Application of non-linear ultrasonic spectroscopy to health monitoring and damage detection in structures



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1. Damage detection by non linear acoustic Basic Principles



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Generalities

- **Classical methods by vibration, optical or electrical control are faced with large difficulties due to the size, the necessity of on-line testing and the need to use non-intrusive methods.**

- **The proposed method starts from the actual insight that in many materials (soils, rocks, concrete, alloys ...), the non-linear elastic properties are linked with the level of damage.**

- **Then by mastering non-linear elastic process and their coupling it is possible now to pull out information from a non linear experiment like :**

a classical high frequency bench of N.D.T. which is modulated by low frequency vibrations produced by a known and localized shaker, then the elastic non linearity of the medium leads to modification of the output spectrum.

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The low frequency spectrum of excitation will be monitored by an array of accelerometers (or geophones).

The high frequency inspection will be driven from a mobile vibrating source (high frequency piezoelectric shaker) and by clamping it at precise check points.

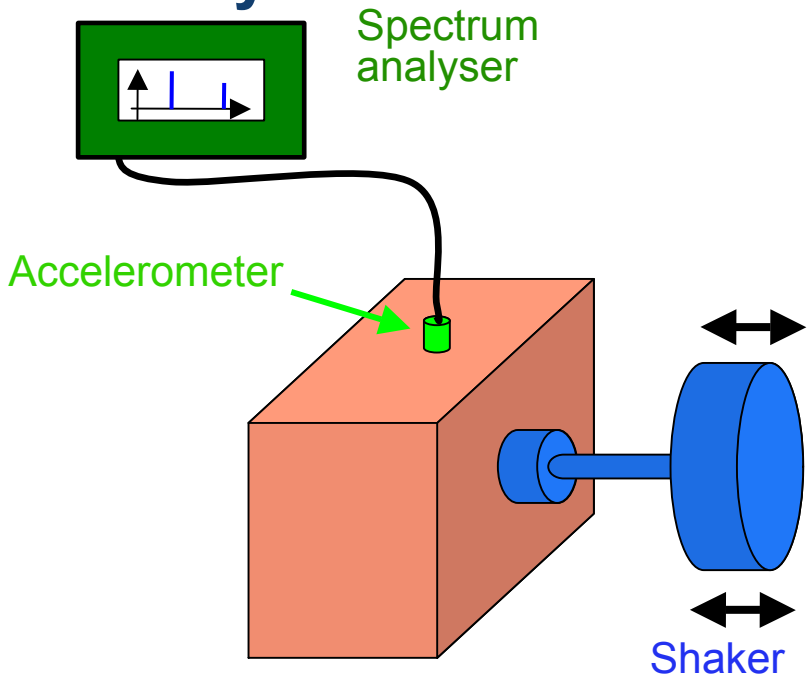
The array of sensors (accelerometer or geophone) reads three groups of signals :

- the low frequency spectrum (ambient low frequency noise, source of continuous fatigue and future damage),
- the high frequency structural response to the shakers
- and the high frequency modulated signal coming from non-linear sources located in the damage area.

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To Vibrate the structure

Vibration response analysis of a structure

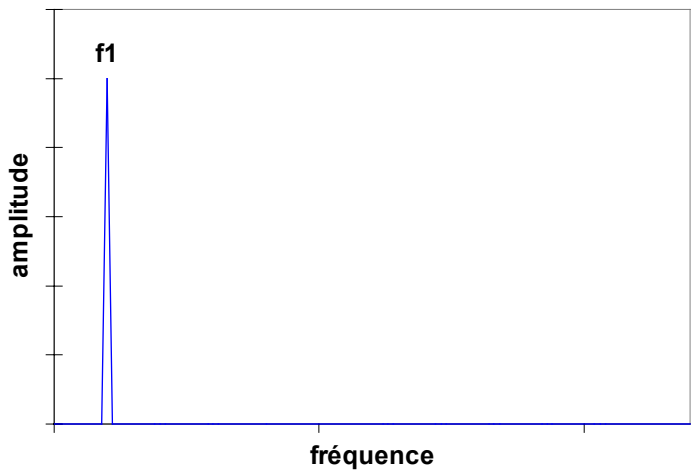


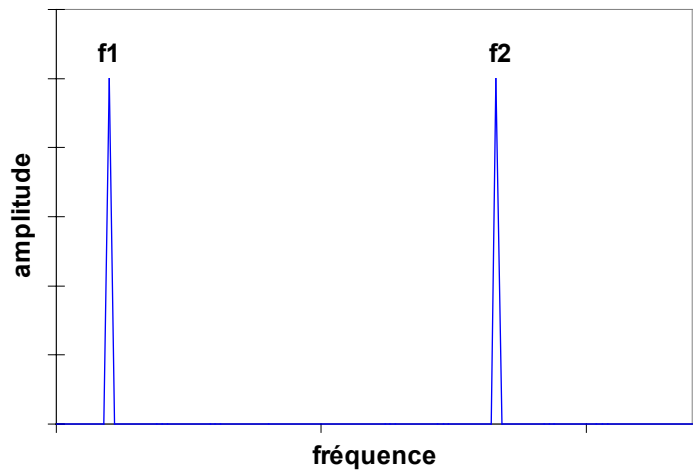
Goal : Damage detection

Default / damage detection

- **The response spectrum of the structure gives usefull information about its health state (crack, delamination …)**

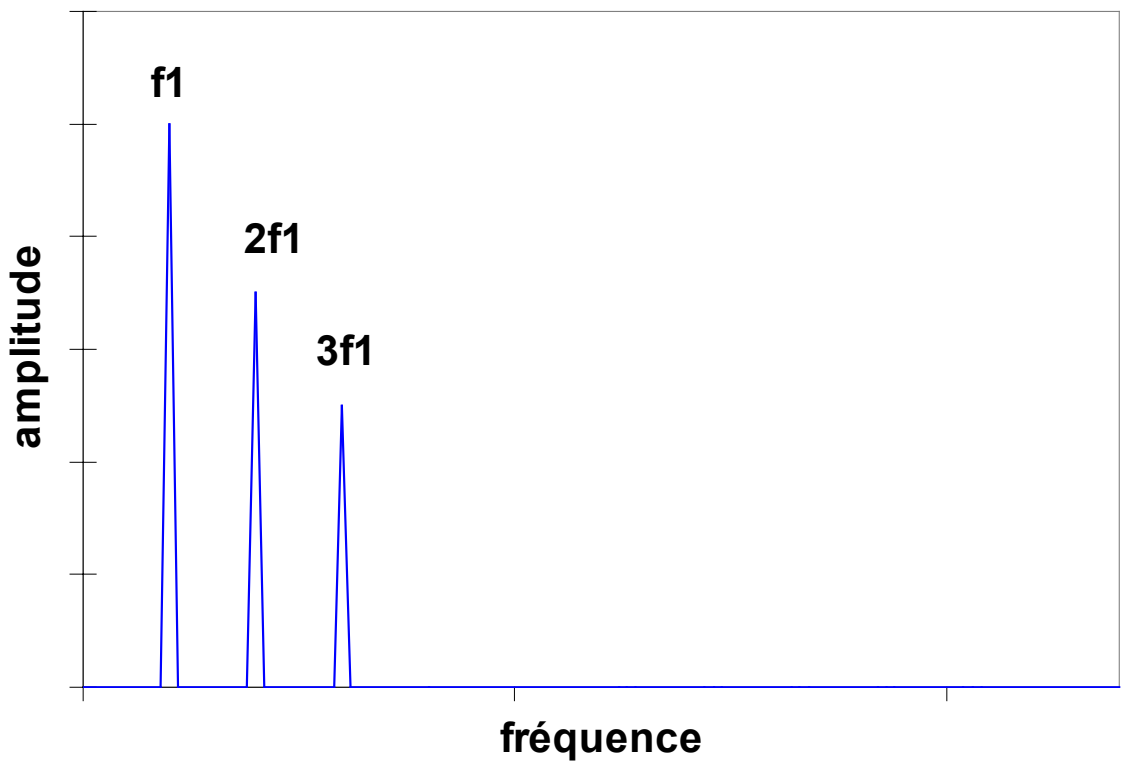
- **Linear behavior :**
  - **One frequency excitation**
  - **Two frequencies excitation : « Superposition Theorem »**





