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# Optimal Command of the Nonlinear Elastic Wave Spectroscopy Method (NWMS)

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**Abstract**—In the present study, the Nonlinear Elastic Wave Modulation Spectroscopy (NWMS) technique is combined to the optimal command in order to enhance the nonlinear effects due to the presence of micro damages in materials such as cracks. This method consists in simultaneously applying two continuous waves with different frequencies; the high probe and the lower pump frequency noted respectively  $f_s$  and  $f_p$ . When the material is damaged, the frequency spectrum exhibits harmonics and sidebands. An open loop NWMS system is modified to a closed loop system by adding a feedback. A simulation study makes possible to find simultaneously the pump and probe frequencies that optimize the nonlinear modulation effects. The considered cost function noted LS (left sidenbad) quantifies the sideband amplitude. For a comparison purpose, an empirical optimisation is achieved by computing a cartography of LS as a function of  $f_s$  and  $f_p$ . Then a genetic algorithm is used to find the optimal pump and probe frequencies.

**Index Terms**—Nonlinear Wave Modulation Spectroscopy, damage detection, optimization.

## I. INTRODUCTION

The Nonlinear Wave Modulation Spectroscopy (NWMS) is a non-destructive control method based on probing the medium with a low amplitude ultrasonic wave of frequency  $f_2$  (probe wave) and exciting the medium with a large amplitude wave with lower frequency  $f_1$  (the pump wave). The presence of any source of nonlinearity in the medium such as a defect will lead to the modulation of the probe wave by the pump wave. This corresponds to the apparition of new frequency components at the so called sidebands, which correspond to the sum  $f_+ = f_2 + f_1$  and the difference  $f_- = f_2 - f_1$  of the pump and the probe frequencies.

The NWMS has been applied by Van den Abeele *et al.* on intact and damaged Plexiglas and sandstone samples to highlight the presence of the frequency components  $f_+$  and  $f_-$  in cracked samples [1]. They have shown that the sidebands amplitude increases linearly with the amplitude of the pump wave  $f_2$  in damaged samples. This method was used for the characterization of highly nonlinear materials like

cracked concrete [2]. It has been associated with time reversal techniques for imaging damages in materials [3]. NWMS was combined to coda waves interferometry method for detecting damages in multiple scattering media [4]. Recently, nonlinear photo-acoustic techniques based on the use of the nonlinear modulation method which allow locally inspection surface cracks without contact have been reported [5]. Pieczonka *et al.* have developed a defect imaging procedure based on nonlinear intermodulation lobes. This allows the localization and characterization of nonlinear defects [6].

The search for the optimal excitation of acoustic systems is a relatively new field in acoustics since this quest began with the work of Mathias Fink on time reversal in the early 1990's [7] for linear systems and the work of Vincent Gibiat on topological energy in the mid-2000s [8]. The work of J.M. Girault and S. Ménigot [9] on optimal command in medical ultrasound imaging gave new impulse to this theme, by showing that the emission of "Smart" acoustic waves could bring much to the analysis and understanding of linear dynamic and nonlinear systems.

The optimal command of acoustic was associated experimentally to the nonlinear Vibro Acoustic wave Modulation method [10], [11]. It was also used experimentally to enhance the nonlinear signature of cracks [12]. In order to better understand and identify the parameters that influence the detection of nonlinearity in NWMS method, a parametric study was presented in a previous work [13]. It was shown that the modulation sidebands amplitude is a good indicator of the presence and the increase of the material damage. This result is used in the present work. In fact, the left sideband amplitude is considered as our cost function to optimize. In a first time, the cost function is optimized as a function of the pumping frequency, then, two parameters were considered simultaneously; the pump and the probe frequencies. The optimization results coincide with those obtained by the empirical optimization.

## II. METHOD AND ALGORITHM

In this section, the simulation method of the nonlinear elastic wave propagation and the proposed method will be described.

