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# Optimal Rayleigh waves generation by continuous wave modulated laser

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**Abstract.** Laser-ultrasound technology is typically employed in case of non-destructive, non-contact inspection of mechanical components. In particular, low power laser sources (diodes) allow to contain implementation costs; on the other hand, identification of the ultrasonic peak is complex due to the low Signal-to-Noise Ratio (SNR), requiring the use of specific signal processing techniques. Features of the ultrasounds generated by the laser excitation, both in terms of frequencies and SNR, cannot be foreseen in advance, depending from the type of material and its thermo-elastic characteristics: it is thus fundamental to dispose of criteria to set in an optimal way the signal acquisition parameters to effectively apply a correct processing procedure and retrieve the useful information. In the work, surface R (Rayleigh) waves generated by a Continuous Wave (CW) low power laser are characterized, using a particular processing technique in the time domain. To identify the most influential input parameters on SNR, a Design Of Experiments (DOE) and a specific analysis are introduced: overall, the distance between source and receiver and the number of ensemble average applied before acquisition strongly affect SNR; the pulse duration results on the other hand influential at the same time on SNR and on the generated ultrasound frequency. Finally, analogies with longitudinal (L) waves generated by the same source are highlighted, allowing also for information on how to set up the investigation based on the type of wave and acquisition instruments employed.

## 1. Introduction

Non-destructive, non-contact inspection of mechanical components through Ultrasound (US) generated by laser sources are today widely employed because of their versatility. With this technology, it is in fact possible to investigate elements integrity subjected to particular boundary conditions: typical testing configurations involve those cases in which the high temperatures forbid the direct application of probes [1], or when the inspection of the component must be carried out during its rotation [2-3]. US which propagates inside the material or along its surface is generated by a single laser pulse or multiple pulses, i.e. through the localized heating and subsequent cooling of the material (thermo-elastic effect). Heating can be obtained through two different types of sources: pulsed laser or Continuous Wave (CW) modulable lasers.

Pulsed lasers are characterized by an energy accumulation phase to which the release in a short time follows (few nanoseconds, e.g. Q-switched) allowing to excite ultrasonic frequencies with a broad band up to 100 MHz [4] and consequently detect discontinuities of particularly reduced extent (mm). Power can reach the magnitude of 10 MW, which involve in addition high ultrasonic amplitudes and



Signal-to-Noise Ratios (SNR). On the other hand, CW lasers (diodes) continuously emit light, which can be modulated to create single pulses. Power around 1 W characterizes this sources category, also referred to as low power sources: low powers are compatible with characterization of materials with low damaging threshold, like plastic/composite materials, membranes [5] or thin protection films [6]. The high power of the pulsed laser source is generally associated to a high price and to an important encumbrance of the instrument, due to the parts designated to energy accumulation: this complicates its implementation on large scale and in complex systems. Since often these drawbacks are not balanced by the above cited advantages, US generated by low power laser sources plays a key role in non-destructive inspections: their presence on the market is encouraged by standardization which is further decreasing dimensions and prices, already an order of magnitude lower than their high-power counterparts. On the other hand, the low amplitude of the generated US (some pm [7]) is associated to a critical SNR maximization, involving the necessity to apply elaborate pre-processing techniques to highlight the US in respect to environmental noise. This makes fundamental to know how the elastic waves features are influenced by parameters in input to the system: in such way it is for example possible to focus the US frequency in an interesting band, as a function of the receiver employed in the specific application.

The present work aims at optimizing the detection of surface Rayleigh US (R waves), by an analysis evidencing the features of the US as a function of several interesting parameters. For what regards modulation of the laser only, the factors which affect the US are the on/off switching quickness (characteristic of the source), pulse duration and sequence randomness. Rise time must be very small to generate the US, since the material must not have the chance to gradually heat (thermal shock). Pulse duration instead modifies the US band, because the more it increases the more the condition of ideal pulse condition is not fulfilled, with a band consequently narrower. From this point of view, detection of frequency characteristics as a function of  $\delta$  can allow for strong advantages in a wide range of application fields, making use of different signal processing techniques [8-10]. Randomness of the sequence is on the other hand fundamental to make the ultrasonic peak detection non-ambiguous through the cross-correlation technique [11], useful in case of small SNR.