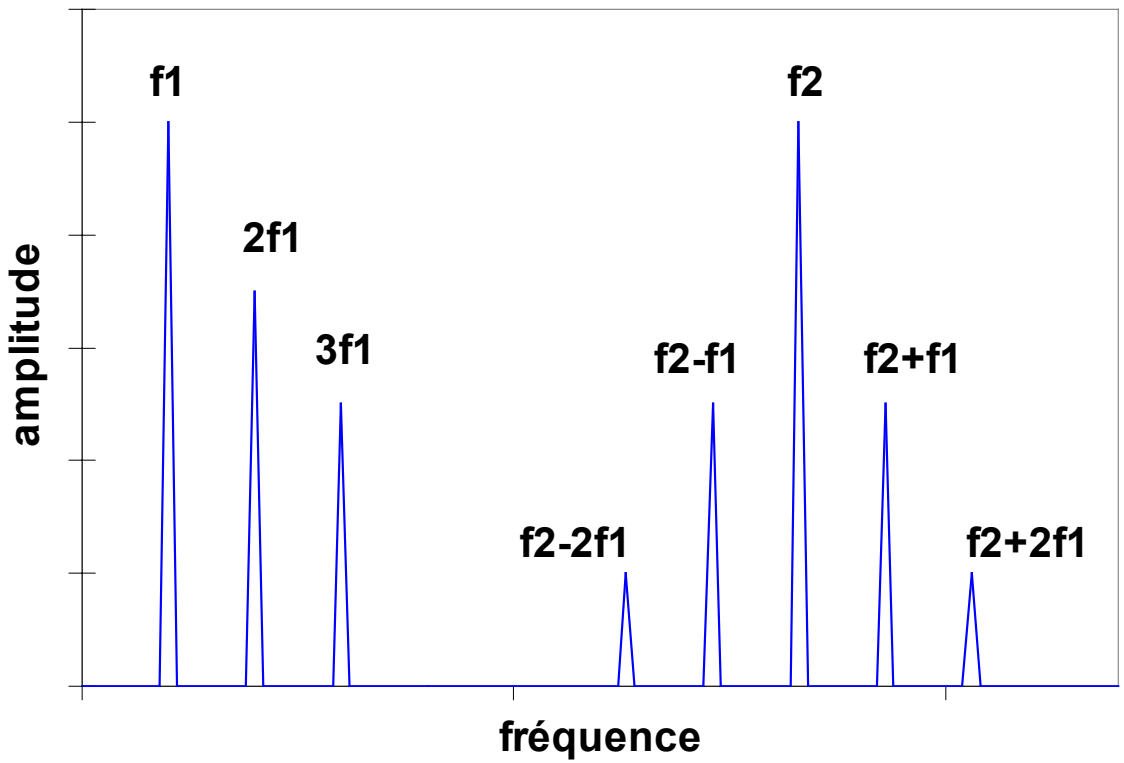
Non Linear behaviour (1)

- One frequency excitation



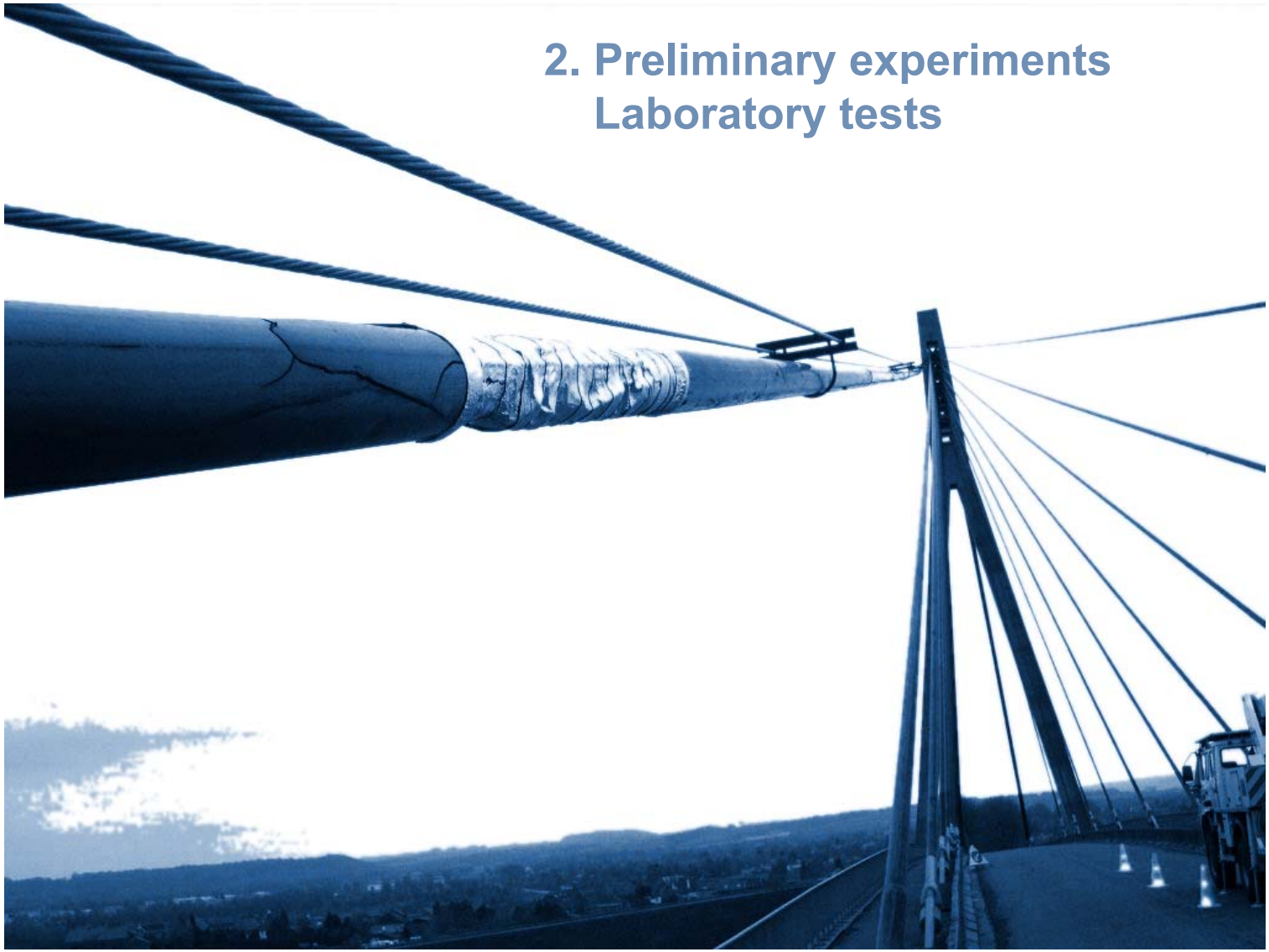
Non Linear behaviour (2)

- Two frequencies excitation



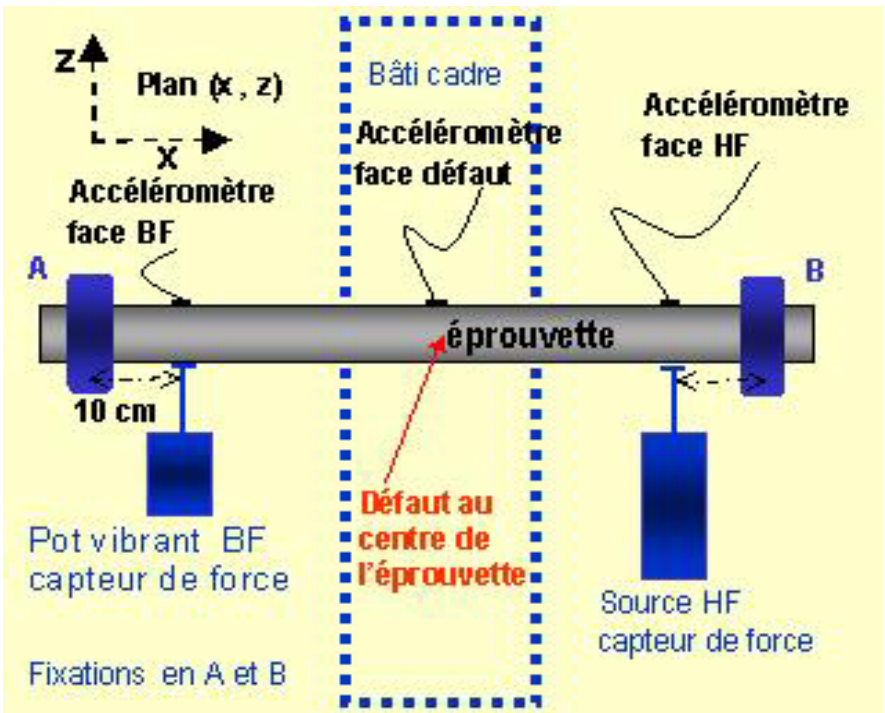
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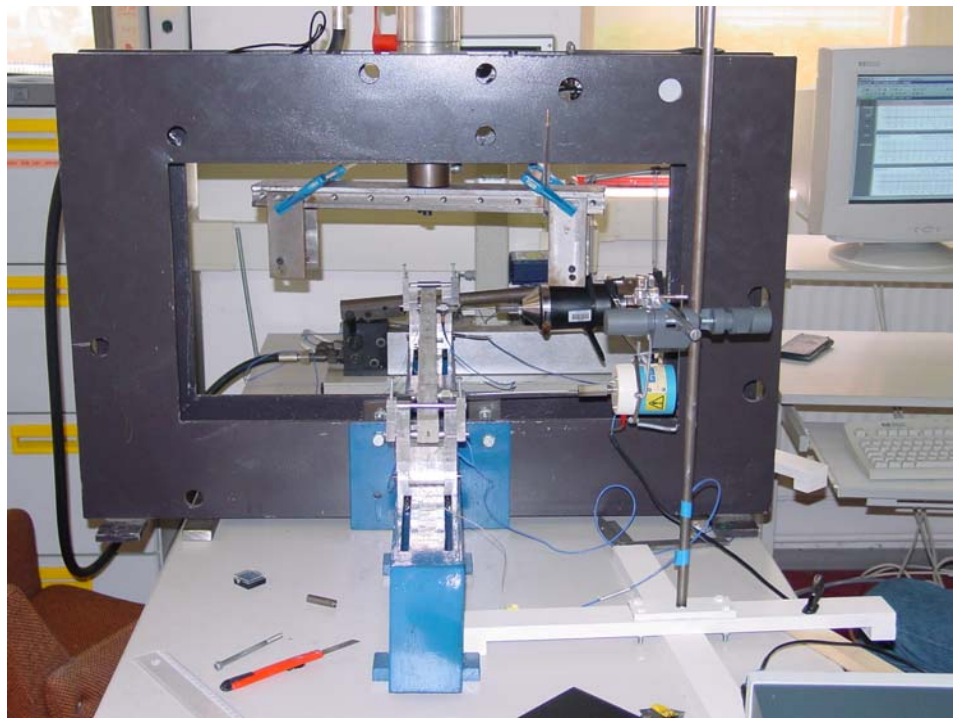
2. Preliminary experiments
Laboratory tests



