Excitation frequency optimisation to enhance harmonics backscattered by a nonlinear medium

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Volodymyr Gatsa[1,2], Sébastien Ménigot[1,2] & Vincent Tournat[2]

[1] ESEO Group, Angers, France

[2] LAUM, UMR-CNRS 6613, Le Mans Université, Le Mans, France

volodymyr.gatsa@eseo.fr, sebastien.menigot@eseo.fr, vincent.tournat@univ-lemans.fr

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Abstract

In non-destructive evaluation (NDE), ultrasound plays an important role in physical structure characterization. However, by application of such methods, a little crack cannot be easily detected due to sub-band noises or attenuation in the material. By using of high excitation power source, cracks in the material resonate and generate nonlinear effects on the propagation of the acoustic waves. This feature of the crack response is used for its study by nonlinear NDE methods. The proposed application is the optimization of the excitation parameter using the feedback of the measured system. Energies of harmonic components of the received signal were taken as cost functions. The derivative-free algorithm was applied to find the optimal excitation parameter which gives the maximum of a cost function. The optimization has been done for the 2D sample of the duralumin plate simulated by a pseudo-spectral wave solver. The optimal values of excitation frequencies for different reference stresses have been found. For reference stress of 800 kPa, a gain of 5 dB can be reached in comparison with excitation at the central frequency of the transducer. The importance of an automatic frequency finding was considered to be more privileged compared to the empirical frequency scanning.

1 Introduction

Over the years the traditional nondestructive evaluation (NDE) techniques have been constantly used in mechanical structures characterization (high-quality linear acoustics, electromagnetic, radiologic, visual inspective methods). However, these techniques are not sufficiently sensitive to the presence of progressive damages at the early stages. Thereby, due to the feature of the defect reaction in a nonlinear manner under specific conditions (*e.g.* amplitude of the wave) the nonlinear parameter calculated from the received information gives possible malfunction finding.

The techniques that allow to explicitly interrogate the material mechanical behavior and its effect on wave propagation by investigation the amplitude dependence of certain macroscopically observable properties are termed Nonlinear Elastic Wave Spectroscopy (NEWS) techniques [17] as nonlinear wave modulation spectroscopy [1, 16, 19], nonlinear reverberation analysis [15, 18] and nonlinear wave propagation spectroscopy [11, 7]. The sensitivity of these previous nonlinear methods to the detection of microscale defects was found to be far greater than that obtained with linear acoustic methods [12].

High stress influences the stress-strain relation at the microscale. Thus, the nonlinear response can come out from the microstructure material features or be produced by the damage (crack). In the case of the microdamage, it appears earlier at smaller amplitudes than traditional material nonlinearity, with the generation of odd harmonics, with hysteresis effect [6]. In this case, a small cracked defect (transparent in a linear ultrasonic NDE) behaves as an active radiation source of new frequency components rather than a passive scattered in conventional ultrasonic testing [14].

Defect detection by the nonlinear energy emanating from the medium depends on the frequency changes of an input signal. Thus, it is possible to optimize the excitation frequency to get a better nonlinear effect. In biomedical imaging, Ménigot *et al.* have proposed the solutions for finding of optimal excitation frequency [10, 8], as well as the form of excitation signal [9]. Houhat *et al.* has adjusted the method for the Vibro-acoustic modulation (VAM) technique for CODA wave interferometry and optimized pump frequency [4].

However, there are no automatic methods used to optimize the parameters of excitations dedicated to the non-destructive evaluation of solids. The goal of this paper is to show its efficiency in maximization of the nonlinear answer of the system, thus microdamage detection. We will simplify the complicity of the problem by reducing the number of parameters in the optimization. The simplest parameter is the transmit frequency. For this, we will adapt the previous techniques of optimal command for the study of solids.

2 Closed Loop Optimisation

The method involves measuring a cost function in an NDE closed loop system. The algorithm is implemented to find the optimal value of a cost function at each iteration. The solution of a waveform parameter then optimized. The closed loop system is presented in Fig. 1.

