Advanced Signal Analysis Method to Evaluate the Laser Welding Quality

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General aspects

Signals detected during the laser welding belong to the class of non-stationary signals

Non-stationary signals cannot be analyzed by the Fourier transform

any non-linear distorted waveform can be regarded as harmonic distortions

The **Orthogonal Hilbert-Huang Transform** has been developed to analyze non-stationary data

combination of the empirical mode decomposition & the Hilbert spectral analysis

Goals

- **demonstrate the effectiveness of the method compared to other ones (WVD, …) used for non stationary signals**
- **demonstrate how this method offer the possibility to analyse the welding quality without using any signal as reference**

Agenda

- Hilbert-Huang Transform (HHT) - fundamentals
- Empirical Mode Decomposition (EMD)
- Hilbert Spectral Analysis - Orthogonal HHT approach (OHHT)
- Analysis of laser welding by the OHHT – results
- Conclusion

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Work programme topic addressed: NMP-2008-4.0-4 Expanding the limits of advanced materials processing applications through a new generation of high brilliance lasers

Hilbert transform

Non-stationary signals are *transient* in nature:

→ *the instantaneous frequency changes within one oscillation cycle*

The Hilbert transform is the easiest way to compute instantaneous frequency

$$y(t) = H[x(t)] = \frac{1}{\pi} PV \int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau$$

$$z(t) = x(t) + iy(t) = a(t)e^{-i\theta(t)} = a(t)e^{-i\int \omega(t)dt}$$

$a(t) = \sqrt{x^2 + y^2}$ istantaneous amplitude

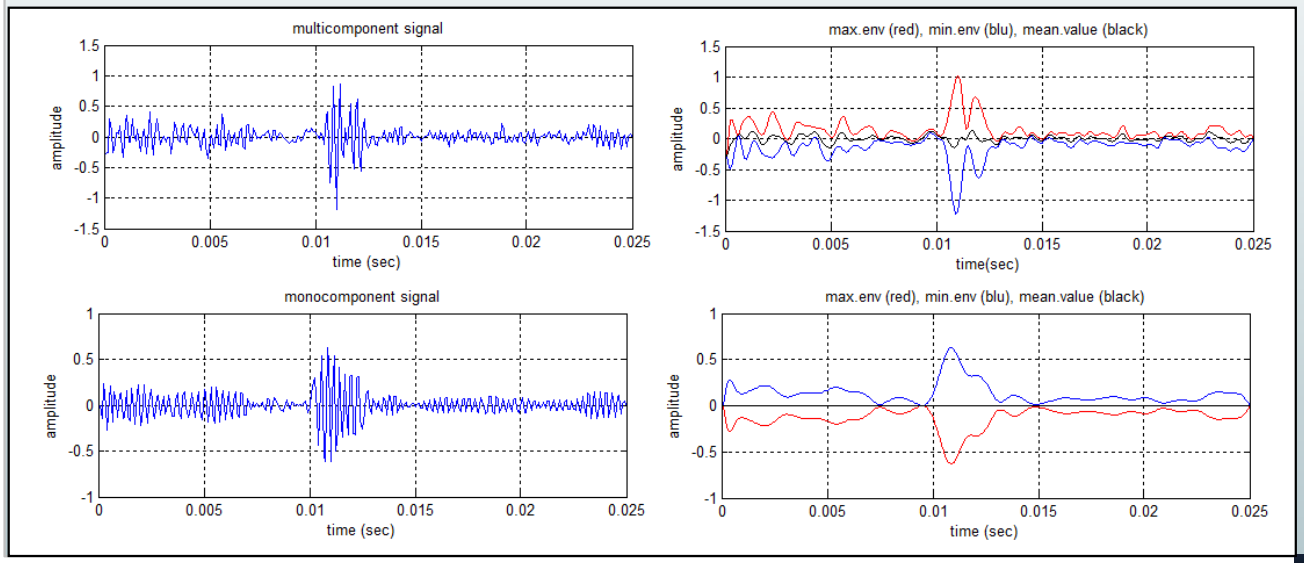
$\theta(t) = arctan\,(y/x)$ phase function

$\omega = d\theta/dt$ instantaneous frequency

Using the Hilbert transform directly, the instantaneous frequency could not be correctly evaluated

The Hilbert transform works well if applied to *mono-component signal* (narrow band-passed signal)