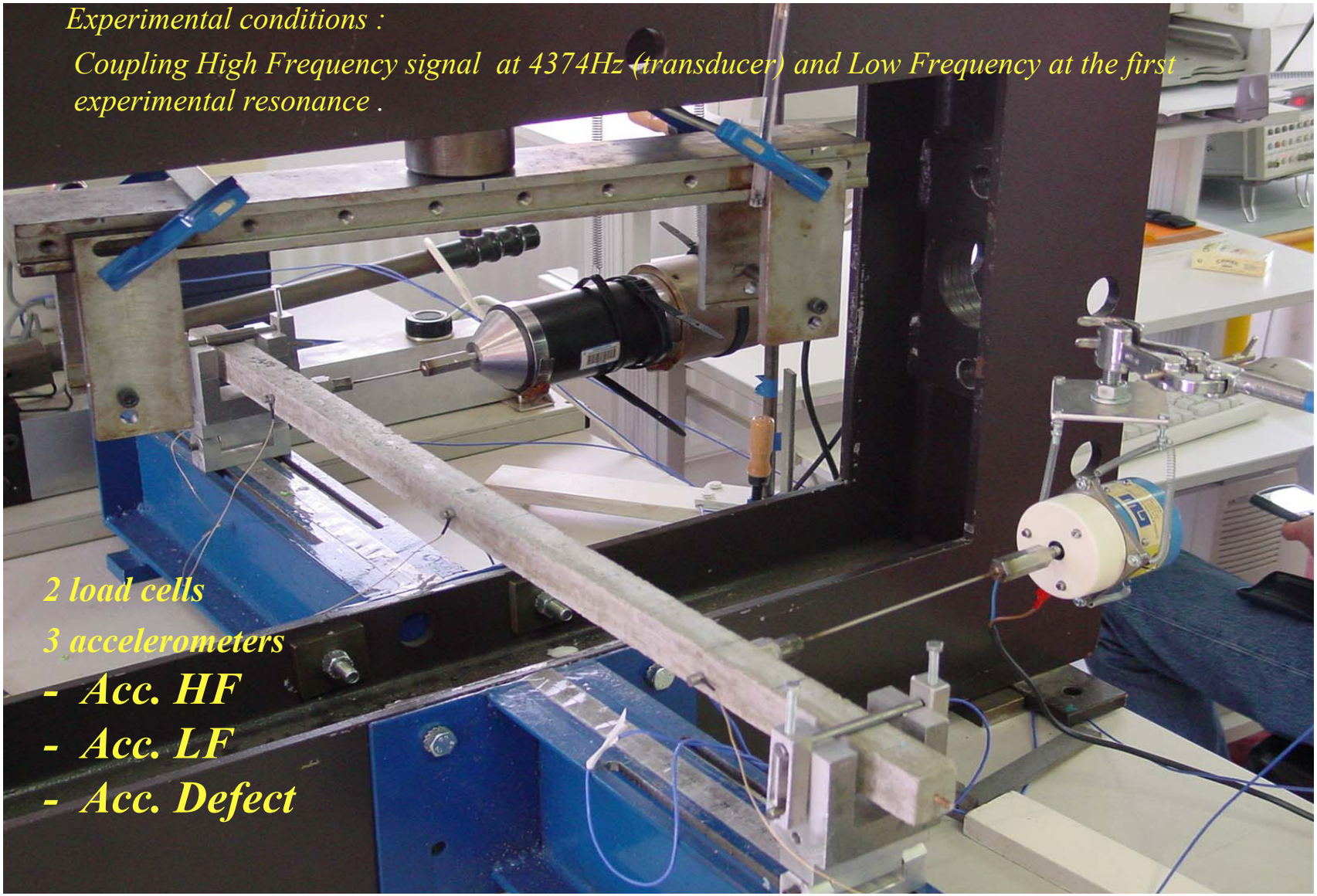
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Experimental Configuration in Vibro-Acoustic Spectroscopy