To maximize SNR in case of R waves generated by a low power laser, in the present work a procedure based on cross-correlation is used, described by the authors in a previous work focused on longitudinal waves (L) [12]. R waves are typically employed to identify surface defects, for example for mechanical components subject to rotating bending [13]; the frequency being the same, with R waves defects of smaller extent can be identified thanks to a lower wavelength. R waves are also characterised by a lower scattering along the path in respect to L waves, because of a small portion of material interested by the wavefront.

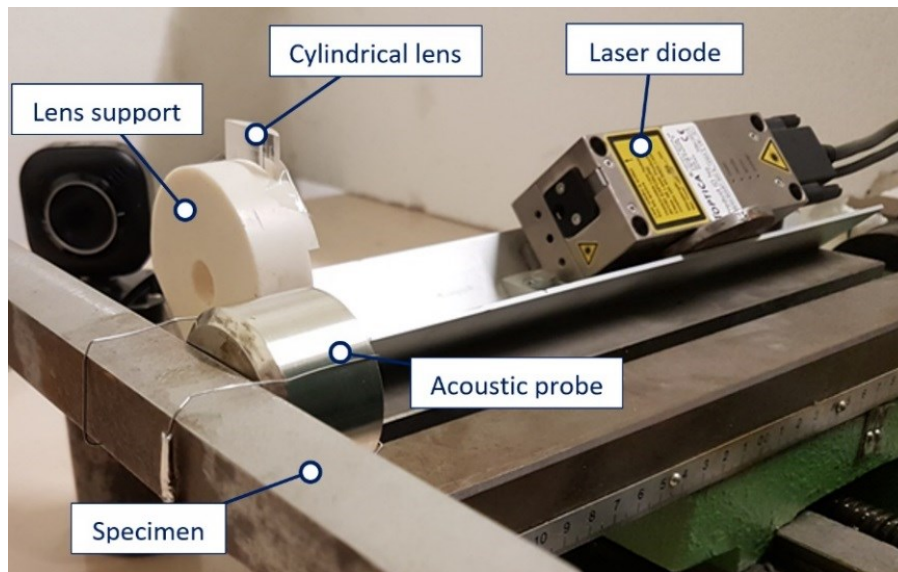
To highlight how SNR maximization is possible in case of R waves, a Design Of Experiment (DOE) has been firstly implemented, appropriate to evidence the parameters which among the others result as influent on SNR (both linked to modulation of the source and to acquisition). A subsequent deepened investigation through contact acquisition allows to quantify the influence of the parameters judged to be statistically relevant. Analogies and differences between L and R waves are finally evidenced, and how a specific testing apparatus can take advantage of their associated features.

## 2. Material

The experimental layout, visible in Figure 1, consists of:

- a modulable CW laser diode TOPTICA iBeam Smart 640 S with a power of 150 mW, wavelength equal to 639 nm and a beam diameter of 1 mm (ellipticity 0.99);
- a cylindrical lens capable of making the wavefront directional [5], with a focal length of 50 mm and reflectivity  $R_0 \cong 0.5\%$ , symmetry axis oriented vertically and sustained by a support;
- a 20 x 20 x 295 mm steel specimen with square section, fixed at one extremity;
- a broadband (from 100 kHz to 1 MHz) Brüel & Kjær acoustic probe applied to the specimen surface irradiated by the laser;

The laser source irradiates the specimen approximately in the centre of the useful area of investigation, to minimize border effects. The beam waist that could be obtained through the laser focusing was measured through a CMOS sensor, highlighting a minor axis of about 30  $\mu\text{m}$ . The major axis is equal to the one available at the laser exit, i.e. 1 mm. The power density thus achieved is equal to 0.5  $\text{kW}/\text{cm}^2$ , being noticeably under the steel ablative threshold [4]. A signal conditioner was connected to the acoustic probe, pre-filtering and pre-amplifying the signal to be acquired: low-pass filter frequency and amplification were set to 2 MHz and 60 dB respectively.



