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# Optimal Command of the Nonlinear Elastic Wave Spectroscopy

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## Introduction

In non destructive testing, improvements have been made possible by taking into account the **nonlinearities**. The Nonlinear Wave Modulation Spectroscopy (NWMS) method is one of this method. It is based on probing the medium with a low amplitude ultrasonic wave at frequency  $f_{probe}$  and exciting the medium with a large amplitude wave with lower frequency  $f_{pump}$ . The presence of nonlinearities linked to the defect to be detected will lead to the modulation of the probe wave by the pump wave. It appears sideband frequencies at the sum  $f_+ = f_{probe} + f_{pump}$  and at the difference  $f_- = f_{probe} - f_{pump}$ . It was shown that the modulation sidebands amplitude is a good indicator of the presence and the increase of the material damage. However, to have a good sensitivity, the question remains : “**How to choose both frequencies  $f_{probe}$  and  $f_{pump}$ ?**”.

Most of time, the transmitted signals are often selected manually, by taking into account the transducer bandwidth only. However, **waveform should take into account all the features of the ultrasound system and of the medium**. The optimal command [1] has been associated to the nonlinear Vibro Acoustic wave Modulation method [2].

## Main Objectives

1. **Optimizing the nonlinear-linear ratio  $R_{NL/L}$**  defined as the ratio between the amplitude of the low frequency intermodulation component (Left Sideband) in the nonlinear case and to its amplitude in the linear case, such as:

$$R_{NL/L} = \log(A_{f_-,NL}/A_{f_-,Lin}). \quad (1)$$

2. **Finding the best frequencies  $f_{probe}$  and  $f_{pump}$  with a genetic algorithm.**

$$[f_{probe}^*, f_{pump}^*] = \arg \max_{f_{probe}, f_{pump}} (R_{NL/L}), \quad (2)$$