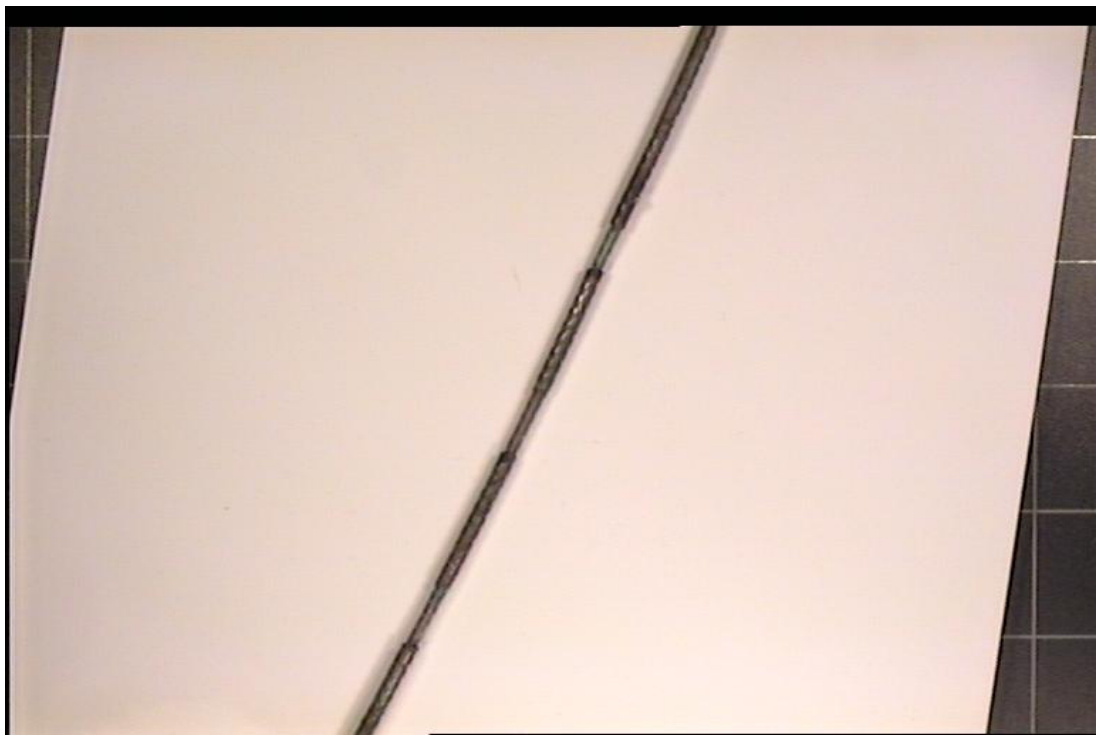




Beam experimentation



Beam experimentation



Chemical attack of the steel rod in order to simulate corrosion

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Beam experimentation



Beams manufactured two by two

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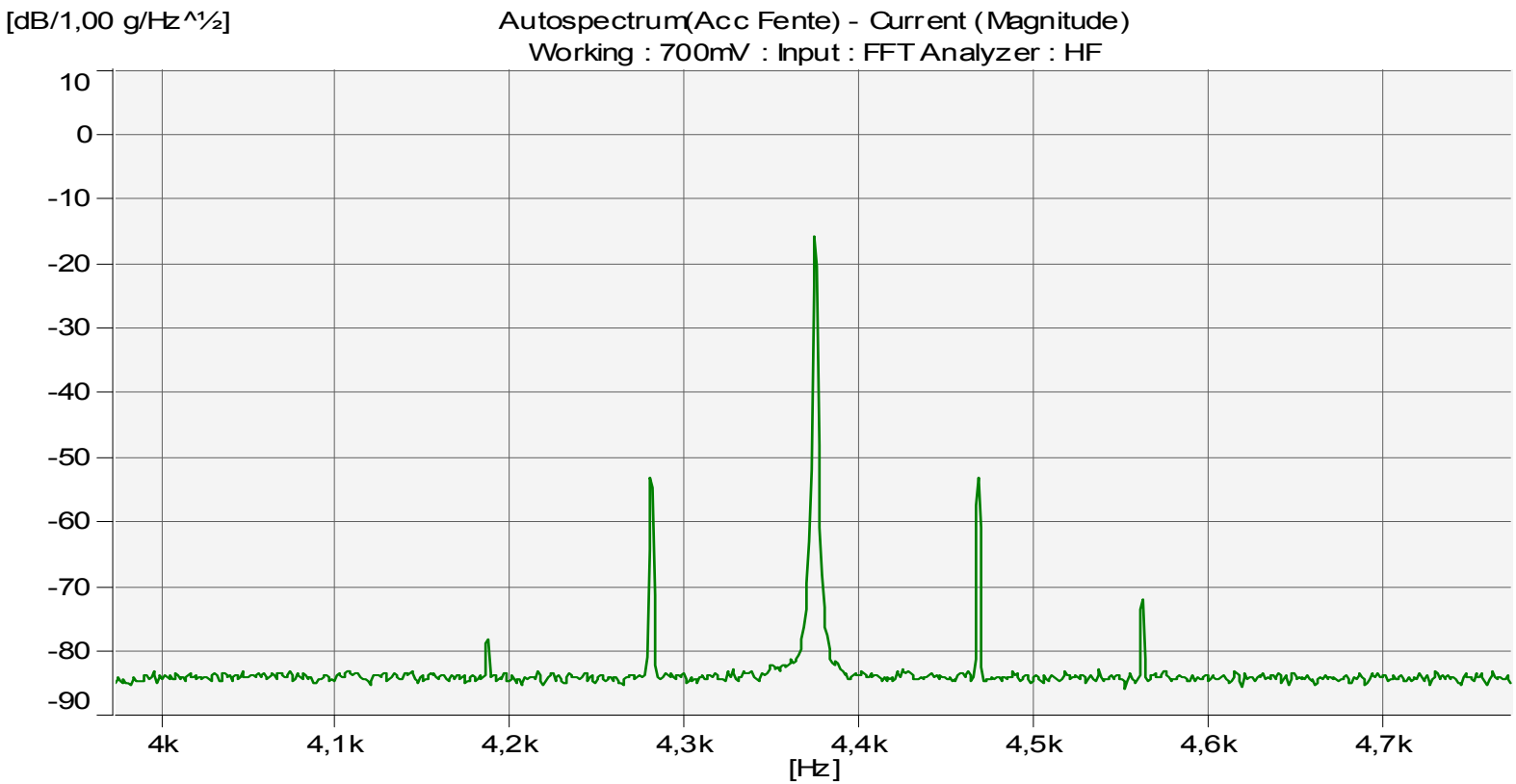
Beam experimentation



Use of silicon at the center of the steel rod in order to simulate a non adherance default

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Beam experimentation - Results



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3. In situ bridge tests



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Cable Bridge Tests





- Main span : 177m
- Symmetric cable stayed-bridge with respect to the deck
- Y pylon
- Two sides : « Maastricht » et « Liege »
- Stay cable « Maastricht 1 » has been put in a safe place

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Excitation system

- *Excitation source : LDS V 455 shaker*
- *Effective useful range : 5-7500Hz - Weight 64kg*
- *Sine force peak : 489N*
- *Maximum displacement : 19mm*
- *Mounted on a special in-house designed support*
- *Connected to the cable above it with a squeezing system that could adapt itself to all the different diameters of the cables that were being examined*
- *The support system stood on a scaffolding that held it approximately 1.5 to 2m off the ground in most of the experiments*

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Excitation system







Our anxiety before the departure of the tests : will the vibration be perceptible in the cable?

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Yes vibration is perceptible



We can observe easily the resonances et anti resonances of the cable:





Vibration can be perceptible to on the deck :

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Main sensors Positioning (accelerometers)

On the stay cable to investigate :

- **Near the shaker;**
- **Higher on the cable;**
- **Even higher;**
- **Near the anchor**







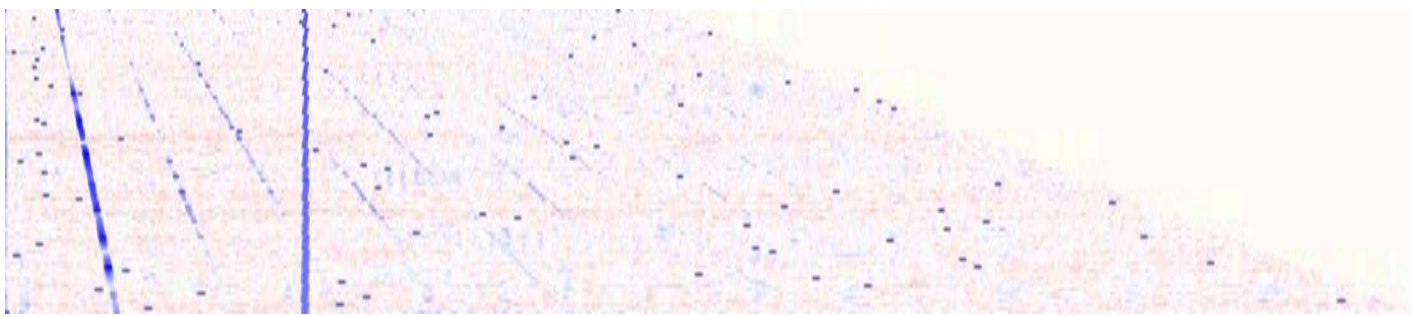


Post processing tools (1)
Development of tools coming from experience

- ***Two important facts :***

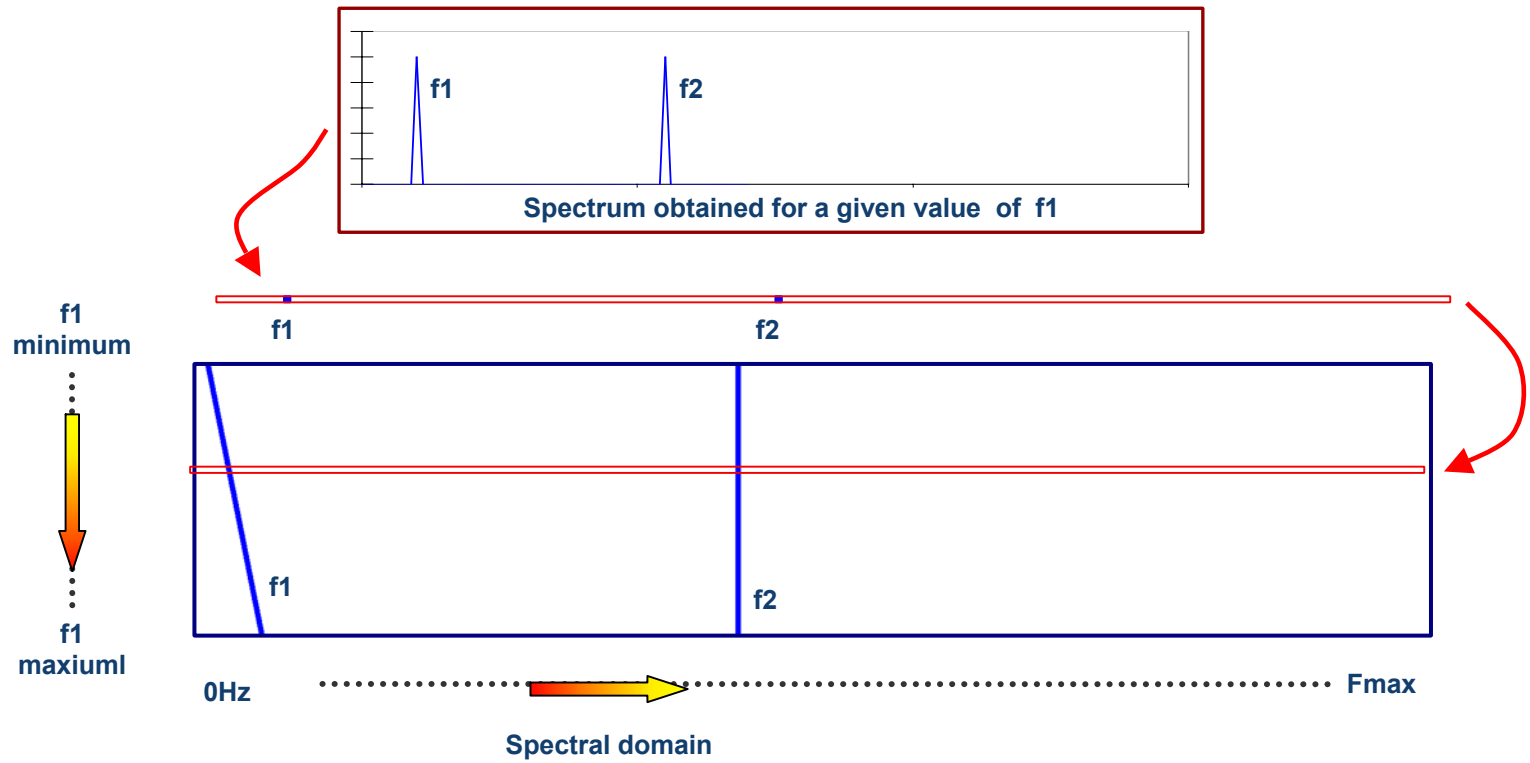
- ***Experimental observation : signals and spectrum are difficult to read and to interpret***
- ***How to exploit the test measurements achieved by using a frequency sweep?***