**Figure 1.** Experimental layout employed in the testing procedure.

### 3. Method

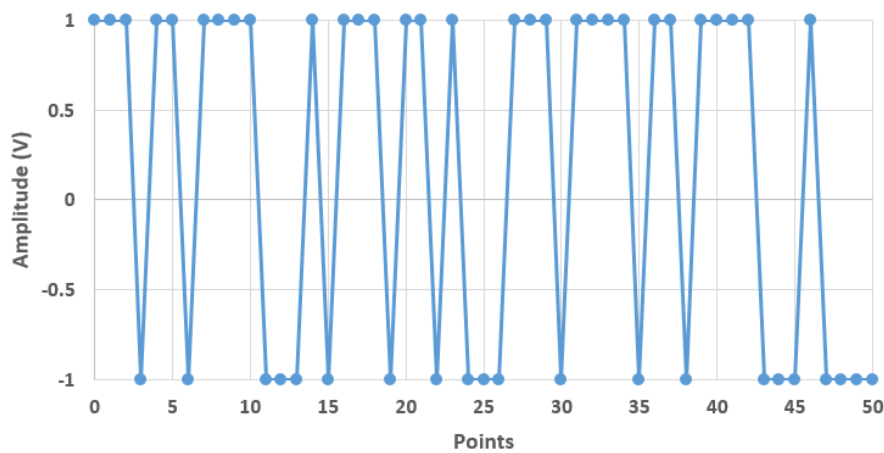
To investigate the global features of the surface US in terms of frequency and acquired signal quality, a time domain signal processing is employed based on cross-correlation technique between laser input (feeding signal) and the received signal. In this type of inspection, the generated US and the environmental noise are often coherent, i.e. characterized by similar frequency content: for this reason, cross-correlation is convenient in respect to other techniques which apply to the frequency domain, such as the wavelet transform [14]. Cross-correlation function between two signals  $x$  (input) and  $y$  (output) changing over time  $t$  can be expressed as:

$$R_{xy}(\tau) = \frac{1}{W} \int_0^{+W} [x(t) \cdot y(t + \tau)] dt, \quad (1)$$

where  $W$  is the time window of the two signals and  $\tau$  is the time shift between them.

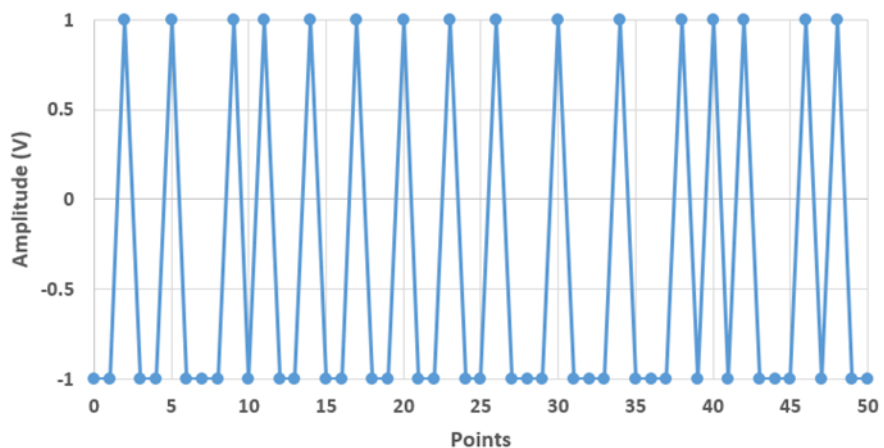
SNR is defined on cross-correlation, as the ratio between amplitude of the interesting portion of the signal and the amplitude of the noise. Definition of reference variables contained in the cross-correlation is reported in [12]. To identify the interesting portion of the signal, a time of flight proportional to the source-receiver distance is considered, compatible with  $R$  waves speed inside the steel specimen ( $v_R \cong 3000$  m/s).