3. **Finding the cut-off frequencies to compute stochastic signals.**

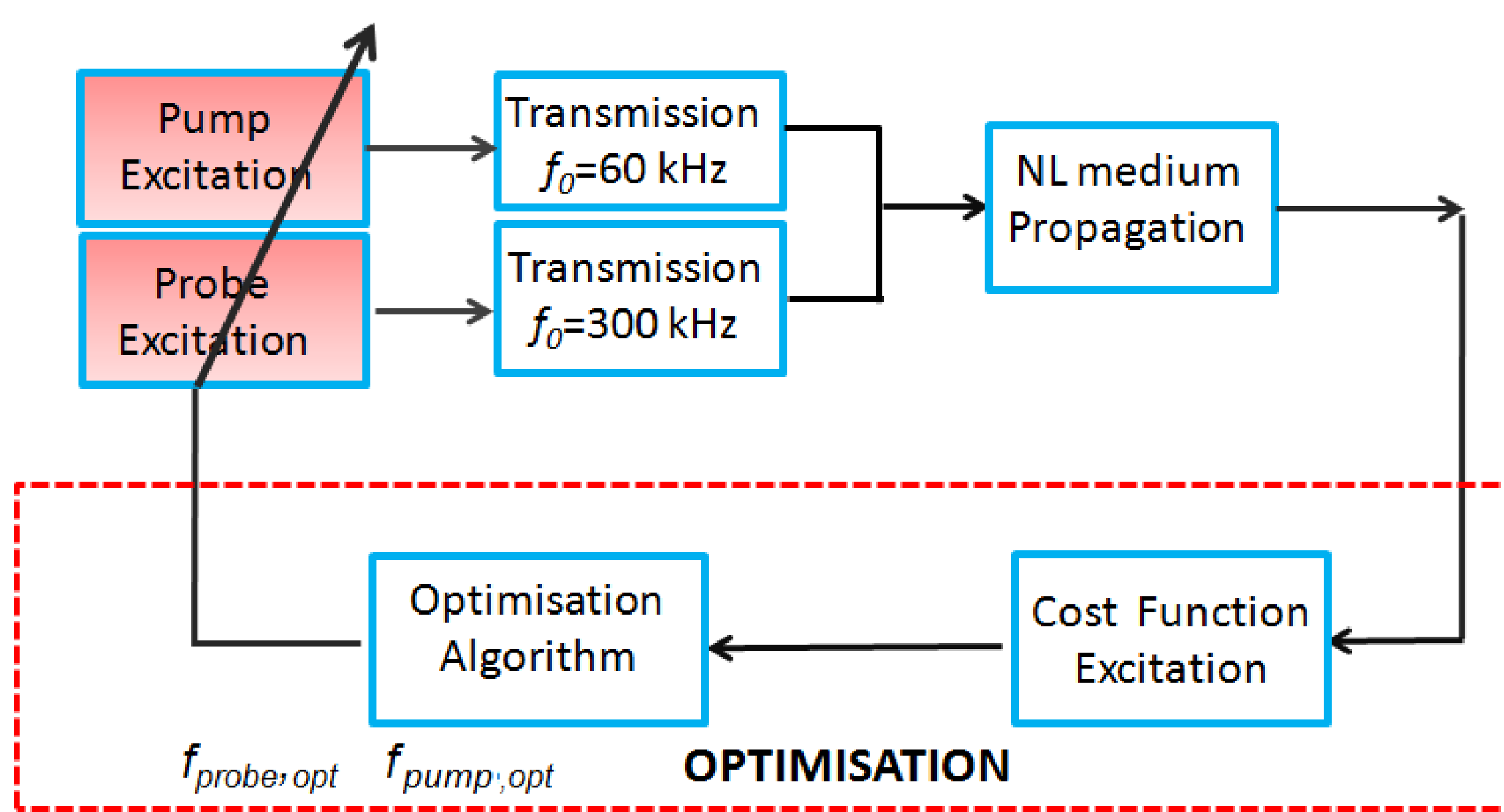


Figure 1: Block diagram of the optimized NWMS system

## Frequency Optimization

1. **Generating 12 solutions composed of a probe frequencies  $f_{probe}$  and a pump frequency  $f_{pump}$**

2. **Transmission of the input signals, for m-th solution:**

$$x_m(t) = A_{pump} \sin(2\pi f_{pump}t) + A_{probe} \sin(2\pi f_{probe}t), \quad (3)$$

with  $A_{pump} = 2 \cdot 10^{-3}V$  and  $A_{probe} = 10^{-4}V$ .

3. **Left sideband Extraction in reception and computation of the cost-function  $R_{NL/L}$ .**

4. **Generating new pair of frequencies  $f_{probe}$  and  $f_{pump}$  by Genetic Algorithm:**

- Keeping the 6 best individual solutions and mixing them by crossover operator;
- Changing randomly 40% of samples by mutation operator.