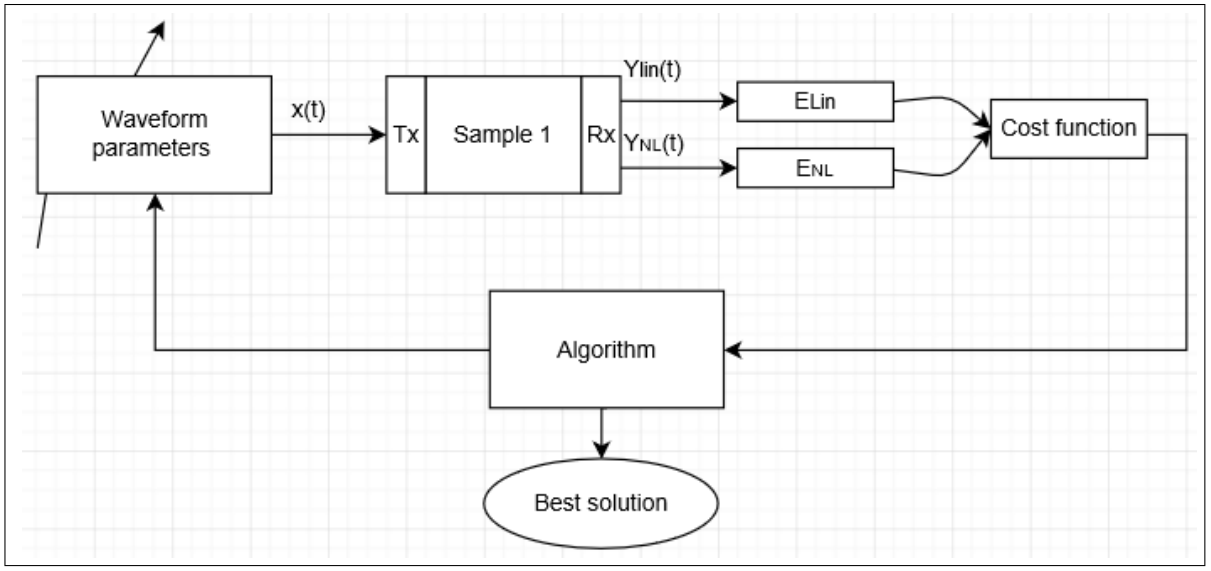

Figure 1: **Block diagram of the NDE system.** A waveform parameter of $x(t)$ is optimized through closed system. In order to find an optimal value of a cost function, the waveform parameter of $x(t)$ is optimized for each measurement.

2.1 Cost function

As previously explained in the introduction, the quantity of transmitting energy into the sample converts to different harmonic components due to nonlinear effects.

In the received signal, we get the part that contains a linear harmonic component and the part that contains a nonlinear harmonic component. The nonlinear harmonic component is the crack response on the stress-strain violation by the wave transmitted in the sample [13]. This nonlinear harmonic component we want to maximize and at the same time reduce fundamental harmonic component.

The nonlinear effects can be appraised with cost function implementation [3]. In our case, the energy of harmonics is a parameter to estimate the nonlinear answer of the system.

If we put the energy of the linear component as the linear cost function E_{Lin} and the nonlinear component as the nonlinear cost function E_{NL}, which are both the energies calculated in a time domain as follow:

$$E = \frac{\sum_{t=0}^{T-1}(Y(t))^2}{T}, \tag{1}$$

where Y is the received signal; T is the number of received samples; t discrete time.

The final cost function FC is the nonlinear linear energies ratio, which is the normalized coefficient between nonlinear and linear responses of the system

$$FC = \frac{E_{NL}}{E_{Lin}}. \tag{2}$$

In particular, the nonlinearity of the crack generates odd harmonics. Consequently, the cost function takes the form of the ratio of the odd harmonic to the fundamental harmonic energies.

If Y is filtered by adjusted digital Butterworth band-pass filter to the initial incident frequency f_0 the fundamental harmonic component Y_{Lin} will be extracted. Similarly, the 3rd harmonic component Y_{NL} can be extracted by the adjusted Butterworth band-pass filter to the frequency of $3f_0$. The orders of the filters have their lowest values with a passband ripple of no more than $Rp = 3$ dB and a stopband attenuation of at least $Rs = 10$ dB.

2.2 Algorithm

A Nelder-Mead Simplex Method algorithm has put into use for the cost function exploration.

It is widely used method for nonlinear unconstrained optimization.The Nelder–Mead method attempts to minimize a scalar-valued nonlinear function of n real variables using only function values, without any derivative information (explicit or implicit). The Nelder–Mead method thus falls in the general class of direct search methods [5].