examples

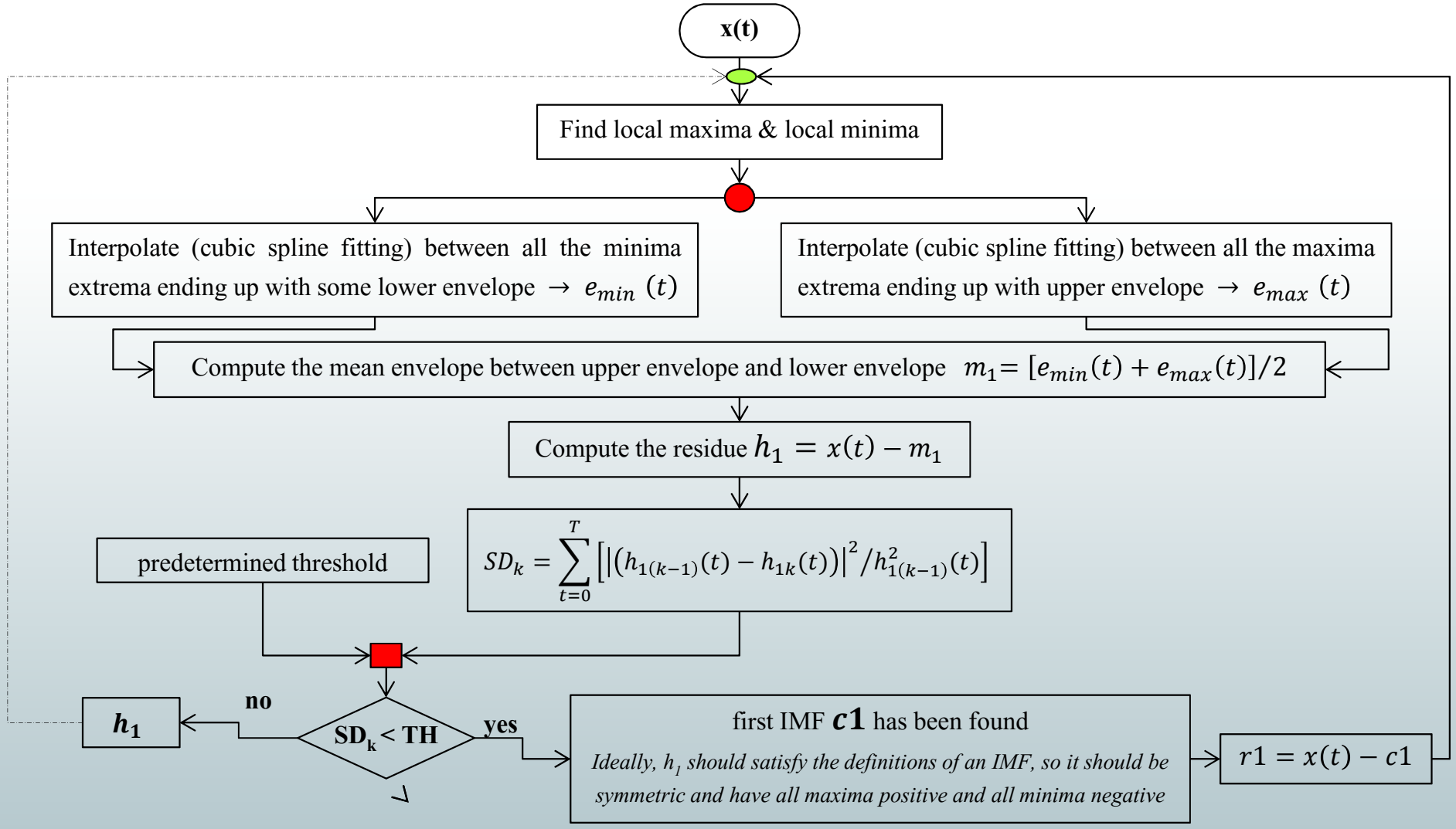


mono-component signal

- in the whole dataset, the number of extrema and the number of zero-crossings must either equal or differ at most by one
- at any point, the mean value of the envelopes defined by the local maxima and the local minima is zero

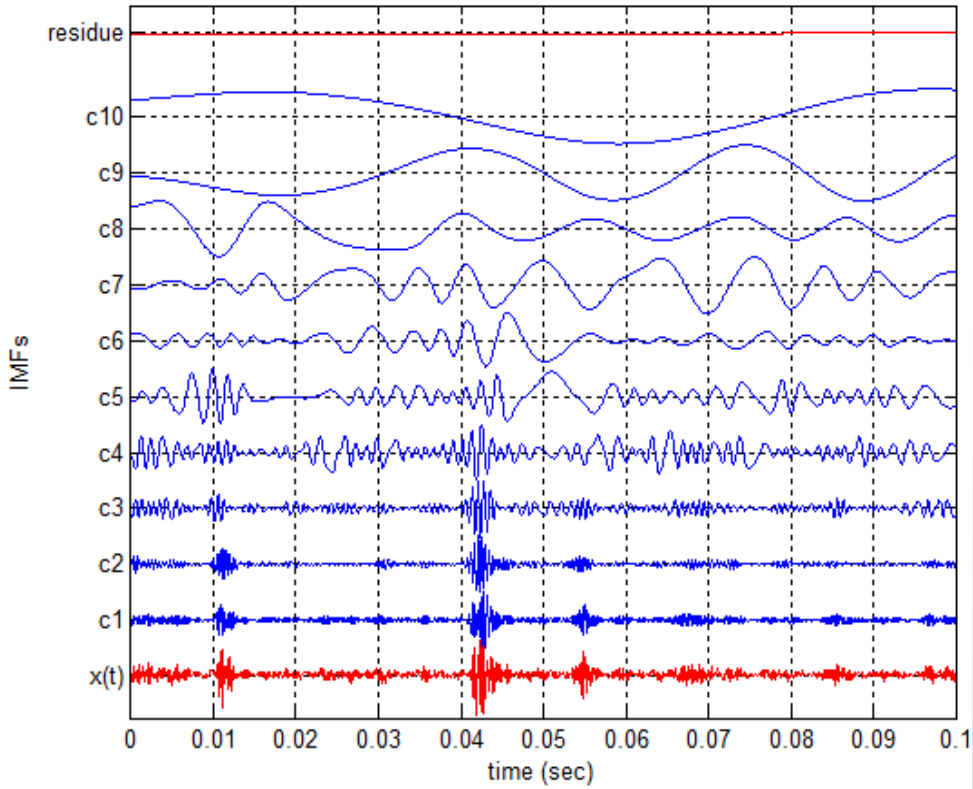
Empirical mode decomposition (1/2)

Huang developed a method, which he calls a ***sifting process***, that decomposes a wide class of signals into a set of mono-component signals (***Intrinsic Mode Functions, IMFs***).