Because of the low amplitude of the US in respect to noise, a laser feeding signal constituted of a single pulse is not sufficient to generate a detectable ultrasonic peak inside the cross-correlation. For this reason, feeding signals made of multiple pulses are employed. In particular, pseudo-noise sequences as the Maximum Length Sequence (MLS [11]) or the Golay code [7] are implemented, in which the modulation TTL for the laser is constituted of pulses with variable durations, separated by low-level periods variable as well. In Figure 2, the first points of a Golay code are shown, in which the associated randomness features are evident.



**Figure 2.** First 50 points of a pseudo-random sequence (Golay code).

Despite the high randomness which allows to highlight an ultrasonic peak in a non-ambiguous way, pseudo-random sequences are mainly characterized by two disadvantages in the examined application field: generated waves have different features (deriving from pulses of different duration) and the output signal band tends to broaden [15]. The latter circumstance would be per se compatible with an increase in SNR (proportional to the bandwidth [10]): the energy is however spread in a wide range of frequencies which do not necessarily match the band of the employed receiver, globally reducing the obtainable SNR. For this reason, T sequences are optimal, in which the pulses have the same duration and randomness is imposed only on low-level points (Figure 3). Each ultrasonic wave which is generated at each T sequence pulse possesses the same features, allowing for concentration of the band in a small frequency range. Features of this sequence category are evidenced in [12].



**Figure 3.** First 50 points of a T sequence [12].

## 4. Results

### 4.1. DOE

A DOE has been set first, to analyse the parameters which influence SNR. Starting from the results obtained for L waves [12], the influence of the parameters analysed in the previous work has been investigated. These parameters are:

- $\delta$  – duration of the single pulse (400÷1600 ns);

- $N_{\text{pulses}}$  – number of pulses constituting the input sequence (200÷1000);
- $d_{\text{pulses}}$  – distance between the pulses constituting the input sequence (average low-level duration 960÷3200 ns);
- $N_{\text{averages}}$  – number of ensemble averages applied to the output before the acquisition (8÷512).

Two additional parameters have been inserted in the DOE: distance  $D$  between the source and the receiver (30÷80 mm) and the input sequence randomness  $S$  (random / not random).

The DOE is constituted of a factorial design with 6 parameters, with a fourth order resolution: the 16 tests necessary to carry out the screening have been repeated in 3 replicates with random distribution, to highlight eventual change in SNR due to the time variable. Considering all parameters, as well as the possible interactions of first and second order, a value of correlation coefficient  $R^2$  (adjusted, representing the goodness-of-fit) equal to 0.67 is derived. In Table 1 the p-values of the first order terms resulting from the analysis are shown. The influence of  $N_{\text{pulses}}$  and  $d_{\text{pulses}}$  on SNR is statistically weak (p-value>0.1). This result agrees with the one in L waves analysis, where these two parameters negligibly influence the SNR. Deleting from the design all terms associated to the two non-significant parameters, a significance of all first and second order terms can be assessed, with a  $R^2$  equal to 0.57 close to the acceptability limit (0.6). Thus, it is not possible to disaggregate the contribution of the single parameters on SNR and analyse their influence separately (superimposition principle). For this reason, the investigation aims at characterizing the US simultaneously changing multiple parameters, considering thus intrinsically interactions among them.