In current research, we are looking to find an optimized parameter of the initial excitation frequency f. Successively after k iterations the algorithm gives the maximum value of the nonlinear response of the system following :

$$f_{opt} = \arg\max_{f_k}(FC). \tag{3}$$

2.3 Waveform

At the iteration k, the excitation waveform x_k of a Gaussian-modulated sinusoidal pulse with the relative fractional bandwidth of 40% is generated by the transducer at frequency f_k.

$$x_k = A \cdot \exp\left(-\frac{\left(\frac{n}{F_s} - \frac{L}{2 \cdot F_s}\right)^2}{(\frac{L}{2 \cdot F_s})^2} \right) \cdot \sin\left(\frac{n}{F_s} \cdot 2\pi \cdot f_k\right) \tag{4}$$

where F_s is sampling frequency; n - vector of points; A - amplitude; f_k -excitation frequency; L - duration of total excitation; $\frac{n}{F_s}$ - discretized time; $\frac{L}{2 \cdot F_s}$ - initial point of Gaussian pulse.

The amplitude of the applying stress is adjusted at each excitation frequency, thus the excitation power stays constant.

$$A = A_{ref} \cdot \frac{P_{ref}}{P_{f_k}}. \tag{5}$$

3 Simulation

The solver calculates the wave propagation in stress-strain states. The simulator applies nonlinear wave equation by a pseudospectral / staggered A-B method, including attenuation model with two relaxation mechanisms of hysteretic behaviour. This behavior, described by the “PM space” representation, characterized by the density distribution, leads to generation of odd harmonics of the initial frequency. The solver has been developed based of the work of O. Bou Matar et al. [2]. The classical non-linearity of elastic propagation of 2nd and 3rd order has been added to the program.

To limit the computation time, the size of the sample is 128 by 64 points, which physically represents 100 mm by 50 mm. The crack was located in the middle of the sample with a size of 8 by 8 mm. The piezoelectric transducers were placed one in front of the other in the middle of the lateral axis, one at the top and the other at the bottom of the sample.

The initial wave excitation signal at the k-iteration x_k propagates through the sample with a crack inside. The crack creates the third harmonic components. The two transducers, Tx on the transmission at 1 MHz and Rx on the reception at 3 MHz filter the signal by their transfer functions.

The parameters of 2D sample correspond to the duralumin material properties presented in Table 1:

where P-wave is the speed of sound of the pressure wave and S-wave is the speed of sound of the shear wave.

In the middle of the sample, crack is presented as the points of the elementary hysteretic units, which generate odd harmonics. The crack properties are in Table 2:

P-wave speed [m/s]	6398
S-wave speed [m/s]	3030
Density [kg/m^3]	3122

Table 1: Material physical properties

Young modulus [Pa/m^2]	70·10^9
Poisson ratio	0.33
Density [kg/m^3]	2966

Table 2: Crack physical properties

4 Results

The optimisation process was done for different reference stresses A at the step of 100 kPa. Results are presented in Figure 2.

