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Study on the Most Influential Parameters in Low-Power Laser Generated Ultrasound

The current work studies the influence of the most widely used time-domain techniques for signal to noise ratio (SNR) increase for laser-generated ultrasound (US), employing a low power (150 mW) modulable diode: these methods utilize highly random pseudo-noise (PN) sequences which, after the use of the cross-correlation, underline the presence of an ultrasonic output. PN sequences can broaden the signal's band through random lengths of LOW and HIGH levels in laser pulses' duration, scattering the energy on a wide range of frequencies: this might represent a disadvantage in case of controls with narrow-band probe, which are the most used instruments for this kind of applications. From this point of view, creation of specific drive signals allows to improve significantly the control on frequency response. A SNR consistent with the ones achievable through the classically adopted methods is highlighted, but featuring an advantageous concentration in the output frequency band.

Keywords: Laser, low power, ultrasound, cross-correlation, sequences.

1. INTRODUCTION

Ultrasounds (US) in industrial applications are mainly used for two different non-destructive testing (NDT) purposes: the characterization of metallic or non-metallic materials and the damage evaluation of mechanical components [1-6]. In this context, laser-based ultrasound inspection lately drew the researchers' attention. Application of a transient heating creates a sudden expansion and a consecutive contraction in the material, generating longitudinal, shear and surface ultrasounds [3]. The technique's fundamental advantage is the possibility of a non-contact inspection, therefore usable in operation too [7-10]. The thermo-elastic effect is generally obtained through pulsed lasers: a brief and single pulse (in ns) with a power of approximately 1 MW, creates a broad band oscillation with frequencies up to hundreds of MHz. Because of the closeness to the material ablative threshold, the high cost and the impossibility to control the bandwidth with pulsed lasers, recent studies [11-15] made use of low-power laser diodes (less than 1 W), which are extremely low-cost and guarantee a definitely non-destructive testing procedure: this could lead also to a non-contact polymer or composite NDT method development, since ablation temperature is particularly low for these materials. Diode is a laser which works as a continuous wave CW source, so the pulse has to be obtained through external modulation (digital or analogic) and the driver modulation signal can be arranged to obtain different signal frequency bands.

In case where mainly the presence of the ultrasonic

wave peak-to-peak PtP is interesting (as in the pulse-receive crack detection), it is useful to use a high period-narrow band ultrasound to match the receiving probe band. In case of material characterization, where the time of flight ToF has to be computed accurately, it is more useful to use a broadband ultrasound, caracterized by a steep slope in time domain, leading to a more accurate ToF evaluation even when noise affects the signal.

The main problem of low-power laser inspection is the resulting displacement's entity (less than 1 pm [11]), so that the ultrasonic evaluation and signal-to-noise ratio (SNR) optimization are particularly complex and articulate. In this type of problems, two fundamental techniques are in use: the frequency domain control and the time domain control. The first one employs phase-sensitive lock-in amplifiers [12], with very high frequencies and narrow-band; the signal is continuously compared to a sinusoidal reference until amplitude and phase coincide: starting from the spectrum, the hidden ultrasonic signal is rebuilt through particular manipulation of Fourier anti-transform. The time domain technique [13], instead, provides for utilization of precise TTL sequences, or pulse trains, to find the expected ultrasonic output without ambiguity through the use of the cross-correlation: the most used codified sequences are the maximum-length sequence (MLS or M-sequence [13,14]) and the Golay code [11], which belong to the pseudo-noise PN, or pseudo random, codes category, capable of spreading the signal bandwidth [16]. This can have different consequence as a function of the NDT purpose considered: having a broadband ultrasound can be an advantage in case of a ToF estimate problem, but also a disadvantage if a crack has to be detected.

The purpose of the study is to identify the appropriate parameters for the optimization of SNR applicable in a laser ultrasound testing procedure. This

can involve the choice of the pulse train in order to place the ultrasonic output frequency in a particular band of interest if narrow band probes are employed. In this perspective, specific drive signals are generated, able to significantly enhance the control on the output band and, therefore, increase the SNR. Since the generated ultrasound shape is strongly dependent from the thermoelastic response of the material, the most important parameter is not the energy amount, but the time distribution of this energy over the modulation sequence. Thus, several important parameters will be therefore considered in order to optimize the US detection.