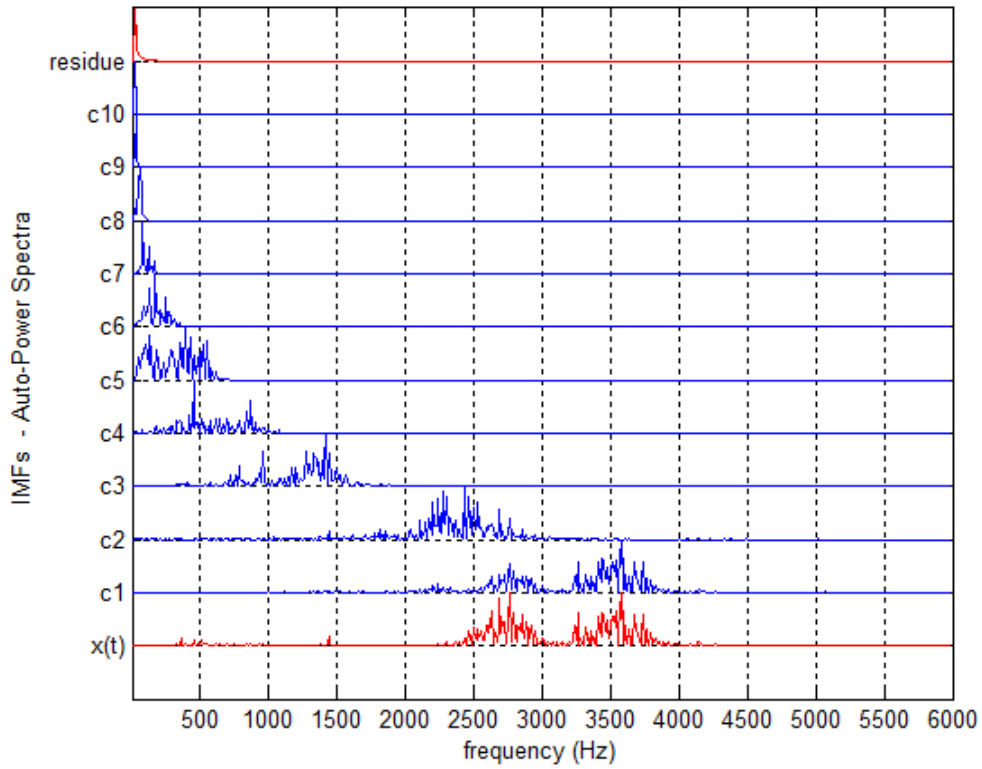


Empirical mode decomposition (2/2)

Empirical mode decomposition (EMD)



IMFs Auto-Power spectrum



- EMD aims at decomposing a signal s into a finite sum of modes $c_1, \ldots, c_n$ and a residue r

$$x(t) = \sum_{j=1}^{n} c_j + r$$

- the modes are less oscillating with increasing j: ***the last IMF presents the slowest oscillations compared to the other modes***

Hilbert Spectral Analysis (HSA)

Once the signal has been decomposed, we apply the Hilbert transform to each IMF component

$$y(t) = H[x(t)] = \frac{1}{\pi} PV \int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau$$

$$z(t) = x(t) + iy(t) = a(t)e^{-i\theta(t)} = a(t)e^{-i\int \omega(t)dt}$$

$$z(t) = x(t) + iy(t) = a(t)e^{-i\theta(t)} = a(t)\left[cos\left(\theta(t) + jsin(\theta(t))\right)\right] \rightarrow x(t) = a(t)cos(\theta(t))$$

Let's introduce the **Bedrosian theorem**

$$\boldsymbol{real}\,\{H[a(t) * cos(\theta(t))]\} = a(t) * \boldsymbol{real}\,\{H[cos(\theta(t))]\}$$

AM and FM components must be separated in frequency

To satisfy the Bedrosian theorem, we have to apply the normalized Hilbert transform instead of a direct Hilbert transform on IMF.

The normalization is given by an iterative process:

1. for each IMF, the envelop $e_i(t)$ is obtained via the interpolation of the extrema points of the absolute value of the ith IMF_i.
2. the normalization is given by

$$f_1(t) = \frac{IMF_i(t)}{e_1(t)}, f_2(t) = \frac{f_1(t)}{e_2(t)}, f_n(t) = \frac{f_{n-1}(t)}{e_n(t)}$$

iteration stopped when $e_n(t)$ is unity

The Hilbert amplitude spectrum $\boldsymbol{H(\omega, t)}$ can be shown in the frequency-time plane, called **Hilbert spectrum**, as

$$H(\omega, t) = Re \sum_{j=1}^{n} c_j(t) e^{i\int \omega_j(t)dt}$$

The combination of the empirical mode decomposition (EMD) and the Hilbert spectral analysis (HSA) is known as the **Hilbert-Huang transform (HHT)**

Orthogonal HHT approach

- Analysis above is based on the hypothesis : IMFs got by EMD could re-compose original signal .

We can use HHT as an available approach of temporal-frequency analysis to estimate the local spectral density of non-stationary signals.

From the characteristic of temporal-frequency analysis , we know that the frequency spectrum of signals will have crossover item.

- The frequency spectrum density of two signals' summation is not the sum of frequency spectrum density of two signal
- Leakage of energy will be happened if we directly use HHT to estimate the local spectral density of non-stationary signals detected during the laser welding, and then the local spectral density estimated by HHT cannot be regarded as the time-dependent spectral density of original signals.