**Table 1.** Parameters used for the DOE and corresponding p-values in a linear regression analysis.

<b>Parameters</b>	<b>p-value</b>
$\delta$	0.034
$N_{\text{pulses}}$	0.561
$d_{\text{pulses}}$	0.209
$N_{\text{averages}}$	0.000
$D$	0.004
$S$	0.009

#### 4.2. Parameters influence

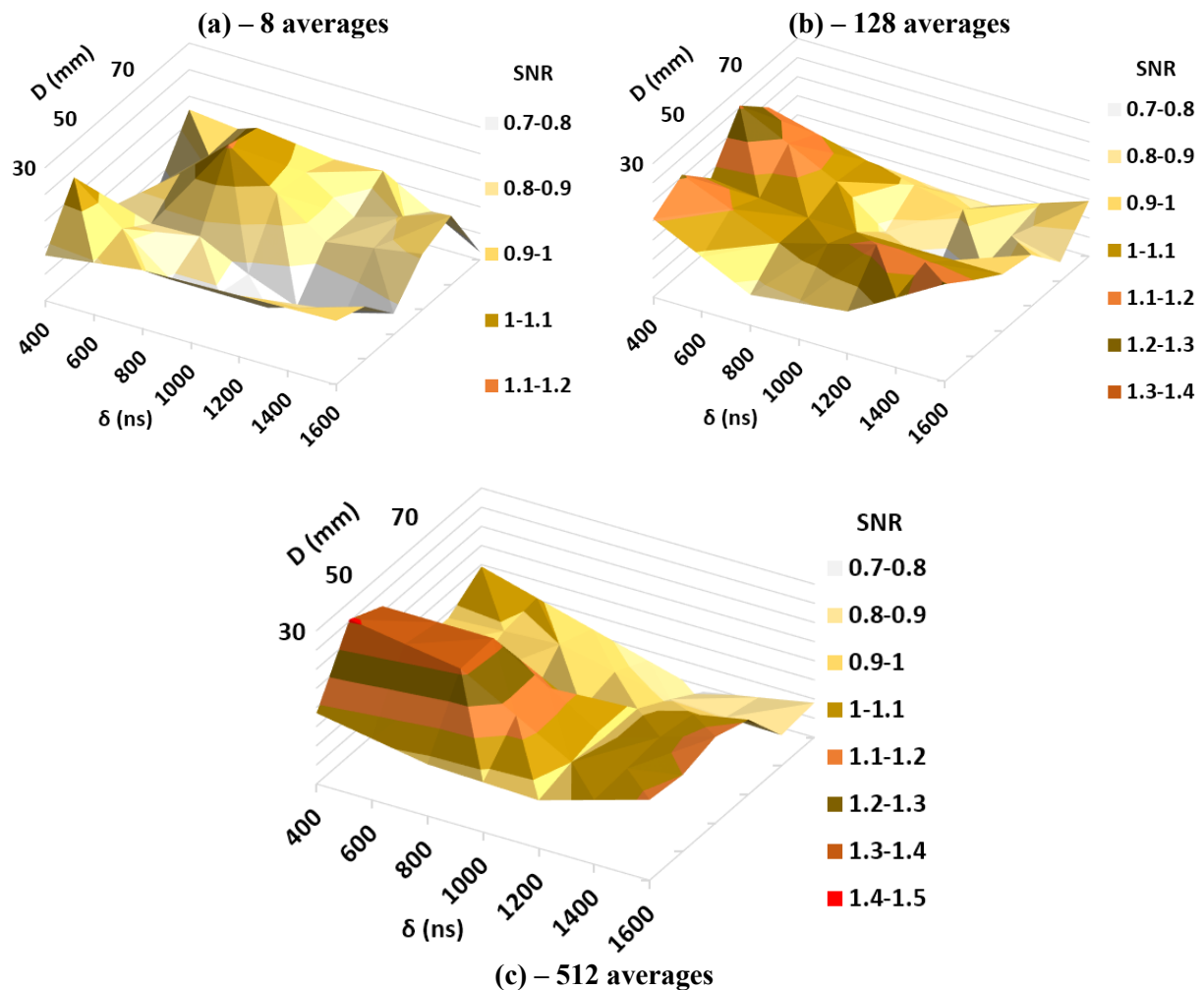
After the screening of the parameters influential on the analysis, a study made of 147 acquisitions has been set, aiming at determining how the parameters intervene on SNR and, secondarily, on ultrasonic frequencies. In particular, the interesting field for the  $\delta$  and  $D$  parameters has been divided in 7 values each, while for  $N_{\text{averages}}$  it has been divided in low-medium-high levels. The input signals involved are represented only by random signals ( $S$ =random), because a strong influence of  $S$  on SNR is coherent with the definition of SNR itself. The sequence randomness is in fact instrumental to obtain a single peak in the cross-correlation; if randomness lacks, the ultrasonic peak is repeated at each pulse repetition, making the contribution of noise not distinguishable from the US one. In case the detection of the US only is interesting rather than the SNR value (presence or absence of cracks), cross-correlation amplitude can be conveniently referred to.