2. MATERIAL

The presented work made use of the TOPTICA iBeam Smart 640 S modulable laser diode, with a CW peak power equal to 0,15 W and a 1 mm beam waist. The testing campaign investigates the generation on a 20 mm radius and 5 mm thick steel disk. The wavelength λ of 640 nm allows the specimen to absorb more than 90% of the incident radiation. Since the power density is 5 order of magnitude under the material's ablation threshold (15 W/cm^2) versus 2 W/cm^2 for steel), the laser beam has to be accurately collimated, in this case through a 75 mm focal length spherical lens, leading to a 30 μm spot diameter, measured by means of a CMOS sensor. To obtain this result, the laser is mounted on a slide able to guarantee an accuracy on displacements of one tenth of a mm, figure 1. Thermo-elastic excitation is identified by the Brüel & Kjaer 8312 broadband acoustic probe, from 100 kHz to 1 MHz, capable of collecting a range of oscillation frequencies as wide as possible. The laser beam is centred on the lens's axis and the lens only laid on the slide; the laser, the probe and the specimen are fixed in respect to the slide. In this configuration, moving the slide means a change in the laser-lens and the lens-specimen distances: the latter allows to obtain the desired focusing.

Figure 1. Experimental layout.

3. METHOD

a. Experimental layout

In figure 2, a scheme regarding the instrumentation used in this study is shown. Specific ON and OFF (Boolean data) sequences are generated via LabView software which, once modified in amplitude, are imposed on the arbitrary waveform generator HP 33120A. The signal which feeds the laser acts as a trigger for the oscilloscope (TEKTRONIX MSO 2024B), through which it can be displayed and acquired at a later time by means of the OpenChoice Desktop software. The diode is digitally modulated (up to 250 MHz) through this TTL, turning ON when the voltage exceeds the threshold of 1.3 V: a HIGH value of 2.5 V has been chosen. The probe output is amplified of 60 dB through the conditioning module Brüel-Kjaer 2638.
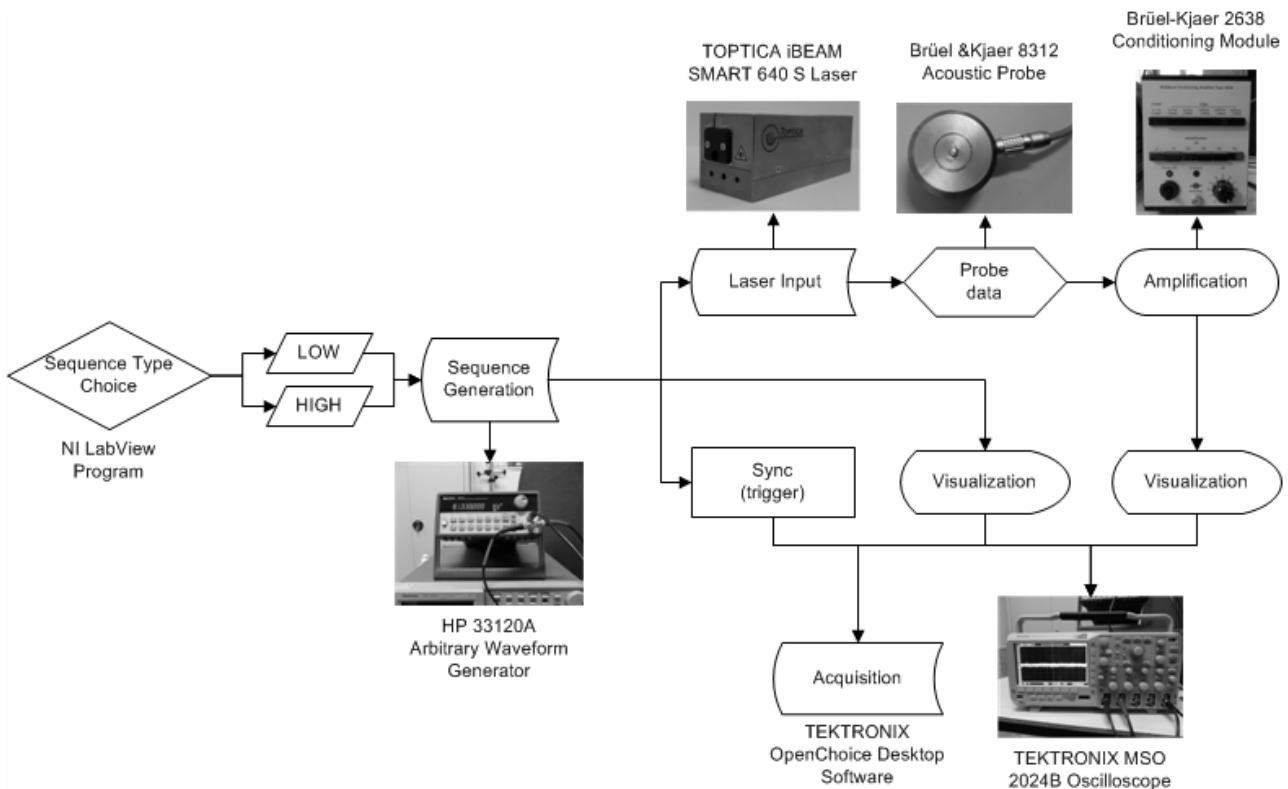

Figure 2. Flow chart regarding the instrumentation.