To avoid this leakage, the IMFs used to reconstruct the original signal must be orthogonal

Huang defined an overall index of orthogonality IO_T and a partial index of orthogonality for any two components IO_{jk}, as follows:

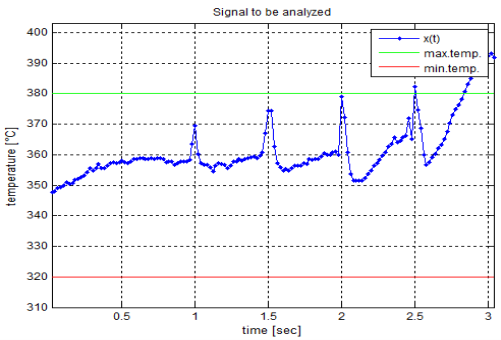
$$IO_T = \sum_{j=1}^{n+1}\sum_{\substack{k=1\\k\neq j}}^{n+1}\int_0^T c_j(t)\,c_k(t)dt \Big/ \int_0^T x^2(t)dt == \sum_{j=1}^{n+1}\sum_{\substack{k=1\\k\neq j}}^{n+1}\sum_{i=1}^{N} c_{ji}c_{ki} \Big/ \sum_{i=1}^{N} x_i^2$$

$$IO_k = \int_0^T c_j(t)c_k(t) \Big/ \int_0^T c_j^2(t)dt + \int_0^T c_k^2(t)dt = \sum_{j=1}^{N} c_{ji}c_{ki} \Big/ \sum_{i=1}^{N} c_{ji}^2 + c_{ki}^2$$

If the IMF components from EMD are exactly orthogonal to each other, the value of IO_T should be zeros, the total energy of decomposed signal E_{tot} should be invariable and the energy leakage between any two IMF components E_{jk} should be zero. Generally, because the IMFs from EMD aren't theoretically orthogonal, the value of orthogonality index is about from 10^{-2} to 10^{-3}

In order to ensure the exact orthogonality of IMFs from EMD and no energy leakage due to EMD, a new method based on the Gram-Schmidt orthogonalization method, referred as the orthogonal empirical mode decomposition (OEMD), has been proposed

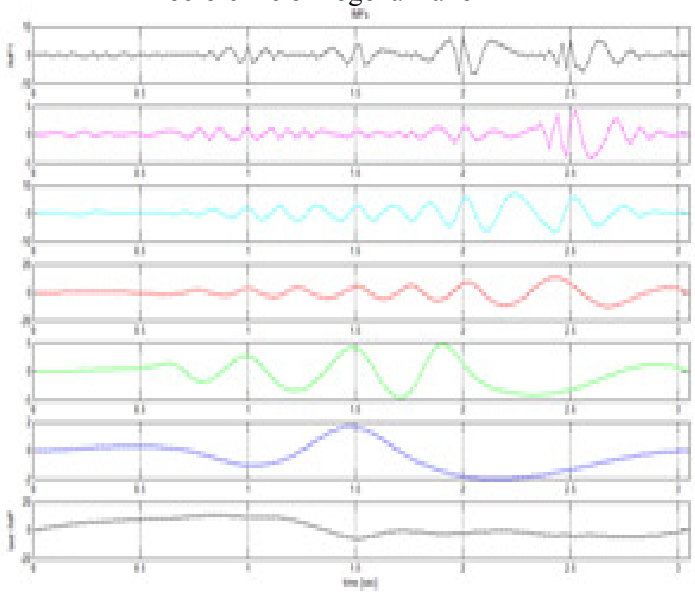
Orthogonal HHT approach for a welding process signal (1/2)



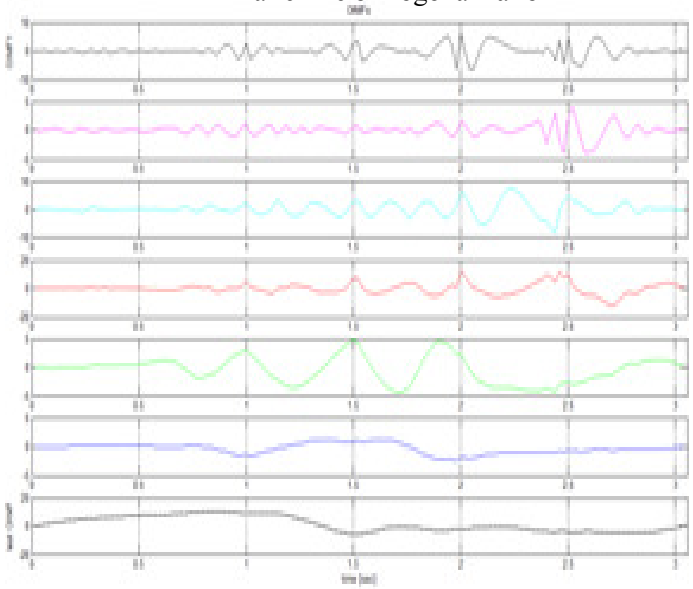
temperature signal detected during the laser welding of polymers