### A. Simulation

Nonlinear propagation of elastic waves in solid media is simulated by using a one-dimensional mass-spring system [14]. Let us consider a one dimensional chain of  $n_s$  masses  $m_i$  ( $i = 1$  to  $n_s$ ) coupled with springs of rigidity constant  $k_i$ . Masse displacements are noted  $u_i$  (Fig.1). For a homogeneous material, the masses  $m_i$  and the rigidity constants  $k_i$  are supposed to be identical

$$m_i \ddot{u}_i = k_i(u_{i-1} - u_i) - k_{i+1}(u_i - u_{i+1}). \quad (1)$$

By adding a dissipative viscous force (of viscosity coefficient  $\beta$ ) which is supposed to be identical for all masses and proportional to the instantaneous velocity  $\dot{u}_i$  and by introducing a quadratic nonlinearity  $A$  in the chain, equation 1 becomes:

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

with the following boundary condition:  $u_0 = 0, u_{n_s+1} = 0$ , which means that there are no displacements at the edges of the system. A micro crack and a delamination can be considered

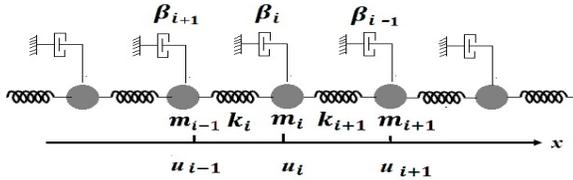


Fig. 1. One dimensional mass spring system

as a softer spring in the chain which means a more important local deformation. We can, also, introduce an inclusion or an inhomogeneity in the material by changing a mass value in the chain. The first mass of the chain, located at  $x_1$ , is excited simultaneously with two sinusoidal pump and probe displacement waves:

$$u_1 = A_1 \sin(2\pi f_1 t) + A_2 \sin(2\pi f_2 t) \quad (3)$$

where  $A_1$  and  $A_2$  are respectively the probe and pump wave amplitudes. Equation 2 is resolved by using an iterative Runge- Kutta fourth order method. The simulation parameters have been deduced from the characteristic constants of the aluminium material according to Table 1.

TABLE I  
SIMULATION PARAMETERS

Name	Expression	Value
Linear density	$\mu$ (kg/m)	2700
Elastic Modulus	$E$ (GPa)	69
Masses Number	$n_s$	40
Chain length	$L$ (m)	0.15
Distance between two masses at equilibrium	$D = L/n_s$	0.00375
Mass	$m = \mu \times D$ (kg)	10.125
Stiffness constant	$k = E/D$ (N/m)	$1.84 \times 10^{13}$
Probe frequency	$f_2$ (kHz)	300

### B. Cost function

The proposed method is an optimal command method using a closed loop, in order to optimize a cost function which is the nonlinear- linear ratio  $R_{NL/L}$ . It is 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:

$$R_{NL/L} = \log(A_{f_{-NL}}/A_{f_{-Lin}}) \quad (4)$$

Indeed, it makes it possible to find the pump and probe frequencies which optimizes the nonlinear modulation effects thanks to

$$[f_p^*, f_s^*] = \arg \min_{f_p, f_s} (R_{NL/L}(f_p, f_s)). \quad (5)$$

The conventional opened loop system is replaced by a closed loop system in which the transmitted pump and probe frequencies are modified by adding a feedback, ensuring the optimization of the cost function. The closed loop system of the NWMS optimization is described in Fig. 2.

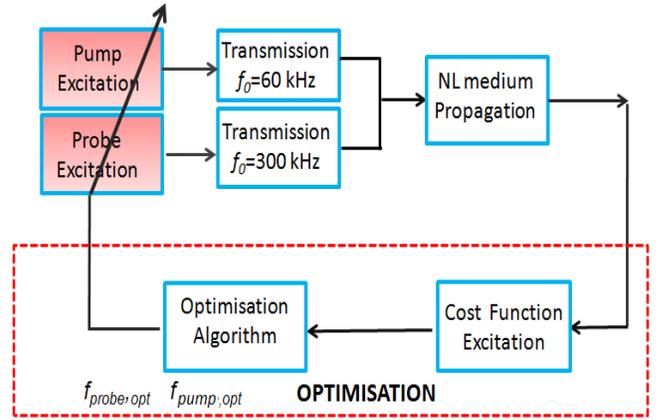


Fig. 2. Bloc diagram of the closed loop optimization system.