The signal corresponding to input and output are then acquired after applying 512 ensemble averages. At a later time, the cross-correlation operation is applied between pulse train (input) and the interesting output signal. The value of τ corresponding to the beginning of the slope which leads to the maximum in the cross-correlation represents the US ToF.

In the cross-correlation operation, it is important to use a trigger signal as random as possible. As can be seen in figure 3, for a random spacing between pulses the resulting ultrasound can be univocally individuated. In the equal spacing case of figure 4, though, an area in which multiple ultrasounds (with same PtP) can be highlighted, making it difficult to determine the ToF. This does not represent an issue when the ToF is known a priori as for materials' characterization, while it is important when the geometrical features of the tested component are not defined, e.g. in thickness measurements or cracks location in pulse-echo inspection.
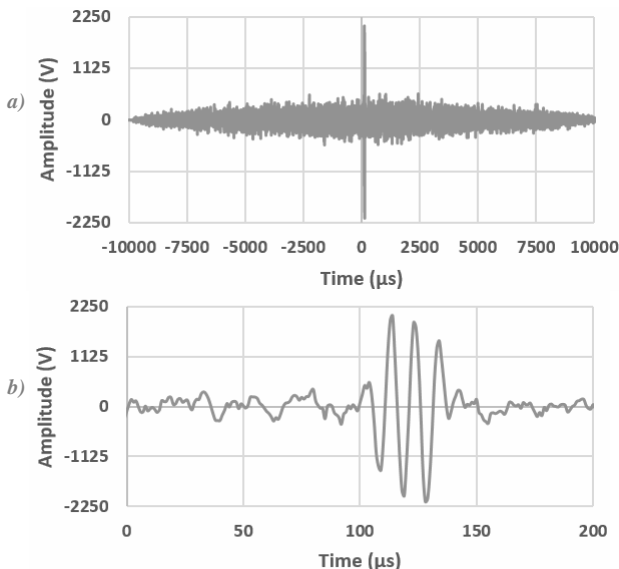
Figure 3. Cross-correlation (a) and relative zoom (b) where the input is a trigger signal with random spacing between pulses.
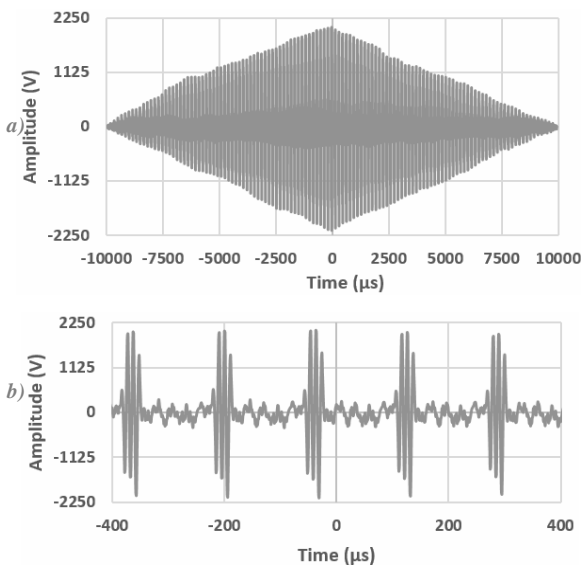
Figure 4. Cross-correlation (a) and relative zoom (b) where the input is a trigger signal with equal spacing between pulses.

SNR of an acquired output signal can be evaluated by means of various techniques [4,5,9], but always through a generic quantity Y:

$$SNR = \frac{Y_{signal}}{Y_{noise}}$$

with subscripts indicating the portion interested only by the ultrasound and uniquely by white noise; in particular, in this work:

$$Y_{signal} = \max(signal) - \min(signal)$$
$$Y_{noise} = \max(noise) - \min(noise)$$

The ultrasound covers a limited window (see figure 3b), while the attention must be focused on the first part of cross-correlation while calculating the noise influence.

b. Driver signals for laser modulation

Pulse trains commonly used are pseudo-random sequences, as MLS and the Golay one. They are generated with the intent of creating perfectly random codes with auto-correlation's maximum at a null shift τ and 0 elsewhere (centred auto-correlation). This also means that the maximum power of the laser driver signal is obtained. This result is not really reached in practice, because of little oscillations for a non-zero τ.