5. Return to step 2.

## Simulation

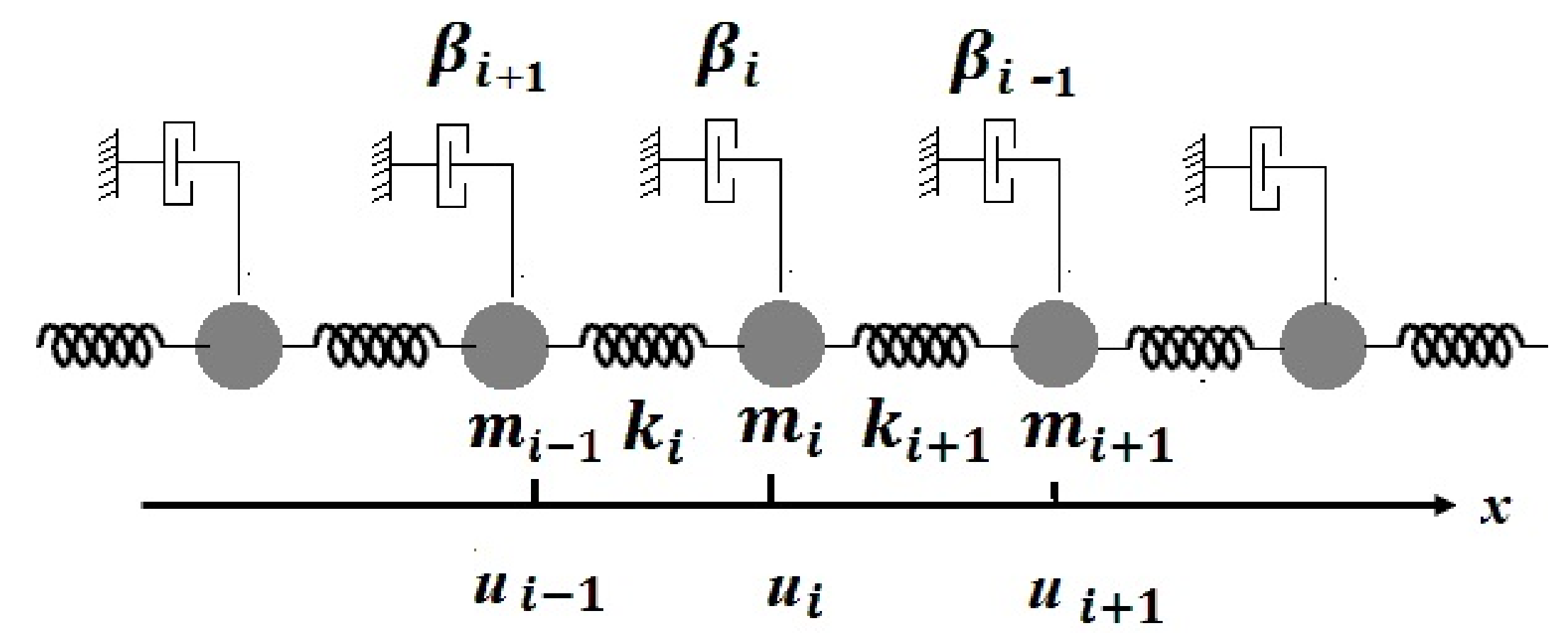


Figure 2: one dimensional mass spring system.

- 1D simulation of nonlinear propagation including a quadratic nonlinearity  $A$ :

$$m_i \ddot{u}_i = k_i(u_{i-1} - u_i) - k_{i+1}(u_i - u_{i+1}) + A_i(u_{i-1} - u_i)^2 - A_{i+1}(u_i - u_{i+1})^2 - \beta_i \dot{x}_i,$$

- Linear density: 2700 kg/m – Elastic Modulus: 69 GPa  
– Masses Number: 40 – Chain length: 0.15 m – Distance between two masses at equilibrium:  $3.75 \cdot 10^{-3}$  m – Mass: 10.125 kg – Stiffness constant:  $1.84 \times 10^{13}$  N/m – Viscosity coefficient:  $10^5$  kg/s –  $A=10^{13}$  N/m<sup>2</sup>