Since SNR depends on the bandwidth portion comprised in the receiver band, it is a function of the excited ultrasonic frequency itself: dependent variables SNR and ultrasonic frequency  $f$  must be individually studied to highlight the global features of the US.

##### 4.2.1. Influence on SNR

In Figure 4a-c the results relative to SNR modification as a function of the parameters is reported, for different values of  $N_{\text{averages}}$ . As predictable, a high number of averages allows not only to increase the maximum SNR which can be obtained, but also amplifies noticeably the useful area (corresponding to

SNR>1). Despite the use of the maximum  $N_{\text{averages}}$  value is preferable in terms of SNR, the time necessary for the inspection increases proportionally: for the investigation, both factors must be accounted for. The US is confounded with noise for high  $D$  and  $\delta$  values: a source-receiver distance of 30-60 mm is compatible with SNR>1 for  $N_{\text{averages}} \geq 128$ . In general, even if an increase in  $\delta$  corresponds to a decrease in SNR, the SNR is globally high due to a combination of effects in the frequency domain.



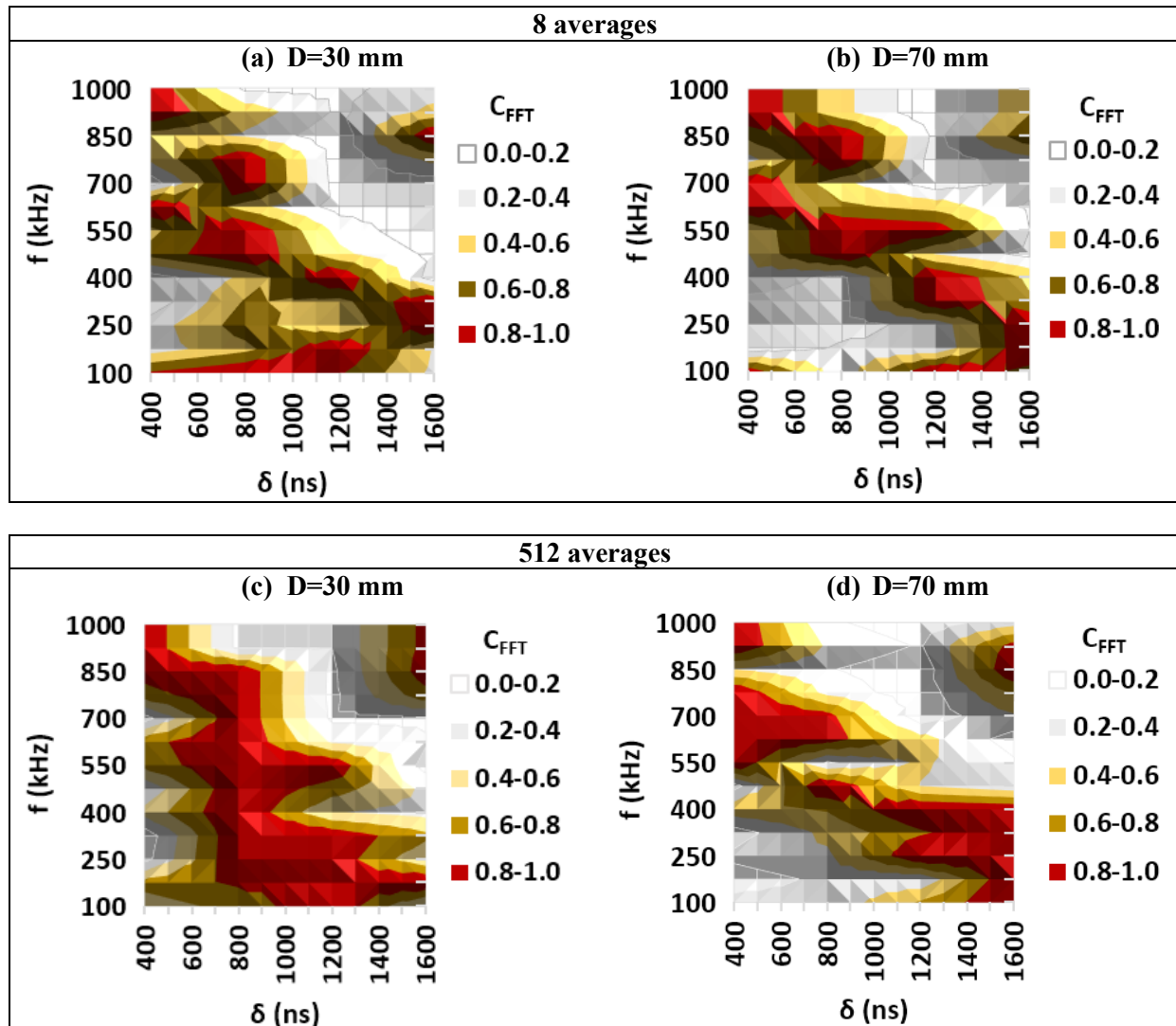
**Figure 4.** SNR as a function of parameters considered as influential through DOE ( $\delta$ ,  $N_{\text{averages}}$ ,  $D$ ).

