded excitations together with Pulse Compression (PuC) technique. In fact, in PuC the frequency spectrum of the coded excitation can be tailored to suit the investigation of a given sample, while the SNR can be increased almost arbitrarily by enhancing the signal time duration. Finally, the system’s impulse response is retrieved by applying the PuC algorithm on the acquired data. In this paper, the use of PuC technique in IRT, UT, ECT will be reviewed and discussed.
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Muhammad Khalid Rizwan, Hamed Malekmohammadi, Stefano Laureti, Pietro Burrascano, David A. Hutchins, Gui Yun Tian, Junzhen Zhu, Qiuji Yi, Marco Ricci

1Department of Engineering, University of Perugia, Italy
2School of Engineering, University of Warwick, UK
3School of Engineering, Newcastle University, UK
4DIMES Department, University of Calabria, Italy

Outline

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→ Pulse Compression (PuC)
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  • Choice of the Signals
→ Application in NDT
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Background

General procedures in Ultrasonic, Eddy Current, Thermography NDT inspections are based on measuring the response $h(t)$ of the sample under test (SUT) to an impulsive excitation which approximates a delta $\delta(t)$ like function (e.g. Pulse Echo).

In circuit theory, the response to a delta $\delta(t)$ excitation is called impulse response $h(t)$ and it describes the input-output relation of the system as $y(t) = x(t) \otimes h(t)$.

Measuring $h(t)$ allows the inspection of the sample as well as the calculation of the response of the SUT to any other possible excitation.
Limits of the Pulse-echo approach

→ Maximum achievable SNR is not sufficient for the defect detection and characterization in the presence of noise or high attenuation

→ Aim is to measure the impulse response even in the presence of noise, to enhance sensitivity of the system

How?

→ Increase energy of the excitation pulse Amplitude of the pulse; constrained by the system and the transducer’s limitations

→ Averages Long time of measurements

Enhance SNR HOW?

Proposed Solution

Pulse Compression

An alternative technique to increase the SNR of the measurement setup

increase the time bandwidth product increase the time duration of the excitation pulse rather than the amplitude

❖ Flexible both in time and frequency shaping
❖ Widely applicable
❖ Various techniques to implement
Pulse Compression (PuC)- *basic principle*

- Pair of signals whose correlation is a delta $\delta(t)$ like function, i.e.,
  
  $g(t) \ast \Psi(t) = \delta(t)$

- Excite the Linear (and in some cases nonlinear) system with one of the signals, $g(t)$

- Impulse response of the unknown system can be estimated when the output is convolved to the second signal $\Psi(t)$ in the pair, i.e.,
  
  $y(t) \ast \Psi(t) = [g \ast h](t) \ast \Psi(t) = h(t) \ast \delta(t) \approx C\tilde{h}(t)$

- SNR is maximized when $\Psi(t)=g(-t)$ *matched filter theory*

**Advantages**

- **High SNR** → Required SNR
  Gain can be achieved by increasing the time duration of the excitation pulse without effecting the bandwidth

- Bandwidth is independent of $T_{\text{PuC}}$

- **Flexibility in time and frequency domains shaping**

- **No hardware complexity for implementation**
Signals for PuC

➢ Ideally, the signal should prevail the property of autocorrelation as;

\[ R_{gg} = \delta(t) \]

➢ In Real cases, the closer the correlation \( R_{gg} = \hat{\delta}(t) \sim \delta(t) \), the more accurate is the estimation of the impulse response, \( \hat{h}(t) \sim h(t) \)

➢ Practically, frequency spectrum of the selected signal should be wide enough to cover the bandwidth of the sample under test

Applications of PuC in NDT

→ Wave Phenomenon  Ultrasonic NDT

- \( \text{SNR}_{\text{Gain}} \) is significantly improved \( \rightarrow \) widely applicable
- \( h(t) \) consists of several reflections/paths
- Due to propagation, duration of impulse response, \( T_h \) is much longer than the required time resolution \( \delta T \), i.e., \( T_h >> \delta T \) \( \rightarrow T_h B >> 1 \) \( \rightarrow \text{SNR}_{\text{Gain}} \) is high