Example of a 2D spectrum obtained later :



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Post processing tools (2)
2D Spectrum - Principle of construction



This test methodology has an impact on the progress of the test !

Post processing tools (3)
Advantage of this 2D Spectrum representation

- Much less sensitivity in the signal / noise ratio.

- Finally we obtain a spectrum which is easy to understand: we only have to find lines in a picture and then we have to explain them.

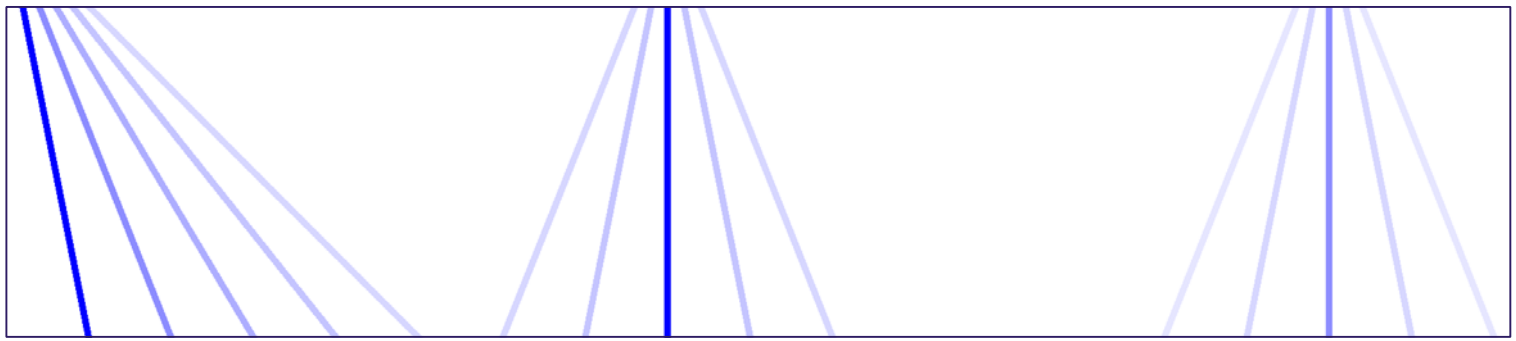
- Easy detection of the possible defaults in the excitation system.

- Absence of problems connected to the resonances and anti resonances of the tested structure.

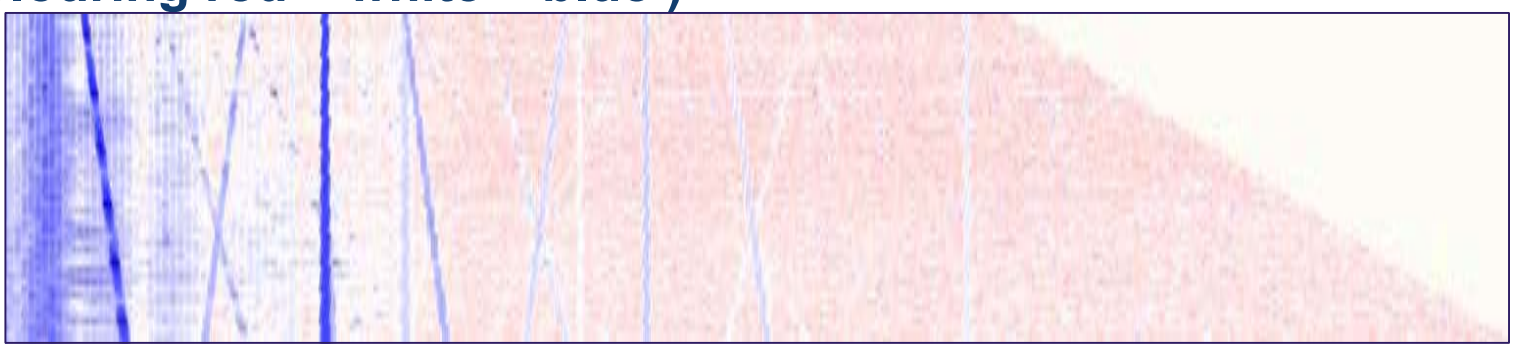
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Post processing tools (4)
What kind of representation in the non linear case ?

From a direct application of the methodology :



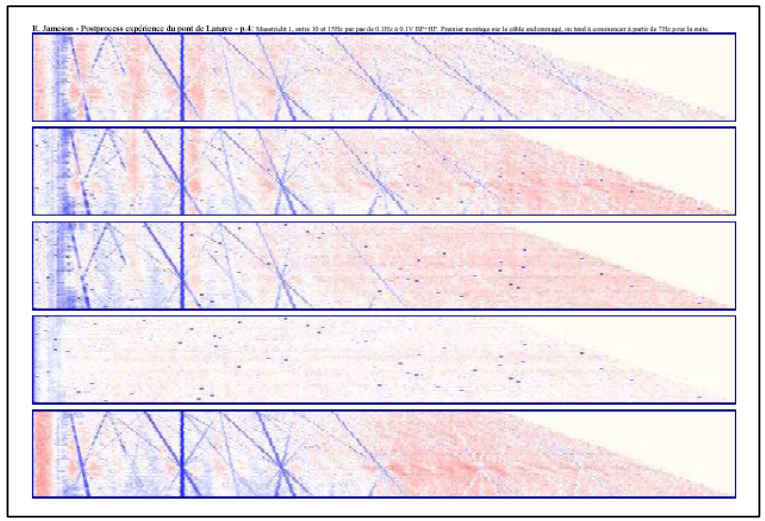
Here is what we obtain from an experimentally point of view (colouring red – white – blue)



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Overview of the main results

Success!