### C. Genetic Algorithm

The genetic algorithm [15] is used here to find simultaneously the optimal probe and pump frequencies. The first step consists of choosing randomly  $N$  pumping and probing frequencies from a uniform distribution on a given frequencies

interval. The cost function is evaluated for each pumping and probing frequencies couple and sorted in descending order. To prepare the next step, the  $N/2$  best pumping and probing frequencies that maximize the cost function are kept for the next generation  $k + 1$  and become parents.  $N/2$  new pumping and probing frequencies named offspring are generated. A percentage of the samples is mutated with amutation rate = 40% to obtain a robust optimization.

### III. OPTIMAL COMMAND OF THE NWMS METHOD

We propose, in this part, to apply the optimal command in the case of the NWMS method.

#### A. Empirical optimization

We propose, in a first time to find simultaneously the optimal pump and probe frequencies which maximizes the cost function  $R_{NL/L}$ . For this purpose, an empirical search for cost function as a function of these two parameters is necessary. We have, therefore, compute a 2D cartography of  $R_{NL/L}$  as a function of the pump and probe frequencies in the figure 3. The pump frequency values vary in a frequency range from 1 kHz to 90 kHz and those of the probe frequency from 1 kHz to 400 kHz. The pump and probe signals are filtered by transducers with central frequencies equal to 60 kHz and 300 kHz respectively. We can note the presence of periodic peaks in the  $R_{NL/L}$  values corresponding to the values of the resonant frequencies of the medium. The values of the pump and probe frequencies which optimize the  $R_{NL/L}$  have been identified as  $f_p = 64.5$  kHz and  $f_s = 371$  kHz for  $R_{NL/L} = 6.98$ . However, they are not equal to the central frequencies of the used transducers.

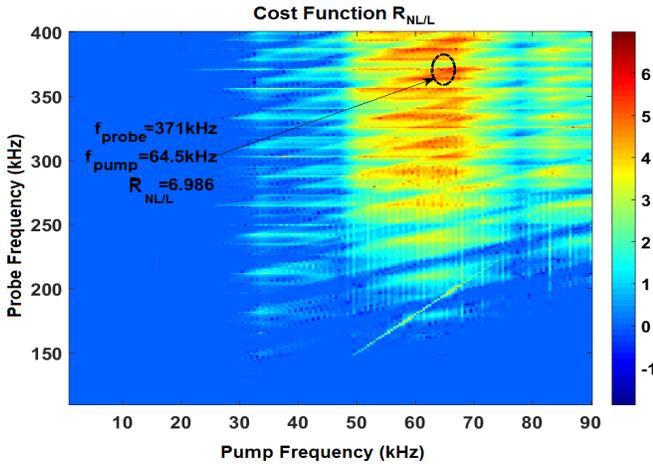


Fig. 3. Cost function  $R_{NL/L}$  cartography as a function of the pump and the probe frequencies.

#### B. Optimal Command of the probe and pump frequencies

Figure 4 shows the results of the genetic algorithm optimization of the pump and probe frequencies simultaneously. For more clarity, the result of the empirical optimization is shown in Figure 4c. The values of the pump and probe frequencies

across the generations are represented in figure 4a and those of the cost function  $R_{NL/L}$  in figure 4b. The initial population of the genetic algorithm is included in a frequency range between 30 kHz and 90 kHz for the pump frequency, and between 250 kHz and 450 kHz for the probe frequency with a population size of 12.