MLS [16] is built from polynomial primitive functions of order f, not divisible in respect to $X^F - 1$ in modulo-2 arithmetic, with $L = F = 2^f - 1$ length and period of the sequence: through various iterations, the elements' position of an input sequence is determined (commonly a set of $2^{f-1} - 1$ values equal to 0 and 2^{f-1} to 1).

The Golay train [11] uses some properties of convolution and Fourier transform/anti-transform to modify the base signal: its origin is therefore very different from the MLS's one (primitive polynomials). It is built through another recursive algorithm, which refers to two complementary sequences $a(i)$ and $b(i)$ made up of '-1' and '1' elements and 2^{n-1} long (with $i = 1,2, ..., n$) and whose sum has an auto-correlation equal to $2n$ if $i = 0$ and 0 if $i \neq 0$. This maximum value is four times the MLS's one of same length.

Randomness in pseudo-random sequences is obtained through a precise order of the TTL's HIGH and LOW values and this can also mean pulses with different lengths.

Figure 5a shows the cross-correlation between a specific TTL and the filtered output signal from the probe. Since the interesting window is 8 ms long, the cross-correlation has double length: the signal is in advance of the laser's activation for times starting from 0 to 8 ms; after the peak value, an exponential decay due to various ultrasonic reflections and mode changes is evident. After 1 ms, the signal is represented only by the noise contribution; figure 5b shows the zoom of 10 μs around the peak.

These drive signals are made of HIGH and LOW levels of different lengths, as generated by the Golay code (figure 6a). Even with a perfect TTL's

randomness represented by the centred auto-correlation, different heating durations of each pulse can lead to an approximately steady thermal state (no ultrasound is generated) and spread the frequency content in the output: in SNR terms, a narrow band probe could not receive a sufficient quantitative of energy in its response band to detect an effective output. In other words, an optimized laser driver PN signal (perfectly random with centred auto-correlation) does not guarantee to obtain an optimal US, since the thermoelastic response of the material has to be considered. For this purpose, in the present study, alternatives to Golay code and MLS were considered. Specific pulse trains were then created: the randomness is only obtained through LOW levels, maintaining an identical activation time for all pulses. The first generated code, which is visible in figure 6b, was named "T" (train) sequence.
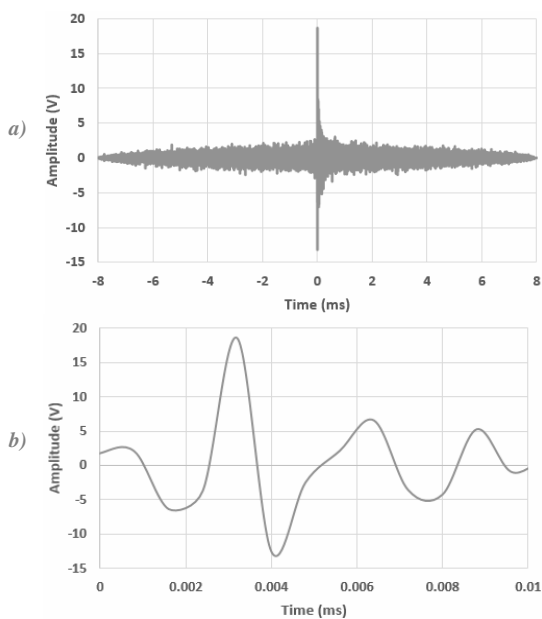

Figure 5. Cross-correlation between output signal and a pulse train (a) with related zoom (b).
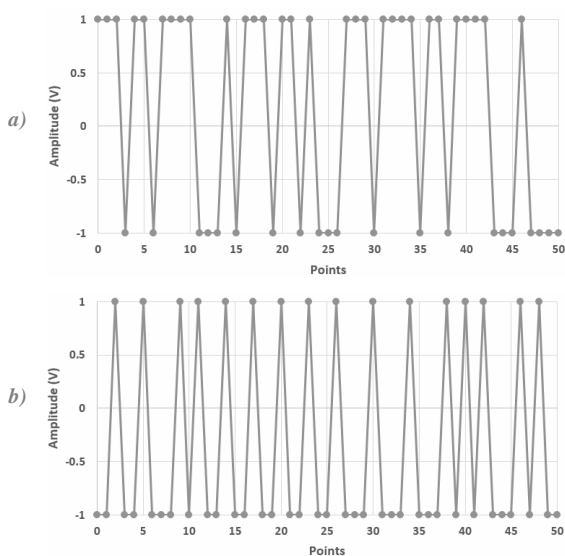

Figure 6. Portion of Golay code (a) and T sequence (b).

