Some Aspects of Signal Processing for Nonlinear Pulse Ultrasonic Mixing Spectroscopy

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Abstract

Principles of nonlinear ultrasonic mixing impulse spectroscopy (NUMIS) show great potential advantages in comparison with other nonlinear ultrasonic methods. It is first of all from the point of view of sensitivity and possibility of quick, simple and precise localization of a defect.

This paper is focused on problems for improve a signal processing, because the sensitivity of nonlinear ultrasonic methods are limited on principle by various noise signals. The problem of sensitivity limits and connected problem of usable dynamic range is discussed in general. One of the important problems consists in optimisation of envelope shape of the exciting tone-bursts. The optimization criterion is maximum suppression of the spectrum of the excitation signal for the frequency band detection of difference frequency.

Next important task was directed to realisation of optimum digital filtration of asked signal with differential frequency and maximum rejection of excitation signals and other disturbing signals inclusive thermal noise. Finally, time dependences of measured signals for detection of a defect place is shown.

Keywords: Nonlinear ultrasonic spectroscopy, mixing principle, sensitivity, burst, dynamic range

1. Introduction

The non-linear ultrasonic spectroscopy (NUS) is developed in order to obtain more appropriate methods in comparison with conventional ultrasonic methods. Specifically, the goal is to achieve a particularly high sensitivity to small defects, less sensitivity to parasitic reflections of the ultrasonic signal and capabilities for complex shapes of test objects [1].

These nonlinear methods are considered in different directions; mainly this is for case with one [3], two or more excitation signals, excitation by continuous signal or by impulse signal. The most published method uses the modulation principle [4-7]. The Time-Reversal method is considered as a most progressive in this time [2].

Published results show that these methods did not achieve expected results, mainly in terms of higher sensitivity and accuracy of localization. These problems were analyzed in [8] and different principles were compared. This article is aimed at perfecting new methods NUMIS, based on the mixing principle, because this principle allows the use of efficient analog prefiltration and thus increase the equivalent dynamic range and sensitivity. The basic block diagram of this method is shown in Fig. 1.

The main idea consists in sending two harmonic bursts with different frequencies \( f_1 \) and \( f_2 \), see Fig. 1 and 3. These bursts are mutually time-shifted in successive steps. When two waves come across in the place of defect with nonlinear properties, the new frequency component with different frequency \( f_d \) will be created. The example with exciting frequencies \( f_1 = 1.5 \text{ MHz} \) and \( f_2 = 1 \text{ MHz} \) and the difference frequency \( f_d = 500 \text{ kHz} \) was shown in [8]. This choice of the frequency values fulfils two aims. It enables the use of sufficient analog pre-filtration, and it also allows the sufficiently precise localization because the high of difference frequency corresponds to a short wavelength. A solving of this problem was published in [9].

Further analysis discusses a problem of limits of the sensitivity as the one of main property of this new NUS method. Following there are analyzed some aspects of the signal processing.
2. Analysis of sensitivity limits for NUS

Various methods of the NUS have different sensitivities. The sensitivity of a NUS method is limited by ratio of exciting ultrasonic signals level and noise level in passband for evaluated signal. It is necessary to discuss all important sources of this noise. These noise sources have various origins and they depend on principle of NUS method. They can operate in both in the part of generation of excitation signals, and in part measured signal processing. The noise sources can be divided to these main groups:

- Higher harmonic components of the ultrasonic exciting signal (generator, exciter, contact between exciter and DUT).
- Additive and differential harmonic components of the ultrasonic exciting signals (mixing and modulating methods with two or more exciting frequencies for one common signal way).
- Equivalent thermal noise of signal processing string (preamplifier, A-D converter).
- Equivalent higher harmonic components and additive and differential harmonic components created by nonlinearity of all signal processing string (e.g. analog preprocessing, A-D converter).
- Other special noise sources (e.g. spectrum spreading of exciting pulses and bursts).

It is evident that the sensitivity is limited by both borders, thermal noise for minimum of processed signal and creating of new parasitic harmonic components for maximum of processed signal. This property is generally expressed by size of possible dynamic range for processed signal. Theoretically, the dynamic range of the signal chain is not directly dependent on the absolute signal level. But on the other hand, it should be noted that the sensitivity depends on the absolute level of the excitation signal and the level of thermal noise.

The basic comparison of various NUS methods from this point of view shows that group of methods with one exciting signal has greatest dynamic range and sensitivity limitation. In this case we evaluate level of created higher harmonic components (e.g. 3rd) for some level of exciting first harmonic component, see (2) and Fig. 2.

\[ f_i = n f_1 \quad | n = 0, 1, 2, ... \]  

(1)

On the other hand the excitation circuit (generator, exciter) product the same parasitic components without possibility of substantial rejection of this effect. By this way we can obtain dynamic range c. 30-40 dB.
Therefore the NUS methods with 2 or more exciting signals with different frequencies have basic advantage that frequency of evaluated signal is different that frequencies of excitation signals and their higher harmonics (2), see Fig. 3. A necessary condition, there are separate paths of excitation for each excitation signal.

\[ f_r = | \pm mf_1 \pm nf_2 | \quad m, n = 0, 1, 2, \ldots \]

It is evident that sensitivity of NUS method is based on frequency filtration of evaluated frequency components. This frequency filtration enables suppression of spurious frequency components in the signal evaluation, especially for systems with two or more excitation signals as it was mentioned above. On the other hand, the frequency filtration has various real limits. Therefore various NUS methods with 2 or more exciting frequency components have different abilities to use the real frequency filtering.