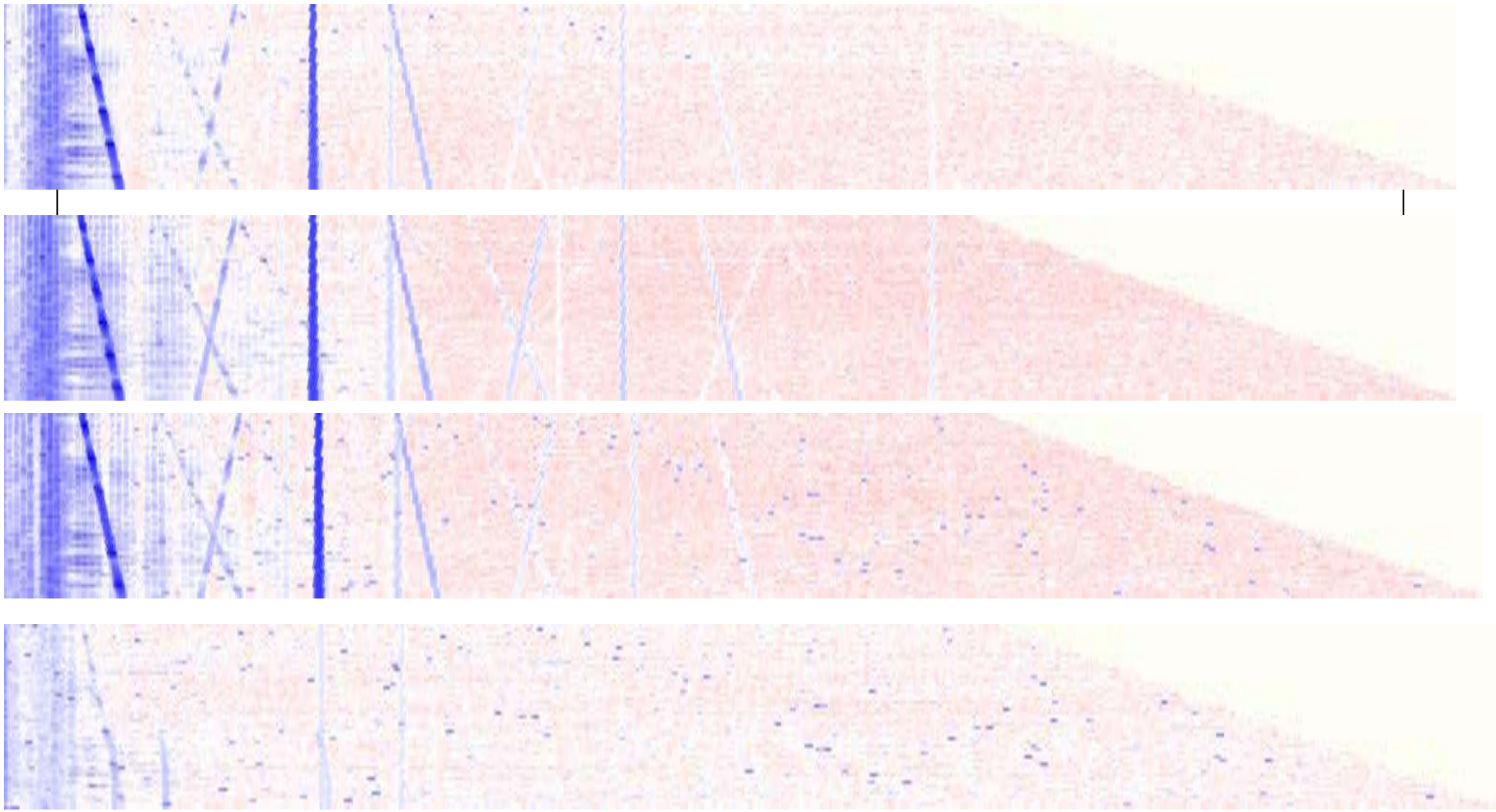
Different behaviour for each of the stay cables :

- **Liege 2: safe, small non linearity**
- **Maastricht 1: strong defaults, exacerbated non linearity seen on all the spectrum**
- **Liege 1: default on the anchor (noticed during the test), non-linearity decreased when we inspect the cable from the anchor to the top**
- **Liege 4: safe, like Liege 2.**

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Illustration : Liege 2

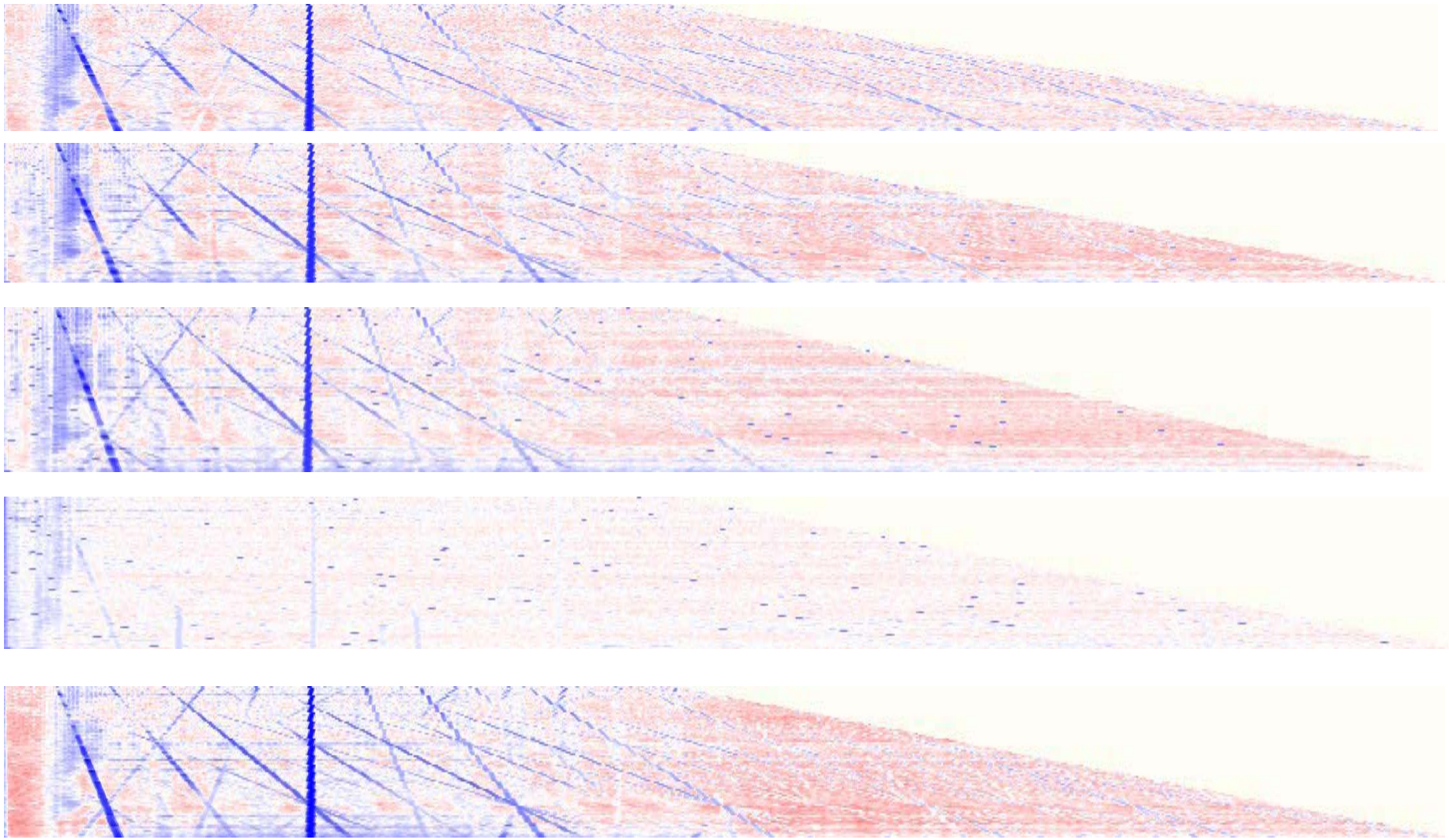
Liege 2, from10 to 15Hz by steps of 0.1Hz - level 0.2V – high frequency at 40Hz.