The optimal pump and probe frequencies are reached by the genetic algorithm after a few iterations (100) with values equal to  $f_{p,opt} \simeq 62$  kHz and  $f_{s,opt} \simeq 380$  kHz, and a value of the cost function  $R_{NL/L} = 7$  (figure 4b) after the 1500<sup>th</sup> generation. The results obtained are quite similar to those obtained by empirical optimization. Indeed, the genetic algorithm is able to reach the global maximum area. A better accuracy could be obtained by a hybridation with more accurate optimization algorithm like a gradient descent or a simplex algorithm [12]. We can also note, that from 100<sup>th</sup> iteration, the values of the cost function  $R_{NL/L}$  vary slightly while the values of the pump and probe frequencies no longer vary. The main advantage of the automatic optimization, in this case, is the time saving. In fact, the empirical study takes a lot of time to compute a cartography of  $179 \times 291$  points.

### IV. CONCLUSION

In this paper, a numerical study of the NWMS method is presented. A closed loop NWMS system makes possible to find simultaneously the pump and probe frequencies which optimize the nonlinear modulation effects thanks to a genetic algorithm. Only some iterations of genetic algorithms is required to find the region of the global maximum. As a perspective, an experimental validation oh the present simulation could be considered.

### V. ACKNOWLEDGEMENT

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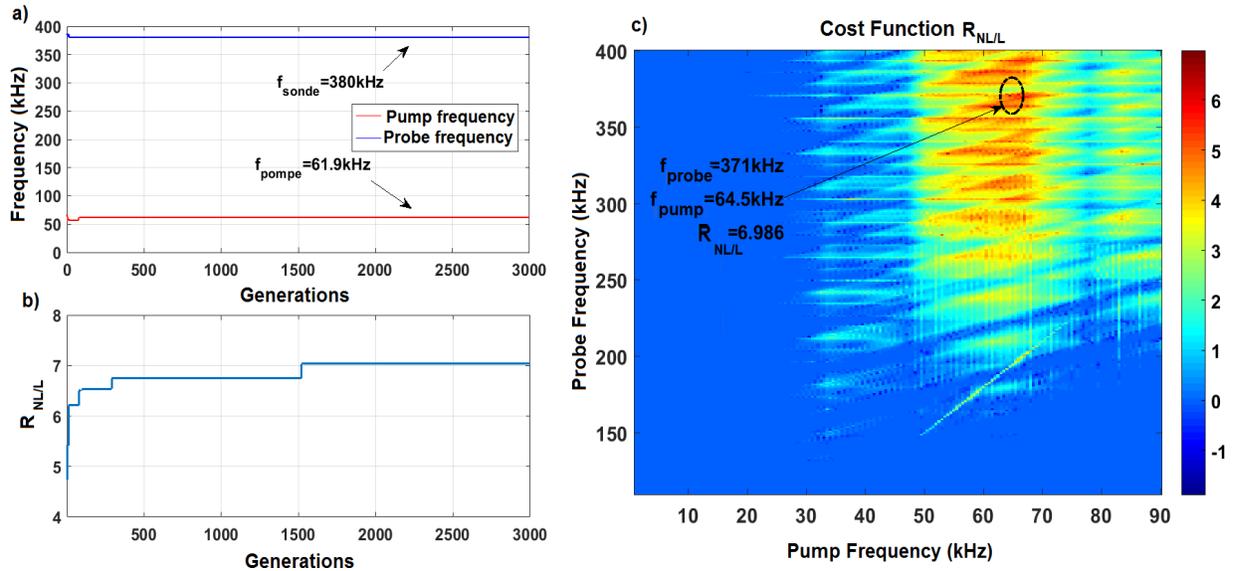


Fig. 4. Results of the genetic algorithm (GA) optimization: (a) Pump and probe frequencies vs. generations. The GA converges to  $f_{p,opt} = 62$  kHz and  $f_{s,opt} = 380$  kHz. (b) The corresponding cost function  $R_{NL/L}$  vs. generations. (c) Empirical cartography of  $R_{NL/L}$  vs.  $f_p$  and  $f_s$ .

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