The frequency filtering in the signal chain can be divided to three possibilities with different properties:
- Passive ultralinear analog signal prefiltering (RLC filters)
- Analog signal filtering (RLC and ARC filters)
- Digital signal filtering

The passive ultralinear analog signal prefiltering has maximum dynamic range with minimal danger of rise of the parasitic harmonic components. The condition is that it is in front of analog electronics chain, especially in front of the amplifier. On the other hand it is not simple to obtain high filtration selectivity. The analog signal filter is used in the analog electronics chain with amplifiers. Therefore the dynamic range of this part is limited by dynamic range of used amplifiers but his filtration selectivity is higher than previous block. It also provides the anti-aliasing filtration for the AD converter. The third type, the digital filtering has the greatest possibility for filtration selectivity, but it has the lowest dynamic range, due to the limited dynamic range of used AD converter.

Various methods NUS with more excitation signals can be compared with regard to the above frequency filtering options. We can divide these methods to two main groups, see fig. 3. In case of use exciting with one signal with low frequency \( f_1 \) and second signal with high frequency \( f_2 \) the methods are based on so-called amplitude modulation (AM), Fig. 3 a. The second case uses frequencies of exciting signals with little difference, see Fig. 3 b. These methods are usually called as mixing.

As we can see, the mixing principle enables higher attenuation of excitation signals by a simpler using of the analog linear prefiltration than AM methods. Therefore the mixing methods can obtain higher sensitivity, because they apply evaluated signals with lower dynamic range to chain of analog and digital signal processing. In other words, under the condition of the same dynamic range of signal processing of both systems, the mixing principle allows to process of input sensed signals with higher dynamic range. Therefore the equivalent dynamic range of all system is higher than dynamic range of the analog and digital processing chain.
The time-reverse nonlinear methods have a little different principle. Nevertheless, the problem limitation of dynamic range is the same, because the dynamic range of all system is lower than dynamic range of the analog and digital processing chain.

The use of pulse (burst) NUS methods brings special problems for sensitivity limitation. These burst exciting signals enables to solve problem of defect localization. On the other hand the use of the exciting burst brings spreading of monochromatic spectrum to wide band. By this way, the spectrum of exciting signals can take noise effect for detected band in case of NUS methods with two or more exciting signals. The aim is a solution to minimize this effect, equivalent to reducing dynamic range of the system and thus the achievable sensitivity. It should take advantage of the two possibilities, optimizing the shape of the excitation signal and the subsequent optimization of digital filtering of the measured signal for obtaining the most accurate form of envelope detected pulse.

To solve the model digital frequency filtering and subsequent envelope detection of the burst was chosen modeling in Matlab. Because the goal is to model the process nonlinearity, the input signal was modeled as a sum of the detected pulse of 800 kHz with a unit height and both excitation pulses of 1.5 MHz and 2.3 MHz with a correspondingly greater height (up to 80 dB). But confirmed the assumption that the signal at 2.3 MHz is detected pulse due to the increased frequency distance less influence than the 1.5 MHz signal. Therefore, it was subsequently used a simpler model with no input pulse 2.3 MHz.

3. Optimisation of the exciting burst shape

As it was discussed above, the use of burst brings spreading of monochromatic spectrum to wide band. Both signals were modeled with the desired sampling rate of 50 MHz. In the first step, they were considered approximately estimated pulses with a rise time of about 15 µs. However, the first modeling showed that spreading the spectrum of the excitation pulse with a finite length and slope of the leading and trailing edges extending to the detection band (800 kHz). Therefore, spectral analysis was made of the excitation pulse of 1.5 MHz and finding suitable envelope function minimizes this effect. In doing so, it was used well-known theory of window functions used for FFT or IIR filtering.

The spectrum of pulse shape without limitation (rectangular window) was compared with the originally contemplated shape \( \sin^2 \) and available alternatives windows in Matlab. This comparison showed a window having the smallest parasitic influence of the detected band 800
kHz window called Nuttall (Fig. 4), which is one of the variants Blackman-Harris window. The result of comparison of the rectangular window, and the window pulse $\sin^2$ Nuttall is shown in Fig. 4 b. Logically greater spread spectrum near the fundamental frequency us in this case does not matter, because the band does not interfere evaluated frequency band.