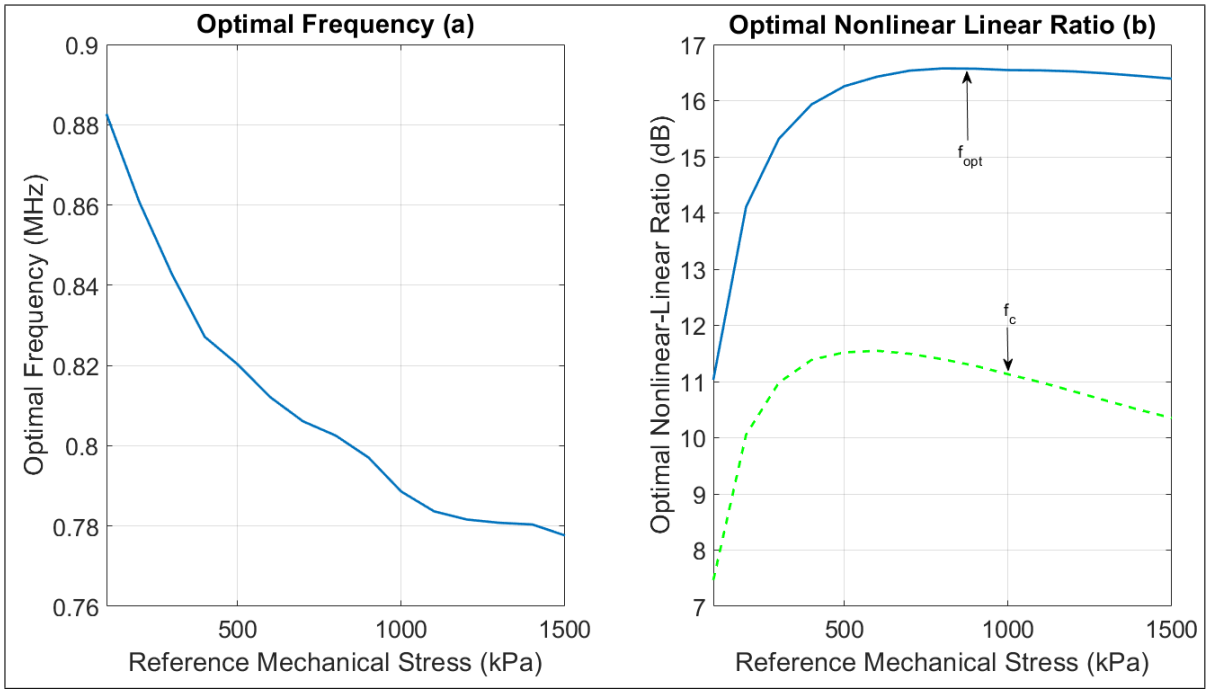

Figure 2: The optimal nonlinear ratio and optimal frequency for different stresses A.

Figure 2(a) represents the optimized frequency (f_{opt}) values for the excitation signal for reference stresses A. It can be seen that the decrease in the varied optimal frequency are not linear after the amplitude of the emission stress exceeds 400 kPa.

Figure 2(b) represents the optimal values of the cost function to reference stresses A (blue line). The optimal values of the cost function are compared with the cost function values on the central frequency (f_c) of the transducer that is equal to 1 MHz (green dashed line). As we can see in the Figure 3 the gain of the cost function between the excitation on the optimal frequency and the excitation on the central transducer frequency can be from 3.5 to 6 dB depending on reference stress.

By way of illustration, the iterative process of excitation frequency optimization is shown for the reference stress of 800 kPa in Figure 4.

The optimal frequency finding is illustrated and compared to the empirical scanning at the 25 kHz step in the Figure 4(a). The algorithm was capable to reach a global maximum of the cost function for 3 iterations at 16.55 dB (Fig.4(c)) near a frequency of 800 kHz (Fig.4(b)).

The gain of nonlinear linear ratio between optimal excitation frequency and the excitation frequency at the central frequency of the transmission transducer Tx is 5.15 dB.

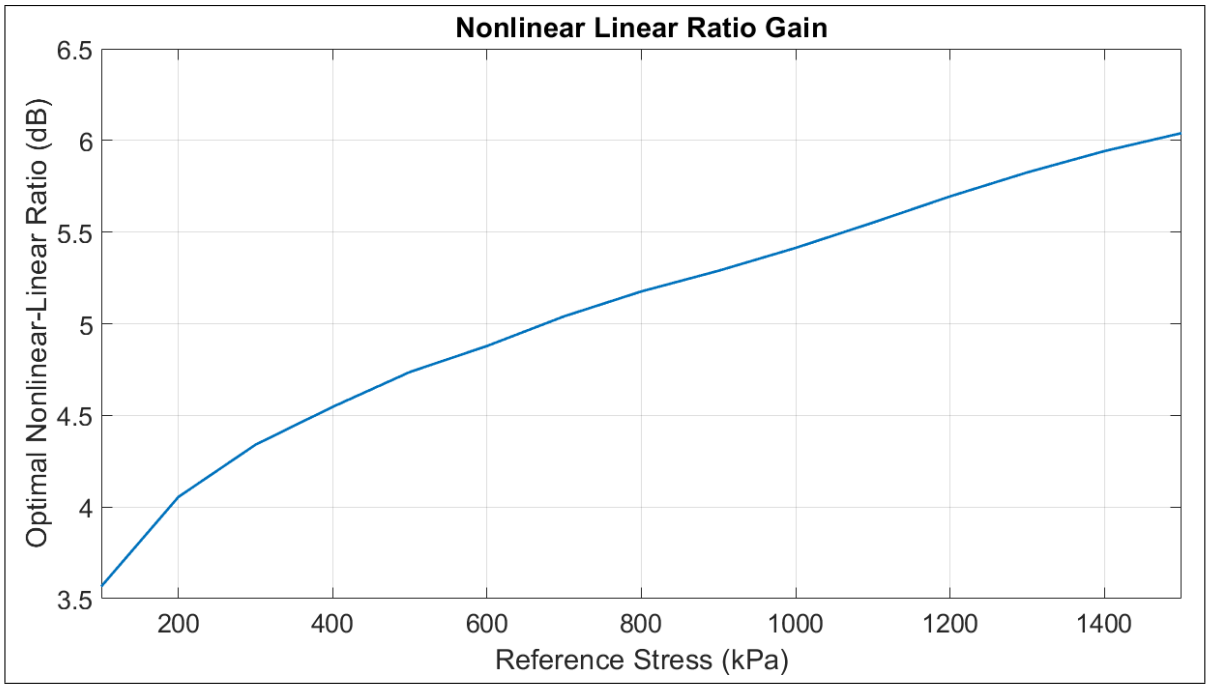

Figure 3: The gain of nonlinear linear ratio between optimal frequencies and central frequency of the transducer.