While the Golay code's associated auto-correlation is perfectly centred with a maximum equal to $L = 2048$

(figure 7a), the T sequence has a higher maximum value but it is not perfectly cenetered (figure 7b).
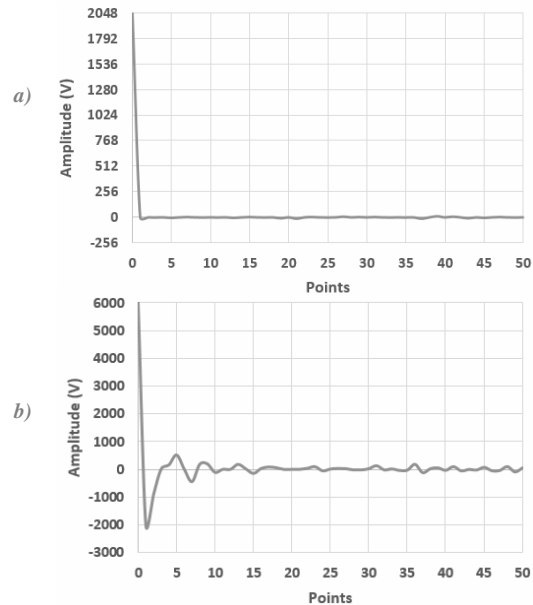

Figure 7. Auto-correlation for (a) Golay code and (b) for T sequence.

In order to unite the PNs' and T sequence's advantages, two more hybrid sequences were created which are named "L" (low) and "HL" (high-low) sequences. The first substitutes methodically the LOW level lengths with the Golay ones; the second uses both the HIGH and LOW levels' durations; in figure 8 the earliest points of the related auto-correlations can be seen. The auto-correlation does not reach the values of the T-sequence, even if higher than in the Golay case; the oscillations around 0 are greater than in the other instances too, so an inferior randomness can be assessed (even before any signal manipulation) despite the intention they were created for.
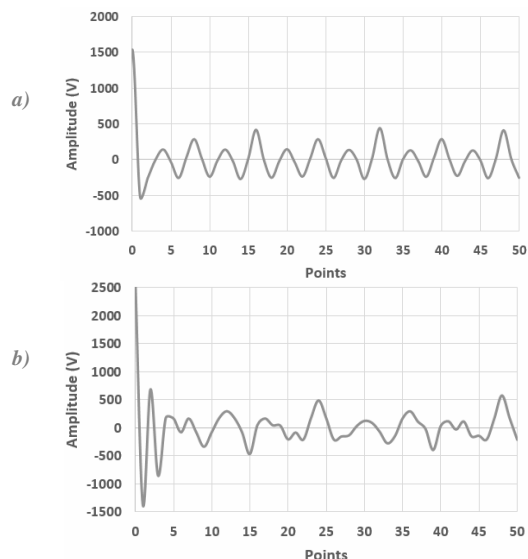

Figure 8. Auto-correlations for the L sequence (a) and for the HL sequence (b).

4. RESULTS

Making use of the procedure cited above [17], the results of the current study are now reported. SNR can

be increased through the use of multiple parameters: between them, the δ variable is yet to be introduced. It is a fundamental parameter, which represents the time length of a single point for the created sequence: in PNs the pulse duration can be longer than δ (multiple of δ, in particular), while for the T, L and HL sequences δ is also the duration of a single pulse (pulses one point long).

Besides the type of studied sequence, four different parameters influence the quality of an acquisition: 1) US frequency band f, 2) point length δ, 3) number of averages $N_{average}$, 4) number of pulses N_{pulses}.

c. US frequency f

Depending on the type of inspection carried on (see paragraph 1), the generated ultrasound frequency can be decisive for an appropriate acquisition. Because of the thermo-elastic effect and property of the heated material, frequency is dependent by the point length δ chosen for a particular sequence (PN or not). Figure 9 shows the Fourier coefficients' values corresponding to frequencies between 0 Hz and 1 MHz as a function of δ, which goes from 266 ns to 2000 ns. In case of MLS and, above all, for Golay code (which are 2048 points long), a very scattered and broad band can be pointed out. For high values of δ, the T sequence shows a narrow band mostly, and a standard deviation not high as in the PNs case, even for low δ values. As can be expected, a higher pulse duration generates a decrease in the main frequency, because of the moving away from the ideal condition of Dirac delta function (perfect pulse). The points in the graph with values above 2 can be approximately compared to a linear trend. For L and HL sequences, the best-fit operation using a straight line can give even better results. Fourier coefficients do not allow to estimate the signal's quality, but only its frequency composition. In these cases, so, it is the SNR which makes the true difference.