## Results

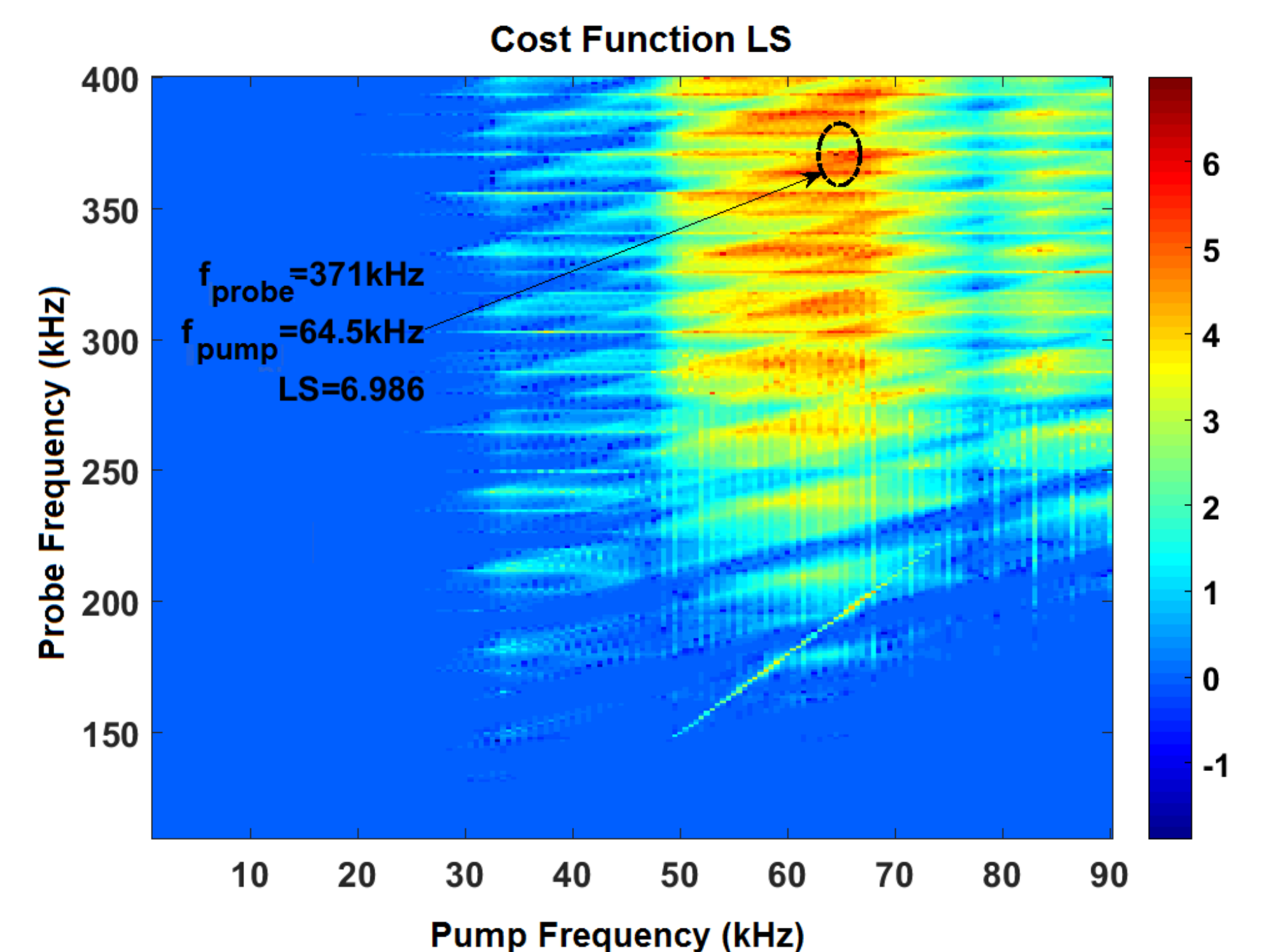


Figure 3: Cartography of the cost-function  $R_{NL/L}$  as a function of the pump and the probe frequencies.