#### 4.2.2. Influence on $f$

The analysis in the frequency domain involved the time window of cross-correlation comprising the US. In Figure 5, the frequency content as a function of the input parameters is reported for the range defined by the receiver band: the graphs for  $D$  equal to 30 mm and 70 mm are shown, for  $N_{\text{averages}}$  values of 8 and 512. The Fourier transform coefficients ( $C_{\text{FFT}}$ ) are scaled in respect to the maximum of the corresponding acquisitions,  $\delta$  being the same, because they possess different energy contribution distributed in a wide range of frequencies. SNR allows for complementary information on the ultrasonic energy contained in the signal.

For what regards the  $D$  parameter, it is possible to highlight how its increase corresponds to a general loss of definition in the frequency components  $f$  (strong dispersion of the coefficients). In correspondence of low values of  $D$ , a small value of  $N_{\text{averages}}$  is however sufficient to evidence a

definite behaviour:  $f$  of the US tends to decrease in an approximately linear way, with a rather broad band for low  $\delta$ .



**Figure 5.** Frequency content  $f$  of the ultrasonic signals acquired, as a function of  $N_{averages}$  (8, 512) and  $D$  (30 mm-70 mm).

## 5. Discussion

Based on Figures 4-5, a high value of  $N_{averages}$  is fundamental for the non-ambiguous identification of an ultrasonic peak (high SNR). On the other hand, the behaviour is however sufficiently outlined in frequency terms even for  $N_{averages}=8$ . A number of averages equal to 128 is thus the best compromise between acquisition quality and time necessary to carry out the inspection.