d. Point length

In figure 10, the graphs for PNs' SNR as a function of δ are shown: PN codes spread the spectrum [14] distributing energy at all frequencies, so it is not possible to identify a univocal behaviour for SNR. Without considering a scale factor, Golay code and MLS have got the same trend as can be expected for PN codes. An unexpected fact is, though, to find a greater value for the M sequence than for the Golay code (almost for every δ value) [15]. Trying to get below 400 ns in point duration, there is no ultrasonic output.

The T sequence, on the other hand, has a definite behaviour, as can be seen in figure 11: SNR raises while δ increases with approximately a logarithmic trend. Effectively, a greater heating time creates higher displacements' amplitude, but at smaller frequencies. In this case, it is possible to use pulse lengths below 400 ns: this occurrence led to no results for PN sequences; globally, the SNR is a little higher than in the MLS case and the maximum that is obtained through the change in the various influent parameters for this sequence.
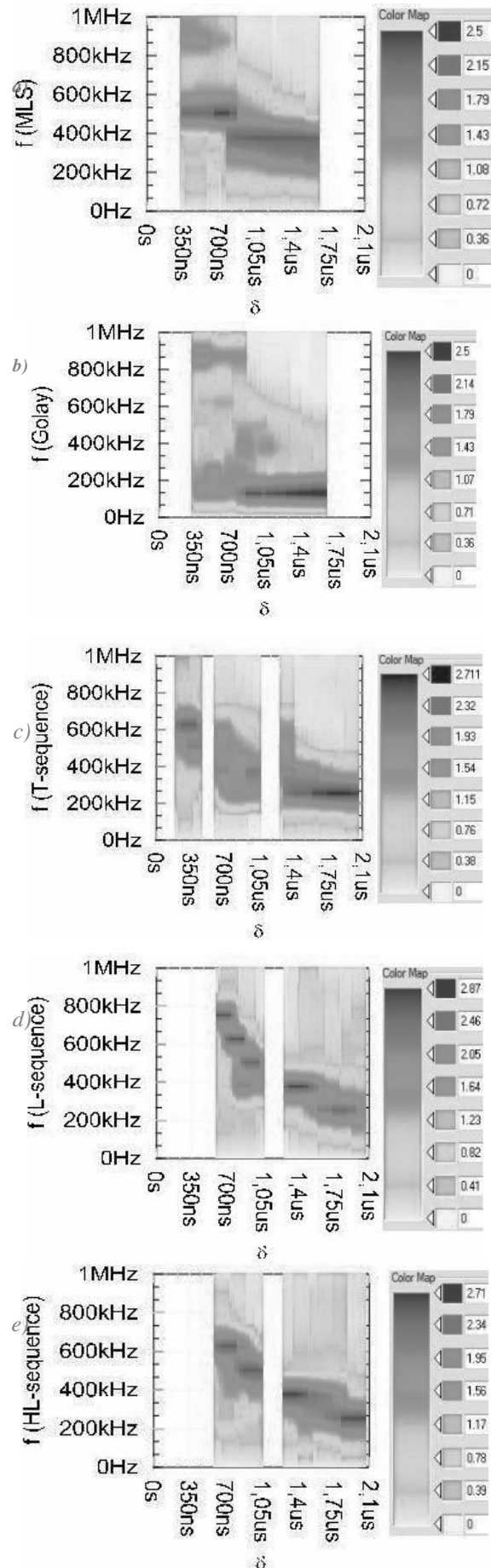