5 Discussion and Conclusions

Optimisation process was first presented and applied for the propagation ultrasound experiment in solids. The optimal values of the nonlinear linear energy were calculated for different stresses A from 100 kPa to 1.5 MPa. We can notice that the optimization converges to different optimal frequencies depending on the stress levels A, which is not taken into account in the usual selection for an excitation frequency.

From this, it follows that the maximums of the cost function do not derive from the choice of the excitation on the transmission transducer central frequency, e.g. at 800 kPa of reference stress, the gain for optimal excitation frequency to the excitation central frequency of the transducer is at 5.15 dB. At the same example, the algorithm finds the maximum of the cost function for 3 iterations compared to empirical scanning that finds the maximum at 5th iteration.

Another important advantage of using the optimal command for real experiments is that it takes into account the imperfections of the transducer and the properties of the explored medium. Usually, this information is ignored when choosing the setting of the excitation parameter.

The frequency optimization method presented in this paper demonstrates that it is applicable in the case of a homogeneous medium with one crack inside by using system objective features, e.g. nonlinear linear energies ratio. We suppose that the frequency optimization by our method under selecting the appropriate cost function can step over the unknowns from more complex explored mediums.

The application of automatic methods to a nonlinear nondestructive evaluation of solids can increase the response of the defect in the studied sample. Automation algorithm tunes the system response and can be used for more complex mediums in order to reduce the time of inspection as well as to reduce tuning errors.

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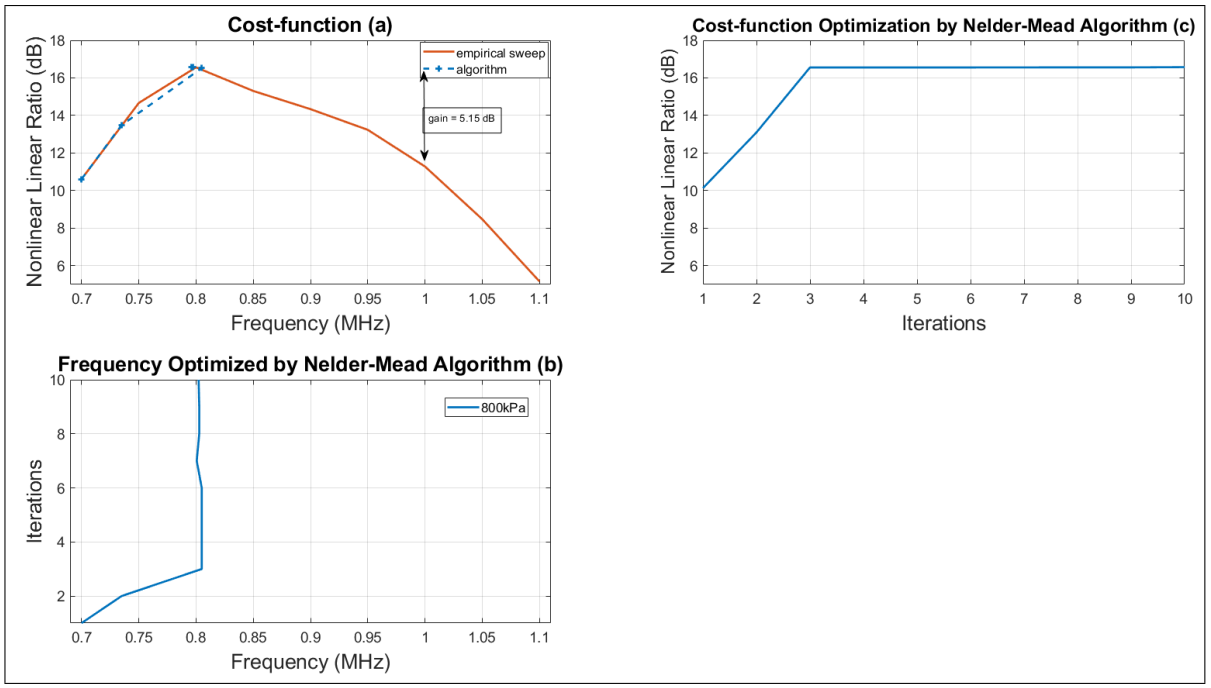

Figure 4: Frequency optimization on a given stress.

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