IMF components without residue

before the orthogonalization



after the orthogonalization



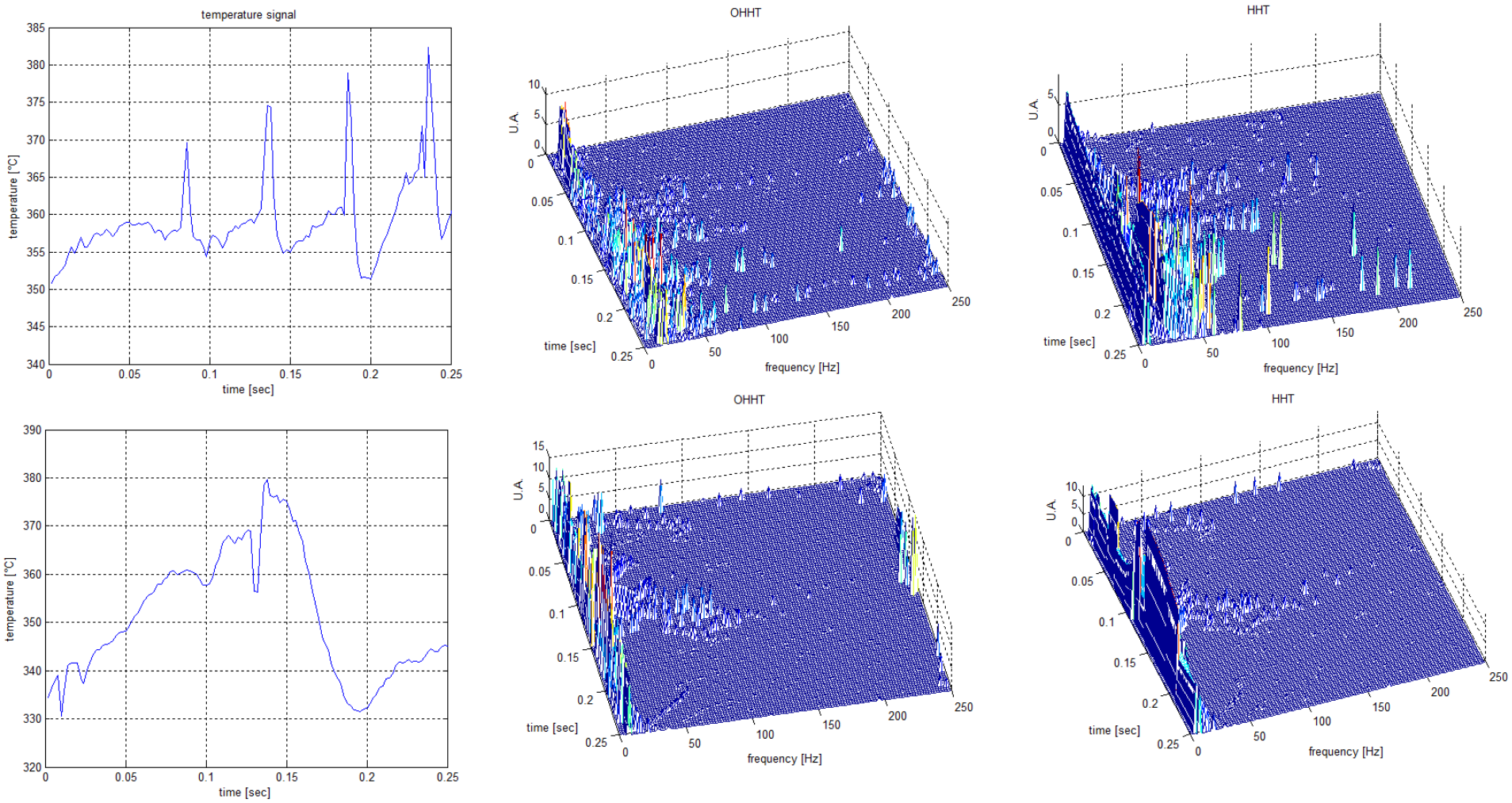
IMF	c1	c2	c3	c4	c5	c6	c7
c1	0,5	0,025	0,0934	0,1198	0,0129	0,0375	0,0176
c2	0,025	0,5	0,0788	0,0173	0,0072	0,006	0,0049
c3	0,0934	0,0788	0,5	0,0684	0,0271	0,0149	0,0112
c4	0,1198	0,0173	0,0684	0,5	0,0212	0,0113	0,0271
c5	0,0129	0,0072	0,0271	0,0212	0,5	0,1568	0,1059
c6	0,0375	0,006	0,0149	0,0113	0,1568	0,5	0,08
c7	0,0176	0,0049	0,0112	0,0271	0,1059	0,08	0,5

Orthogonality indexes of IMF components

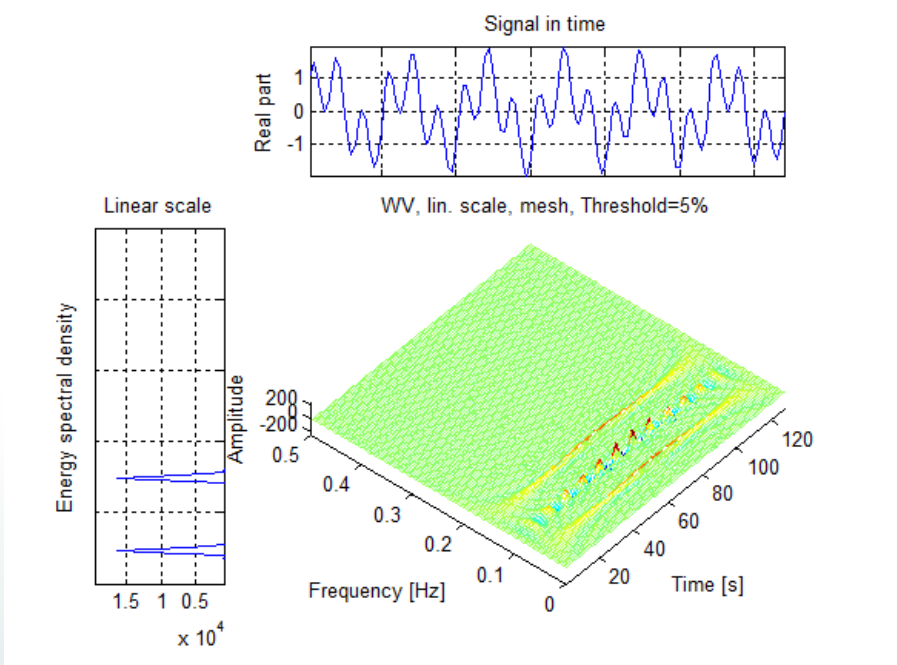
OIMF	c1	c2	c3	c4	c5	c6	c7
c1	0,5	2,20E-17	3,92E-17	1,57E-17	3,03E-18	4,69E-18	1,06E-17
c2	2,20E-17	0,5	3,68E-17	7,50E-18	1,30E-17	1,01E-17	4,43E-18
c3	3,92E-17	3,68E-17	0,5	6,97E-18	1,38E-17	4,58E-18	3,33E-18
c4	1,57E-17	7,50E-18	6,97E-18	0,5	1,45E-17	9,85E-18	9,28E-18
c5	3,03E-18	1,30E-17	1,38E-17	1,45E-17	0,5	5,50E-17	1,07E-17
c6	4,69E-18	1,01E-17	4,58E-18	9,85E-18	5,50E-17	0,5	3,11E-17
c7	1,06E-17	4,43E-18	3,33E-18	9,28E-18	1,07E-17	3,11E-17	0,5