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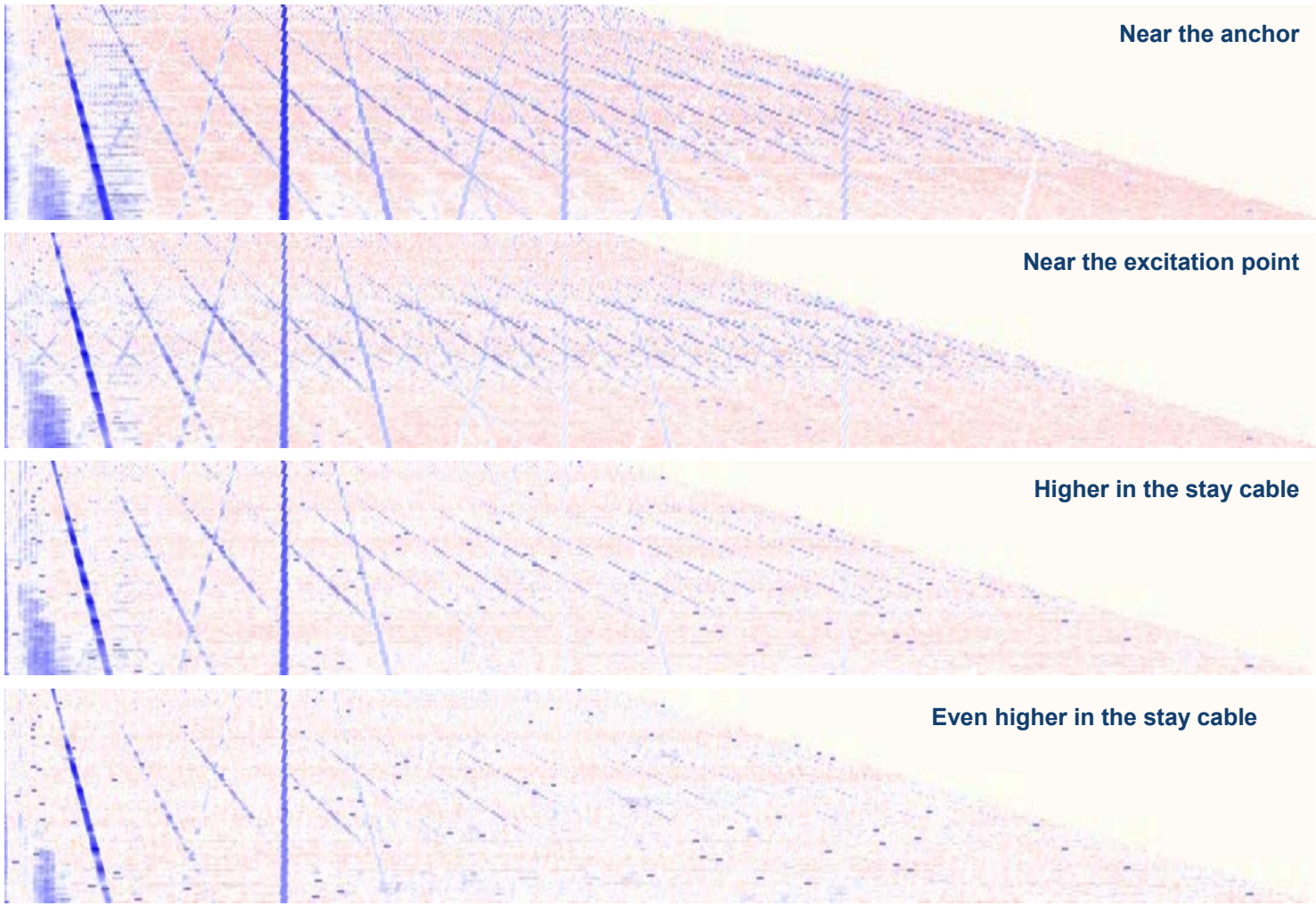
Illustration : Maastricht 1

Maastricht 1, from7 to 15Hz by steps of 0.1Hz - level 0.2V – high frequency at 40Hz.



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Illustration : Liege 1



Broken support system at the level of the cable's anchor



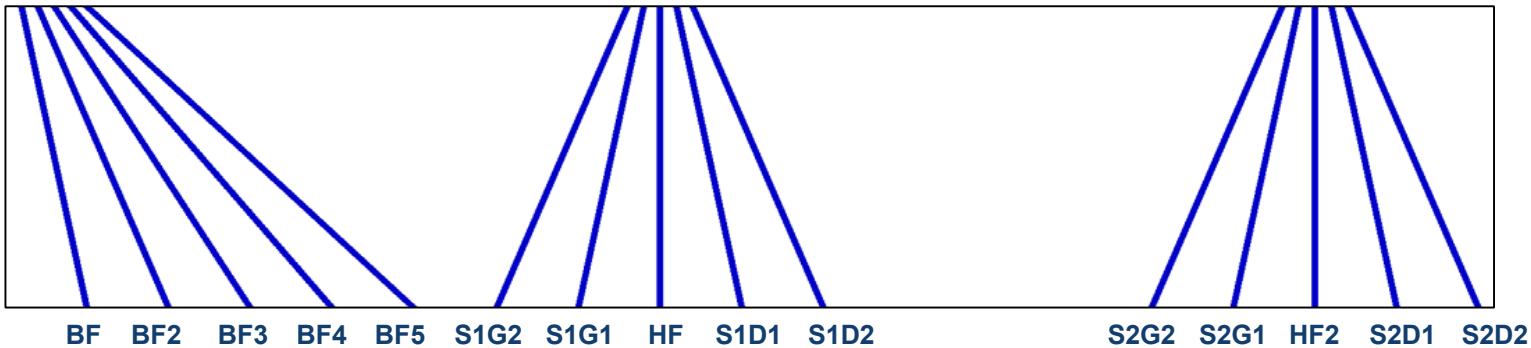




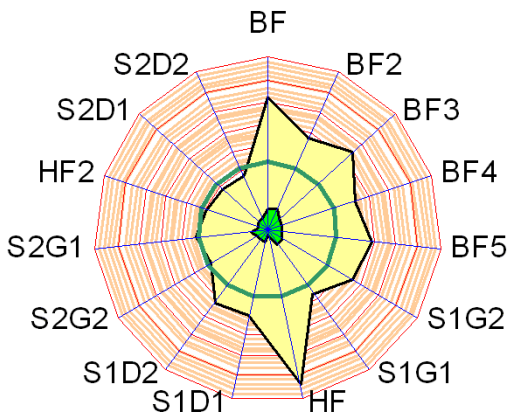
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Representation in term of radars diagram

In order to have another kind of representation of the spectrum, we have developed another model



- A 2D spectrum becomes a radar :

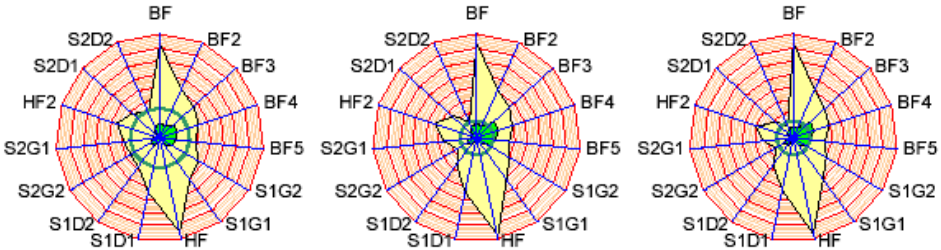


Advantage :

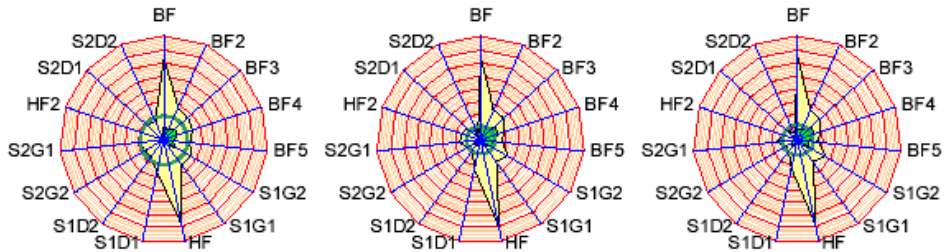
- **Direct relation with the 2D spectrum**
- **Quantitative aspects**

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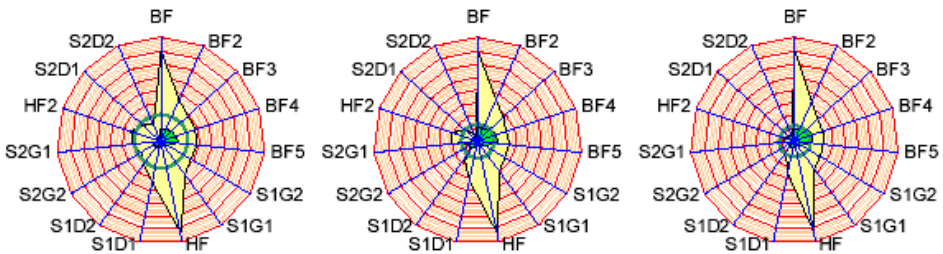
Radars diagram : Liege 2



Liège 2, entre 10 et 15Hz par pas de 0.1Hz à 0.3V BF+HF. HF à 40Hz, échafaudage déjà renforcé.



Liège 2, entre 10 et 15Hz par pas de 0.1Hz à 0.1V BF+HF.