→ Diffusion Phenomenon  EDDY Current, Thermography

- \( \text{SNR}_{\text{Gain}} \) is reasonable, but other advantages exist
- \( h(t) \) is smooth and exponentially decaying
- Time duration of the impulse response \( T_h \) is greater than time resolution \( \delta T \), but reasonable
**Choice of the Signals**

**Swept frequency Signals:**
- Chirps (both linear and nonlinear)
- Chirps are the widely used signals in PuC NDT
  - Easy control over the bandwidth and almost a flat spectrum

**Coded Signals:**
- Binary codes, mapped into continuous waveforms (bits in the form of square wavelets), e.g. Multi-Length Sequences (MLS), Golay Complementary Sequences, Barker Codes, etc.
PuC Ultrasonic NDT: Results comparison to PuE

- PuC (using a Linear chirp as an excitation signal) and PuE UT inspections of a steel forging, 1.5m long and diameter of 0.6m
- Using the same transducers, V108-VIDIOSCAN from Olympus
- AWG Vp-p;
  - in case of PuE 200V
  - in case of PuC 24V

SNR\textsubscript{Gain} is enhanced significantly in case of PuC

PuC Ultrasonic NDT: Results

- Echograms of PuC UT inspection of forgings
- SNR\textsubscript{Gain} is significantly high, because the duration of the signal (4m) is much higher than the resolution (in mm)
- Exploit the advantage of broad bandwidth of a Linear Chirp
- Obtain the optimum frequency of Inspection
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PuC Thermography, **Setup**

- Heating Source: 8 x 50W LED chips
- Thermal Camera: Xenics Onca-MWIR-InSb IR
- Signal Generation/Acquisition: Labview™
- Camera in Reflection mode, 40 FPS

[1], [2] Diagram and the setup from presentation of Hamed Malekmohammadi, Comparison of optimization strategies for the improvement of depth detection capability of Pulse-Compression Thermography. QIRT-2018

PuC Thermography, **Results**

- CFRP sample with defects at different depths
- Impulse Response $h(t)$ is slow, $\text{SNR}_{\text{Gain}}$ is not very high
- Binary Sequences, Barker Code is used for PuC
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PuC Eddy Current Inspections, Setup

- Comparison of Time and Frequency domain analysis for defect detection, using Linear chirps (varying duration of the signal)
- A surface defect of (0.1x0.4x3 mm³), covered with another sound plate of thickness = 2 mm
- SNRgain is better because the time resolution of impulse response is in between the UT and thermographic NDT
- In this case, time domain analysis outperforms the frequency domain analysis in terms of defect detection
- One can obtain more robustness of the system to the lift off variations, while applying time or frequency phase analysis

PuC Eddy Current Inspections, Results

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Conclusions

• PuC procedures enhances the sensitivity of NDT techniques,

• As discussed, the PuC methods,
  ➢ Applied in UT inspection of large structures, improved SNR has resulted in better spatial and temporal resolution
  ➢ Applied in Eddy currents testing, lift off compensation can be achieved via time and frequency phase analysis
  ➢ Applied in thermographic, thermograms with improved SNR and fidelity can be achieved

• The PuC method can easily be incorporated to the NDT systems with simple hardware

• Flexibility over the time and frequency domain shaping of the signal, spectral density of the excitation pulse can developed well matched with the bandwidth of the system

• One can exploit the broadband of the PuC procedure to obtain a multifrequency defect evaluation system, to gain the optimum frequency of inspection for a specified SUT

• An NDT system with improved SNR gain opens further application of the method for the inspection of highly attenuating materials and structures, like CFRP and GFRP

• Performance of the PuC NDT system can further be improved combing other advanced signal and image processing techniques

References


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