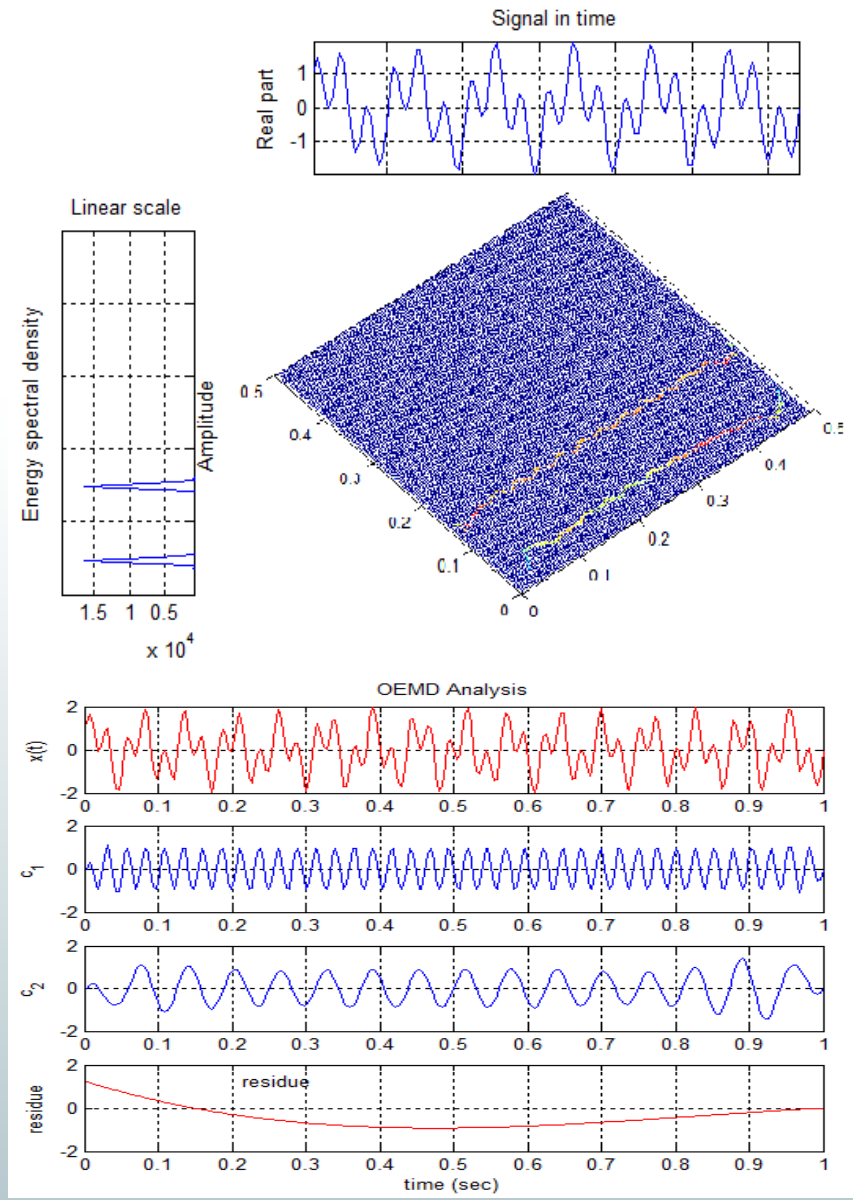
Orthogonality indexes of OIMF components

Orthogonal HHT approach for a welding process signal (2/2)



WVD *vs* OHHT

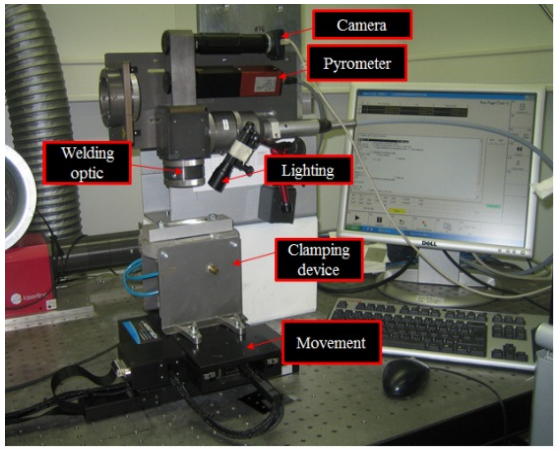




- WVD presents interference terms placed between the signal components
- OHHT is interference free

The effectiveness of OHHT compared to WVD, has been demonstrated

Analysis of laser welding by OHHT



lay-out used for the welding of polymeric components at VTT lab

Laserline LDF400 fiber coupled diode laser, where the operated at 940 ± 10 nm

- laser beam was guided via Ø 400 µm optical fiber to a welding optic.
- focal length used was 100 mm resulting an Ø 0.6 mm focal spot on the work piece.

Processing head was equipped with on axis pyrometer and camera.

- ❑ Pyrometer used was Dr Mergenthaler GmbH infrared pyrometer with Lascon controller, model EP100P/PCI with maximum sampling rate is 10kHz.
- ❑ In the experiments the used sampling rate was 5 kHz. To limit the amount of data points the data was saved at 500Hz.
- ❑ In the experiments the pyrometer was used only for observation of weld temperature to see how defects affect the temperature.

- ❖ During welding laser head was kept stationary and clamping jig with workpiece were moved with XY unit with constant speed on 10mm/s.
- ❖ **Material used in the experiments was polypropylene Sabic 579S with natural color and thickness of 1mm as upper joining partner. Lower partner was Sabic 579S with black outlook and thickness of 1mm**
- ❖ In polymer welding the welded parts have to be kept together during welding to be able to conduct heat from lower part to upper part.