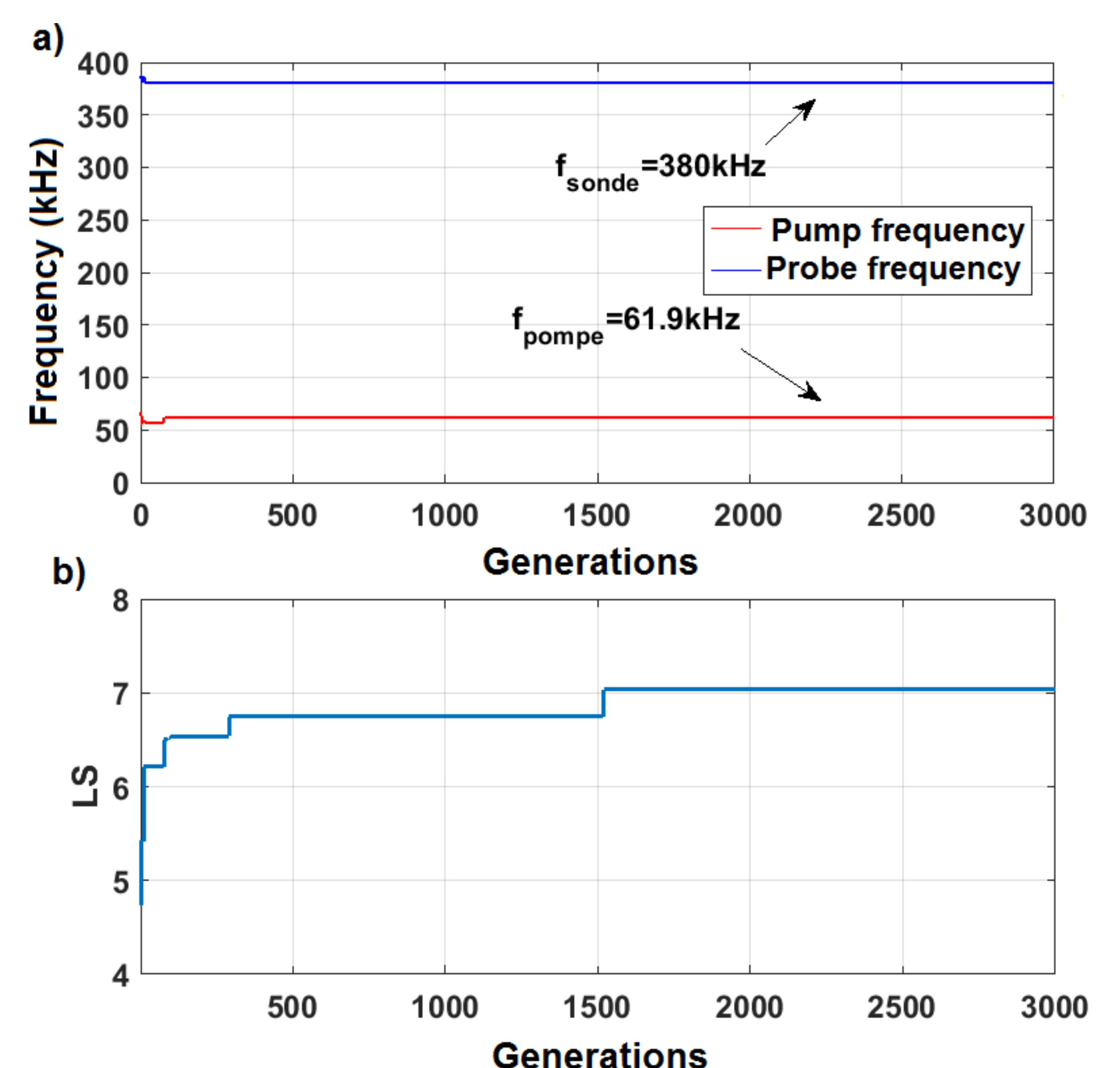


Figure 4: Results of the genetic algorithm (GA) optimization: (a) Pump and probe frequencies vs generations. The GA converges to  $f_{p,opt} = 62$  kHz and  $f_{s,opt} = 380$  kHz. (b) The corresponding cost function LS vs generations.

## Conclusions & Forthcoming Research

- The cost function  $R_{NL/L}$  quantifies the **nonlinear modulation effects** to help crack detection;
- Optimal settings are **automatic** thanks a genetic algorithm;
- **Only some iterations** of genetic algorithm is required to find the region of the maximum global;
- Experimental validation.