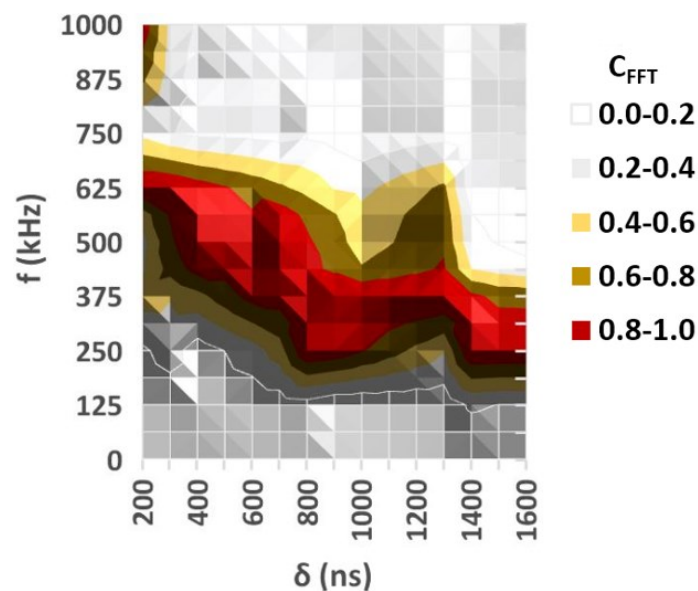
For what regards the  $D$  parameter, the investigation demonstrates how the US is totally mixed with noise ( $SNR < 1$ ) at the upper limit of the interesting field. For this reason, an increase in the used power or the employment of additional processing techniques would be desirable for investigations when  $D$  is higher than 80 mm.

In general, the SNR value derives from two distinct factors which combine into the  $\delta$  parameter. If  $\delta$  is high, the band gets narrower and the energy is focused in a small range of frequencies, while the central ultrasonic frequency tends to be no more contained inside the receiver band itself (Figure 5);



on the contrary, a small value of  $\delta$  does not generate a significant ultrasonic signal, but its band is wider. The two effects compensate until a value of 800 ns is reached; for the examined variability range and the specific acquisition system employed, it is preferable to use a short duration pulse (higher SNR). If ultrasonic frequencies outside the identified range are to be used, it is necessary to rely on different  $\delta$  values and receivers.

From the analysis in the frequency domain emerges the possibility to select a value of  $\delta$  to be employed: a wider or narrower ultrasonic band around a central frequency of interest can be obtained (approximately linear trend, Figure 5c), to tune characteristics of the wavefront and specifications of the receiver. R waves features can be directly correlated to L waves ones, as visible in Figure 6: the linear trend is in fact discernible, even though central frequencies result lower and the band is in general narrower in respect to R waves. Independently from the type of wave considered, thus, high  $\delta$  are preferable in piezoelectric probes-based inspections (narrow band); lower values can be instead adopted to make the US totally fit to acoustic probes or interferometers band (broad band).



**Figure 6.** Frequency content for L waves as a function of  $\delta$  ( $N_{\text{averages}}=512$ , modified from [12]).

## 6. Conclusions

The work aimed at characterizing R surface US generated by a low power laser, to allow for the optimized acquisition in a wide range of application fields where the low cost and the experimental layout simplicity play a key role.

By a DOE, a screening has been carried out regarding the most influential parameters to optimize the SNR. Among these, the number of pulses in the input sequence  $N_{\text{pulses}}$  and the distance between pulses  $d_{\text{pulses}}$  seems to have a weak statistical significance ( $p\text{-value}>0.1$ ). Considering terms related only to the pulse duration  $\delta$ , the distance  $D$  source-receiver and the number of ensemble averages applied to the acquired signal  $N_{\text{averages}}$ , an acceptable goodness-of-fit can be obtained ( $R^2=0.57$ ).

For the feeding signals generation, T sequences were employed [12] with same duration of the TTL low-level points. A SNR which increases as  $N_{\text{averages}}$  increases can be highlighted but extremely low at the extreme limit of the variability range for  $D$  (80 mm). A low value of  $\delta$  globally corresponds to an increase in SNR because of the generation of waves with frequencies totally contained in the receiver band, even if an increase in  $\delta$  increases the amplitude of displacements of the investigated material surface. Globally, these two effects compensate each other up to  $\delta=800$  ns. It is also worth noting that the central frequency of the US decreases linearly when  $\delta$  gets higher, with a band that tends to be narrower. This can play an important role in the choice of pulses duration for the source based on the

type of inspection (L or R) and to the instruments employed for the acquisition, be they broadband or narrowband receivers.

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