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A New Highly Sensitive Variant of Nonlinear Ultrasound Spectroscopy for Non-destructive Testing

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Abstract:

Non-destructive testing by ultrasound nonlinear modulation spectroscopy has two basic variants of realisation. The ultrasound excitation uses harmonic signals with relatively near or distant frequencies as using of mixing or modulation principle. This paper presents comparison of these two basic methods and it explores new possibilities for rising sensitivity. Especially the time necessary for exciting and sensing signals is compared. The second part discusses the possibility of using of the burst-wave exciting mode for these methods. First, the excitation by phase coupled pulse signals is derived for the obtaining of result long lime signal without waste of its useful energy. Nevertheless this output long time signal consists of time-separated pulses and therefore the analogue pre-filtration cannot be used to suppress the excitation signals. Therefore a new variant of mixing method is derived, where such exciting frequencies are used that result signal with different frequency has a relatively high frequency and a shorter period than the exciting signal. On the other hand, the frequency difference between this result component and exciting signal is sufficient for using LC linear filters with sufficient attenuation of exciting signals.

Keywords:

NDT, non-linear spectroscopy, modulation, ultrasound, cracks, pulse exciting

1. Introduction

Non-linear ultrasound spectroscopy is a new progressive non-destructive testing (NDT) technology with various methods ([1-4] etc.). Especially the modulation methods with two exciting signals appear as very perspective methods for NDT. The main advantage consists in creation of the new frequency component with different

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frequency than exciting signals. Therefore it is not sensitive to reflected and spread exciting signals and a theoretical sensitivity is very high.

Nevertheless the practical sensitivity in cases of published results ([5-7] etc.) is considerably lower than theoretical possibilities. This fact has more reasons. One of the main causes consists in the limited dynamic range of currently used systems for signal processing and high dynamic range of measured signal. The usable dynamic range can be risen (ultra-low noise amplifiers, 16-bit AD converters etc.), but a more effective way consists in the suppression of exciting components in a measured signal by linear analogue pre-filtration.

This problem is more complicated in the case of pulse (burst-wave) excitation. It is necessary to say that pulse mode has an advantage in the minimisation of the problem with standing waves and it enables a localization of cracks. On the other hand, the pulse mode offers lower energy of detected signal and the time of pulse can be shorter than the period of result signal. It is a problem to use frequency filters for the suppression of exciting signals in this case.

2. Comparison of Methods of the Nonlinear Ultrasound Modulation Spectroscopy

The nonlinear ultrasound modulation spectroscopy uses an excitation by two harmonic signals with frequencies f_1 and f_2. In a nonlinear environment this excitation creates a new signal with result frequency components f_r by this equation:

$$f_r = \left| \pm m f_1 \pm n f_2 \right|, \qquad m, n = 0, 1, 2, \ldots, \infty \tag{1}$$

This general equation can be used for two typical examples:

1) Relatively distant values of frequencies f_1 and f_2 (as amplitude modulation)
2) Relatively closed values of frequencies f_1 and f_2 (as mixing)

The first variant with relatively distant values of excited frequencies (for example low value of f_1 and high f_2) produces a signal with the most interesting difference components that corresponds to side bands of classical amplitude modulation

$$f_r = f_2 \pm f_1 \tag{2}$$

as it is shown in Fig. 1 in time and frequency domains.

The second variant uses the excitation ultrasound signal with relatively closed values of frequencies f_1 and f_2. In this case we consider a new frequency component created according to the following relation

$$f_r = f_2 - f_1 \,. \tag{3}$$

This case is usually named mixing and it is shown in Fig. 2. Except of difference component, the additive component is created similarly as for AM, but we don’t use it for preferable properties of difference component.