In these tests five different error sources were used

- ❑ correct welding parameters were found out

error sources

- **1st** human hair with thickness of 60µm. This hair between parts causes air gap between parts
- **2nd** constant air gap between parts. A scotch Magic tape was used to create a 60µm air gap
- **3rd** wrong lower joining partner. This was ABS (Terluran) polymer which has totally different melting properties than the other partner
- **4th** grooves on lower part. Grooves were 50, 100, 150 and 200µm wide and the depth was 60µm. These grooves create local air gap which causes temperature rise
- **5th** metallic part on top of the parts which will prevent beam hitting the weld zone and also the temperature should be really low

Analysis of laser welding by OHHT

temperature signal
refereed to welding of polymeric materials

- **without defect** , presents slow oscillations within a fixed temperature range (T_{min}:T_{max})
- **in presence of defects**, due to different causes, oscillates more or less abruptly

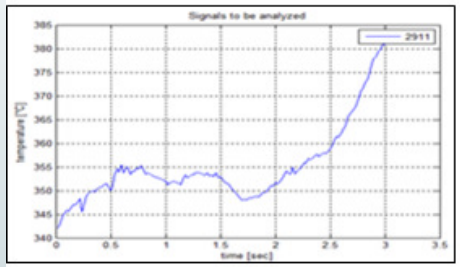
EMD aims at decomposing a signal x into a finite sum of modes $c_1, \ldots, c_n$ and a residue r where the modes are less oscillating with increasing *j=1:n* **the last IMF presents the slowest oscillations compared to the other modes**

- calculate the correlation coefficient matrix between the signal and each IMF component without considering the residue (the correlation coefficient matrix represents the normalized measure of the strength of linear relationship between variables)
- compose the correlation coefficient array $\mathbf{R_{x,IMF1}}$, …… $\mathbf{R_{x,IMFn}}$, where the first element corresponds to the correlation coefficient between the signal and its IMF_1, and the last element corresponds to the correlation coefficient between the signal and its IMF_n
- calculate the max value and relative position [**max**($R_{x,IMFj}$), **pos** (max($R_{x,IMFj}$)]

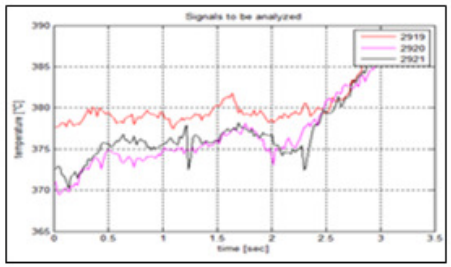
if the position corresponds to the last Orthogonal IMF, the detected signal is correlated to the component with slowest oscillation and theoretically doesn't present defects or at least doesn't present relevant defects.

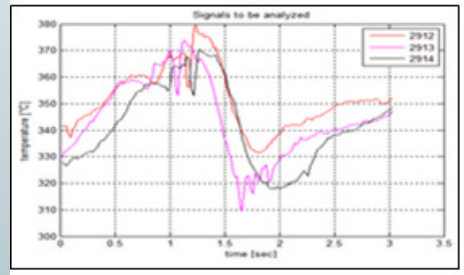
2911	2912	2913	2914	2920	2921	2922
0.068	0.0383	0.0904	0.0895	0.0469	0.0978	0.1504
0.0777	0.1459	0.1912	0.0288	0.0312	0.1117	0.3522
0.0941	0.1277	0.0519	0.0928	0.0279	0.0664	0.3063
0.1425	0.2595	**0.8028**	0.375	0.1358	0.1085	**0.6633**
0.4684	**0.8114**	0.3288	**0.8721**	**0.3372**	**0.3184**	0.419
	0.3987		0.303	**0.3535**	0.0382	0.0995
					0.1793	0.0117
						0.0593
ok	ok	ok	ok	?	ok	ok

2911 - no defects

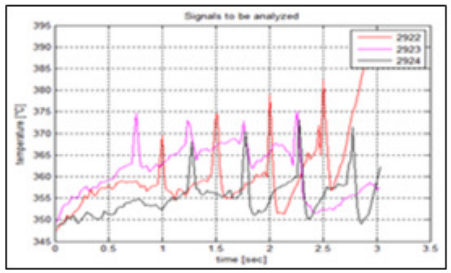


2920, 2921 wrong material (PP+ABS black)





2911: 2913 - 60 µm hair between parts



2922, grooves on the black

Analysis of laser welding by OHHT

2911	2912	2913	2914	2920	2921	2922
0.068	0.0383	0.0904	0.0895	0.0469	0.0978	0.1504
0.0777	0.1459	0.1912	0.0288	0.0312	0.1117	0.3522
0.0941	0.1277	0.0519	0.0928	0.0279	0.0664	0.3063
0.1425	0.2595	**0.8028**	0.375	0.1358	0.1085	**0.6633**
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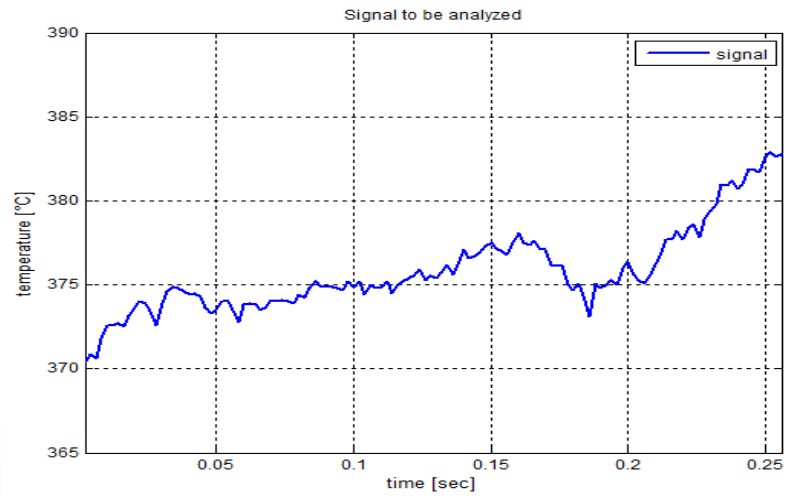
	0.3987		0.303	**0.3535**	0.0382	0.0995
					0.1793	0.0117
						0.0593
ok	ok	ok	ok	?	ok	ok