Figure 9. Frequencies and related Fourier coefficients, in a grey scale map, at various values for Golay (a), MLS (b), T (c), L (d) and HL (e) sequences.
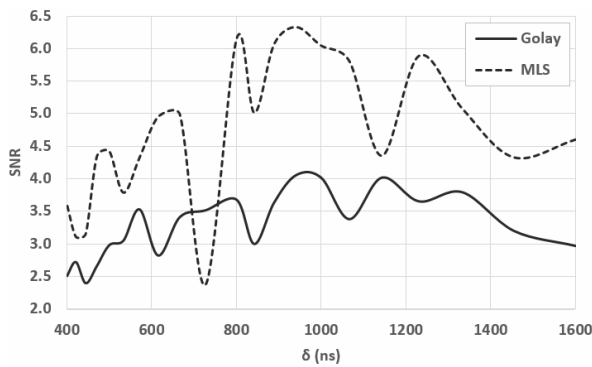
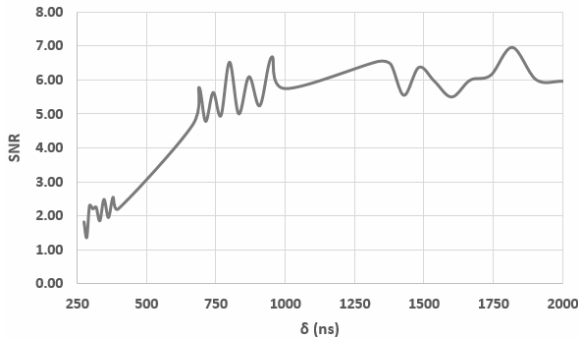**Figure 10. SNR for PN sequences using the point duration as the independent variable.**

Figure 11. SNR for the T sequence as a function of the point duration .

For L and HL sequences, the testing campaign determined that ultrasound waves are not evident for this kind of codes, regardless of the narrow frequency band shown in figure 9d/e. Thus, SNRs are scattered randomly as a function of δ (figure 12), making it unnecessary to further study these sequences since ultrasound cannot be adequately detected.

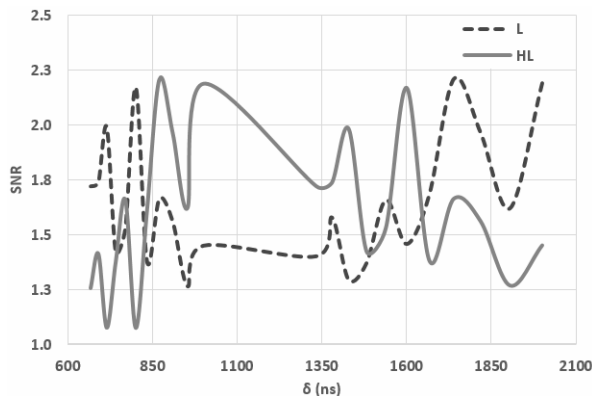**Figure 12. SNR for L and HL sequences as a function of .**

e. Number of ensemble averages $N_{average}$

An ensemble averages number equal to $N_{averages} = 512$ was performed before every signal acquisition, in order to acquire data with a very low noise influence. Since the averaging process does not affect the mechanism of ultrasound generation but only the noise entity, $N_{averages}$ influences the SNR in the same way regardless of the analysed sequence. So, referring to the Golay code as a behaviour indicator and in the special case where $δ = 800$ ns, an asymptotic trend for the SNR while increasing the number of averages can

be seen in figure 13: SNR quickly increases for a low number of averages, the SNR obtained through the application of 512 averages is 5, and 4.5 using $N_{average}$ equal to 128 or 256. On the other hand, the advantage in terms of data collection time is evident, respectively ¼ and ½, while maintaining a high SNR.
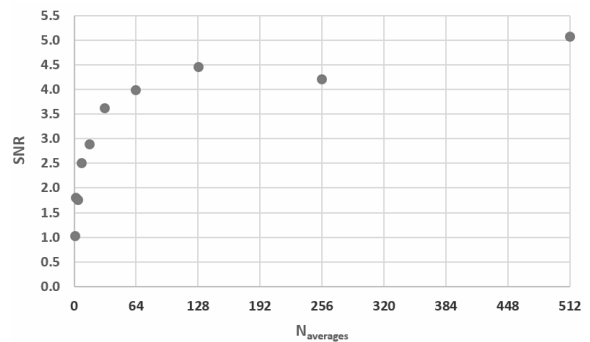

Figure 13. SNR variation as a function of the number of ensemble averages $N_{averages}$ applied before the acquisition.