4. The optimum digital signal processing for frequency filtering

We can consider different variants of digital frequency filters for filtration. It was chosen IIR filter due to the simple configurability and modifiability of the parameters (order, quality factor Q, resonant frequency, filter type). For ease of experimental modeling technology was selected cascading band-pass $2^{nd}$ order blocks with a choice of quality factor Q and the same resonant frequency $f_o$. This frequency was set to $f_2 - f_1$, therefore 800 kHz. The approximation resulting from a cascade connection of $2^{nd}$ order block with the same parameters for the specified purpose quite comfortable with the group delay is reasonable dependence and leads to minimal change in the shape of the detected pulse. More complex variants of approximation (eg. Bessel) would not bring a significant improvement and optimization process would be considerably more complicated.

During this optimization were considered excitation pulses with a final length and shape of a given window function Nuttall (Fig. 4a), as is evident from the previous chapter. The influence of the excitation signal has been tested only for less distant frequency of 1.5 MHz, because the influence of the pulse is below 2.3 MHz and nonlinear effects are modeled. For consistent optimization is needed to monitor the effect of multiple variables. An important parameter is the level of the excitation signal. In all these cases, the maximum level is applied excitation signal $U_2=10\,000\times U_1$ so $U_2/U_1=80$ dB.

For the pulse was chosen 20 signal periods, which at a frequency of 1.5 MHz, corresponding to 13.3 $\mu$s (667 samples), so the rise time is about 6.6 $\mu$s (334 samples). The individual options figure shows the envelope of the detected pulse of 800 kHz (blue), the total signal as sum of excitation and detected signal (1.5 MHz and 800 kHz) after filtration IIR (green) and the detected envelope of the filtered signal (red).

In terms of the properties of IIR filtering and the 800 kHz signal detection is necessary to evaluate influence of the order of the filter, the filter type and quality factor. To detect the envelope of the pulse and the subsequent influence of filtering it is necessary to select other
parameters. As the most important and most sensitive proved choice of values order and filter quality factor, so the parameters that determine the selectivity. Due to the mutual relation of both parameters in influencing the selectivity there were considered variations of values of quality factor and different variations of the order of the filter.

The example in Fig. 5 a) - c) shows the influence of chosen values of the quality factor $Q$. The effect of filtration of IIR filter is insufficient and the influence of the excitation pulse disproportionately increases for low $Q$. Excessive increase in the value of $Q$ leads to an excessive decline in the level of the detected pulse.

Filtration efficiency can be checked for various levels of the interfering excitation signal, using the optimal values of the selected parameters. Fig. 5 d) shows a comparison for the ratios $U_2/U_1=60$ dB, 70 dB a 80 dB. As shown, the influence of the excitation signal is negligible up to 70 dB, only when it increases to 80 dB it is starting to show.

5. Practical verification

The results of shown optimization were used in the practical measurement on a real sample with crack. We scanned the series of time responses for gradually shifted burst with frequency 1.5 MHz. Example of one measured signal (both excitation and one scan) for time delay 16 $\mu$s is shown in Fig. 6. It is apparent that the sensor signal has value almost 1 V after amplification 60 dB. Excitation bursts were scanned through a voltage divider 1:100.

After digital processing according to the above-mentioned results we obtain waveforms of the envelope signal with the difference frequency of 800 kHz as shown in Fig. 7. To test the purity of excitation signals were also measured waveforms for generating excitation signals themselves. This was tested parasite transmission of these signals to 800 kHz band by any of the above principles. They are shown under the designation 29u15a (1.5 MHz), and 98u20a (2.3 MHz) in Fig. 7 and are drawn dashed. It is evident that the transfer of parasitic excitation signals to the measuring band of 800 kHz is minimal and practically does not affect
the actual measured waveforms of differential signals. Thus it determines the basic equivalent sensitivity to the value of about 0.5 µV at the amplifier input.

Figure 6. Example of one measured signal (both excitation and one scan) for time delay 16 µs

Figure 7. Series of time responses for gradually shifted burst with frequency 1.5 MHz

It is possible to determine the time offset between both bursts for the defect site as about 27 µs from the set of curves in Fig. 7. It corresponds to the shift 13.5 µs from middle in direction to exciter 1.5 MHz. This is a starting point for locating of the defect [9].
6. Conclusion

This article discusses the problems of sensitivity for methods NUS and specifically deals with some aspects influencing the sensitivity of the new method NUMIS. It shows that this method should be among the most sensitive. Specifically, it is focusing to some of the parameters and factors limiting the sensitivity of this method. It deals with parasitic transmission of excitation signals to the evaluated bandwidth for the signal with the difference frequency. It shows that the excitation pulse bursts spread spectrum in principle and therefore it is looked for a shape of the burst excitation so that the effect was minimal.

It also deals with the optimization of the subsequent digital processing so as to make the most suppression of excitation spectra of bursts on the shape of the evaluated differential signal with frequency. This is realized in an optimum manner as frequency filtering, as well as means of obtaining the envelope function of the detected pulse. Verification of these processes to practical measurements shows that the proposed procedures are successful and allow us to achieve high sensitivity of this new method.

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