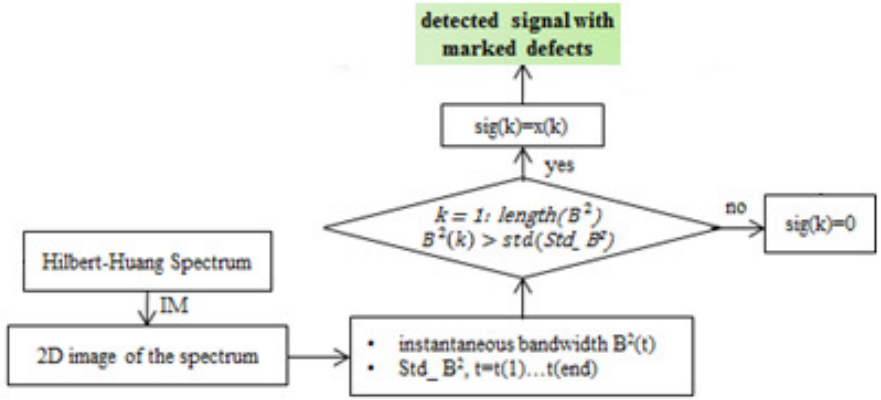
- Even if the position corresponds to the last Orthogonal IMF, the detected signal is not strongly correlated to the component with slowest oscillation, because there is a second correlation coefficient, $\mathbf{R_{x,IMF5}}$, closed to the last one $\mathbf{R_{x,IMF6}}$

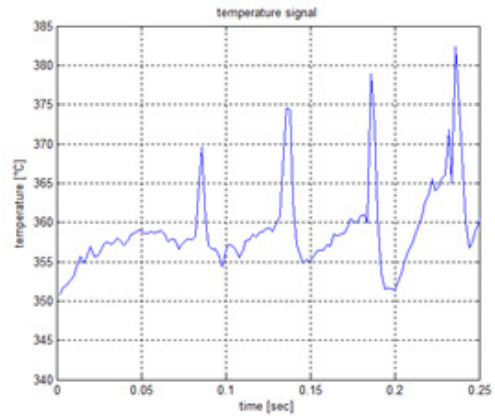
A second condition has been added

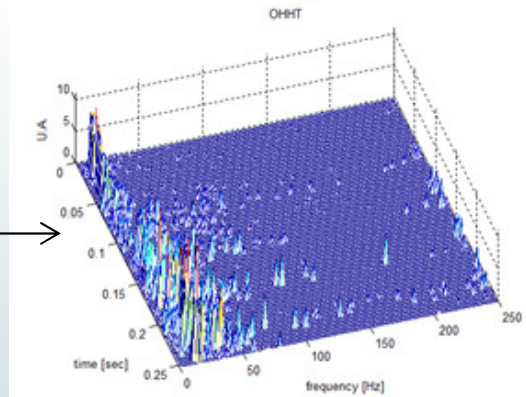
the position must correspond to the last Orthogonal IMF
the relative value must be higher than the sum of the other correlation coefficients referred to IMF_1….. IMF_{n-1}

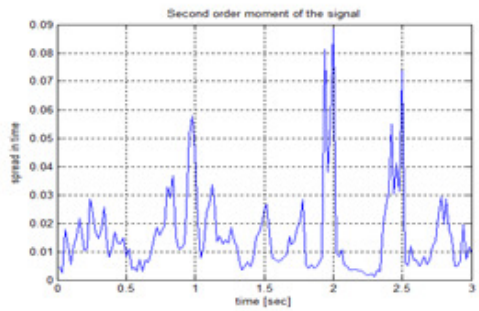
The possibility to analyse the welding quality without using any signal as reference has been demonstrated

Analysis of laser welding: last steps









- Without considering the residue, the Hilbert-Huang transform is evaluated. The output is the Hilbert Spectrum to be shown in 3D image
- Once the Hilbert Spectrum has been obtained, its second order moment in time is calculated:

$$f_m = \int_{-\infty}^{\infty} f\, HS(t,f)\, df \Big/ \int_{-\infty}^{\infty} HS(t,f)\, df$$

$$B^2(t) = \left[\int_{-\infty}^{\infty} f^2 HS(t,f)\, df \Big/ \int_{-\infty}^{\infty} HS(t,f)\, df\right] - f_m(t)^2$$

$f_m(t)$ is the first order moment in time and describes the averaged positions of the signal.

The second order moment describes the spread in time of the signal

- The step ends by calculating the standard deviation of the second order moment
- the last step individuate the presence of defects. **The samples of the second order moment which exceed the standard deviation are classified as defects**

Conclusion

The presented work introduces the method of **Orthogonal Hilbert-Huang Transform** (OHHT) for laser welding data analysis and proposes approach estimating the weld quality by OHHT combined with its second order moment.

It reveals the following:

- Because there is no strict orthogonality among IMF components decomposed by conventional EMD, leakage of energy may be happened if we directly use HHT to estimate the local spectral density of non-stationary welding laser data.:
  - the work proposes the orthogonal HHT (OHHT) method avoiding leakage of energy.
  - OHHT is a universal approach and is suitable for all non-stationary signals.
- The analysis of Pearson's correlation coefficient allows to determine **the welding quality without using any signal as reference**
- The Hilbert spectrum, combined with the second order moment, allows to localize the defects.

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ThankS For Your AttentioN

QuestionS (??) & CommentS (!!)