f. Pulses number N_{pulses}

The influence of the pulses number N_{pulses} on the SNR is presented for Golay (which represents PN codes) and for the T train. A δ value equal to 800 ns has been chosen, with a time window 8 ms long entirely occupied by the pulses. As shown in figure 14, Golay code has a SNR extremely dependent from the number of pulses, with a maximum in SNR which is not in correspondence of the maximum number of pulses used: this can be due to a loss in randomness because of the closeness between generated ultrasounds. On the other hand, the T train application allows to obtain a SNR which tends to increase as the number of pulses raises, even if not as quick as in the Golay case. For Golay code, this parameter is the one which allows to obtain the maximum SNR (6.5).
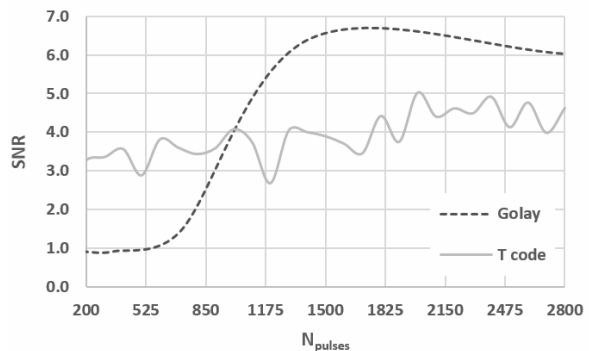

Figure 14. SNR as a function of the number of pulses N_{pulses} inside a time window 8 ms long and equal to 800 ns, for Golay code and T sequence.

5. CONCLUSION

A modulable laser diode was employed in order to analyse the key-characteristics of ultrasound waves generated via low-power pulses in a steel disk. In the first place, the pseudo-random sequences mostly used in this field (Golay and MLS) were studied, highlighting the main features in the examined application: the output can be accurately located

(centred auto-correlation or quasi-perfect randomness) but the response band is extremely wide, because of the ON and OFF durations which are random and can be more than one-point long. Based on the type of NDT carried on (thickness measurements, pulse-receive non destructive inspection, etc.), this might represent an advantage or a disadvantage. In addition to this, since the ultrasound generation mechanism is influenced by many parameters, higher heating times can be considered as a steady heating which does not generate ultrasound. In order to ideally allow an efficient acquisition with narrow band probes (which are the most commonly used in ultrasonic inspections), three different sequences were created:

-the T sequence uses random LOW lengths;

-in the L sequence, the LOW lengths are equal to the Golay ones;

-the HL sequence employs the succession of Golay HIGH and LOW levels as the LOW lengths.

The last two come from the idea of putting together the advantages of the T sequence (band concentration) and of the PNs (high randomness), even if the latter were not achieved effectively.

Some important parameters which can affect the detection of the ultrasonic wave were accurately studied; the results are reported below:

1) f: T, L and HL sequences are characterized by an output frequency which drops linearly with a raising δ, while PN codes generate a very spread spectrum;

2) δ: the δ variable mostly influences the T code SNR, leading to a very high SNR (7), which is the maximum obtainable for this kind of sequence with a change in the other parameters. SNR vary in the same way (but with different coefficients) for Golay code and MLS, while δ does not influences it for L and HL sequences, because of a difficult ultrasound detection. L and HL sequences were, thus, no further considered;

3) $N_{averages}$: the number of averages highly influences the SNR (regardless of the sequence considered). Although all the signals were acquired after the application of 512 temporal averages, the use of a lower value in future studies is desirable in order to drastically reduce inspection time while ensuring a high value in SNR;

4) N_{pulses}: the right number of pulses allow to obtain the maximum SNR for PN codes (almost 7), but a high value of this variable is necessary in order to detect the ultrasound. For the T code, on the other hand, the values in the PN codes case are not reached, but the detection is assured even if N_{pulses} is low.

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АНАЛИЗА НАЈУТИЦАЈНИЈИХ ПАРАМЕТАРА У ЛАСЕРСКОЈ ГЕНЕРАЦИЈИ УЛТРАЗВУКА МАЛЕ СНАГЕ

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Тренутни рад анализира утицај најчешће коришћених временско – доменских техника за однос сигнала и шума (SNR) повећањем ласерско генеришућим ултразвуком (US), користећи мале снаге (150 mW) модуларних диода: ове методе користе високо хаотичне псеудо (PN) секвенце које, након употребе унакрсне корелације, наглашавају присуство ултразвучног излаза. PN секвенце могу да прошире банду сигнала кроз случајне дужине ниских и високих нивоа у трајању ласерске пулсације, расипањем енергије на широком распону фреквенција: ово може представљати недостатак у случају контроле са ускопојасним сондама, које су највише коришћени инструменти за ову врсту апликација. Са ове тачке гледишта, стварање посебних сигналних погона омогућава да се значајно унапреди контрола над опсегом фреквенција. SNR у складу са остварљивим класично усвојеним методама је истакнут, али садржи повољну концентрацију у излазни фреквенцијски опсег.