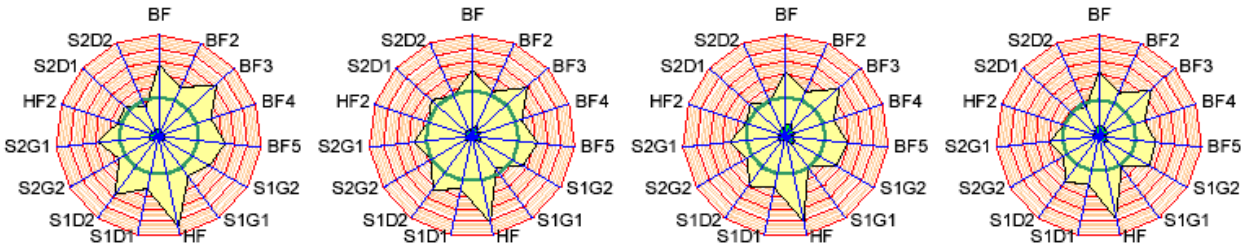


Liège 2, entre 10 et 15Hz par pas de 0.1Hz à 0.2V BF+HF. HF à 70 Hz. N.B.: Correction d'échelle (pics)

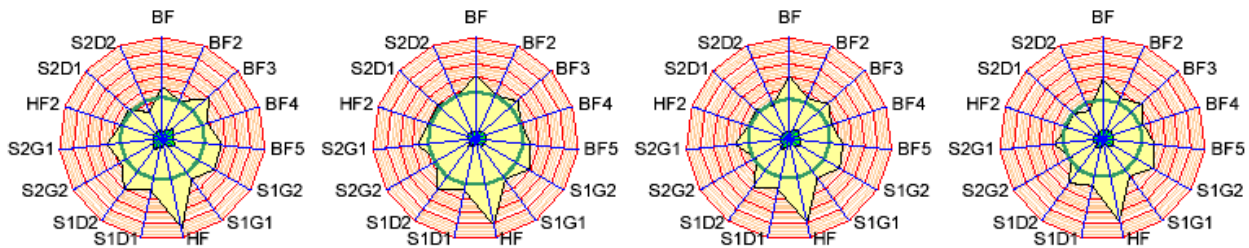
Robbie Jameson – 15/12/03 – postprocess de l'expérience de Lanaye

2

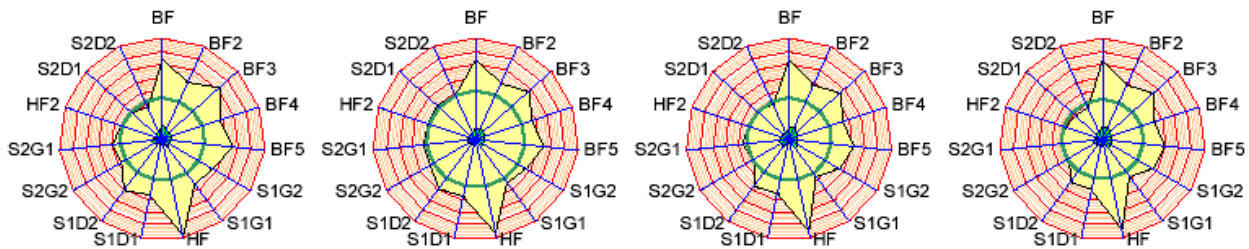
Radars diagram : Maastricht 1



Maastricht 1, entre 10 et
15Hz par pas de 0.1Hz à 0.1V BF+HF. Premier montage sur le câble endommagé, on tend à commencer à partir de 7Hz pour la suite.



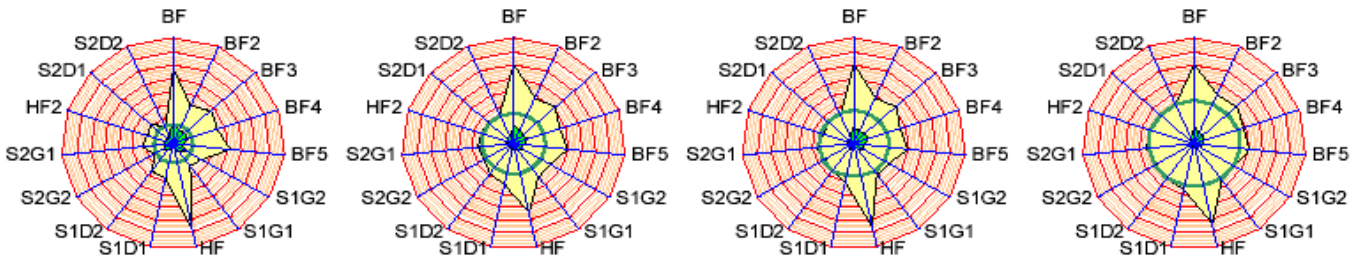
Maastricht 1, entre 7 et
10Hz par pas de 0.1Hz à 0.1V BF+HF. Mesure de correction de manière à avoir une plage commençant à 7Hz. Correction d'échelle.



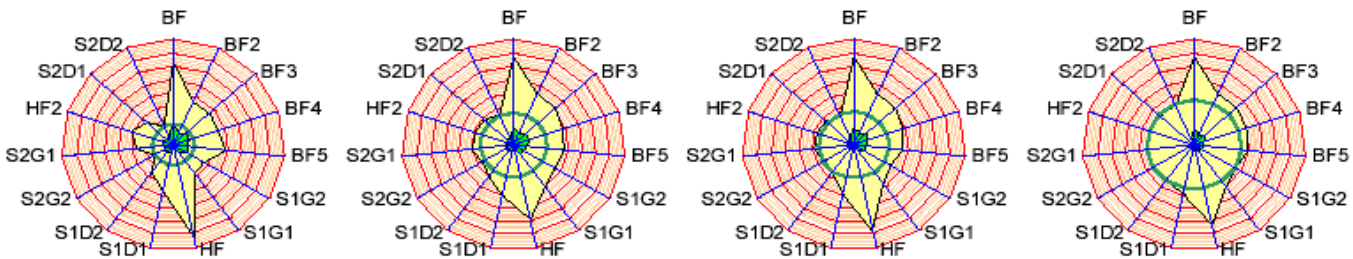
Maastricht 1, entre 7 et
15Hz par pas de 0.1Hz à 0.2V BF+HF.
3

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Radars diagram : Liege 1



Liège 1, entre 7 et 15Hz par pas de 0.1Hz à 0.1V BF+HF. Changement du câble du capteur sismique entre 8 et 8.1Hz.



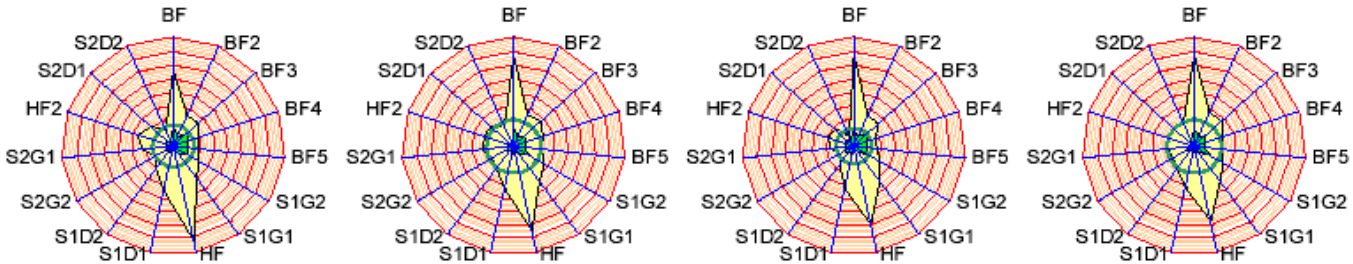
Liège 1, entre 7 et 15Hz par pas de 0.1Hz à 0.2V BF+HF. On découvre un phénomène de choc au niveau de l'ancrage.

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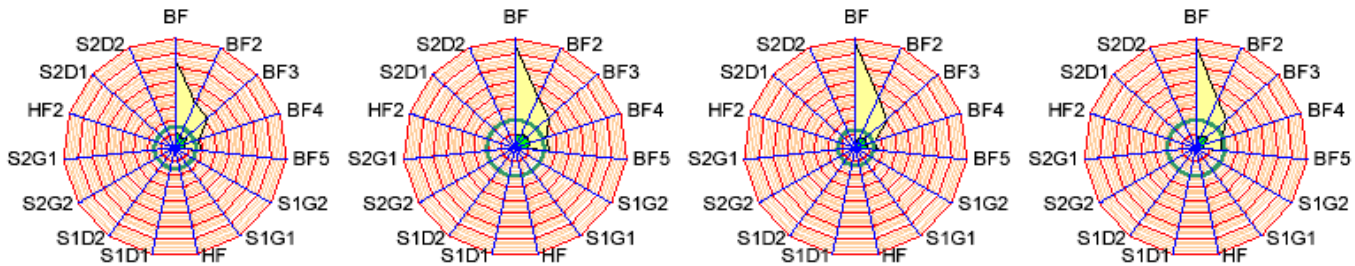
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Radars diagram : Liege 4



Liège 4, entre 7 et 15Hz par
pas de 0.1Hz à 0.2V BF+HF. Dernier câble de la série.



Liège 4, entre 12 et 14Hz
par pas de 0.1Hz à 0.2V BF seule. Essai sans HF à comparer avec une première mesure effectuée sur Liège 2.

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4. Conclusions



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Conclusions

This innovate method of detection of default in stay cables has considerably evolved since the beginning of this study

Good and significant results have been obtained

A new test methodology, coming from the experiment, has been implemented

From the test point of view :

- Spectral purity of the sources
- Method f1 + f2 with sweeping with respect to f1, and 2D representation
- It is possible to interpret the spectrum from a quantitative manner

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Perspectives

It remains to do :

- *Simulation / modelling (in progress)*
- *New tests in order to continue the development of the tools which will permit to dispose of a reliable method and associated software*
- *Localization (theory / experiment)*

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