We can compare both cases from two important points of view: the possibility of the suppression of excitation signals by filters and the time necessary for the evaluation of result signal. It is necessary to have in mind that differential and additive components carry some meaningful information and they are much lower than carrier excited component f_2. The lowering of dynamic range by suppression of exciting component f_2 is very difficult especially if we have to use linear LC filters [8, 9]. Both discussed principles (Figs 1 and 2) can be compared. We can see that the first case with AM needs non-realisable filter whereas the suppression is easily feasible in case of mixing principle. Nevertheless this principle is usually applied [4, 7].

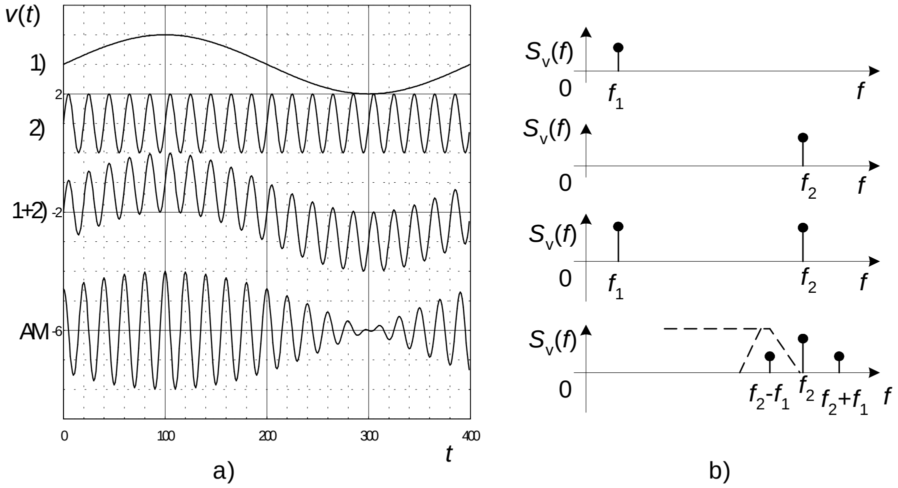

Fig. 1. A creation of amplitude modulation in case of excitation of nonlinear system for relatively distant values of frequencies f_1 and f_2 (AM): a) time domain, b) frequency domain with marked possibility of filtration

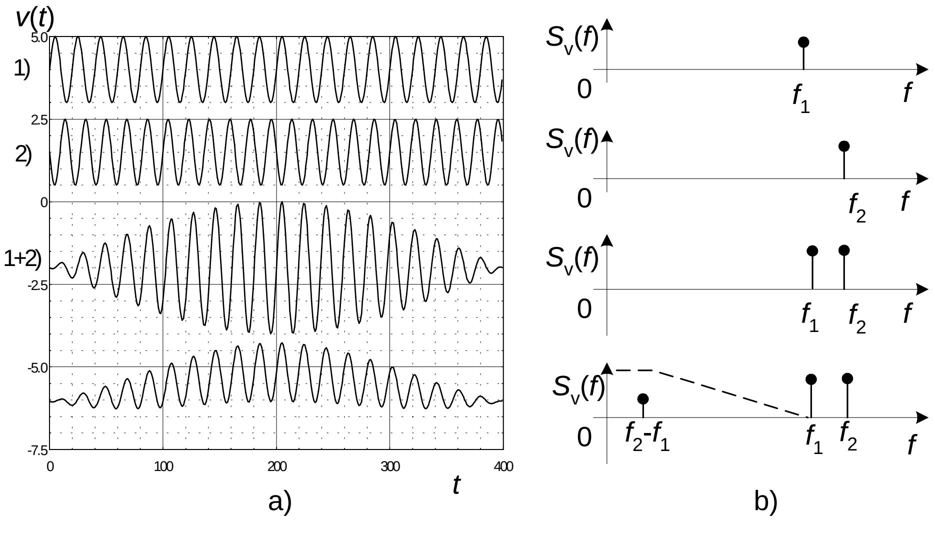

Fig. 2. A creation of differential component in case of excitation of nonlinear system for relatively closed values of frequencies f_1 and f_2 (mixing): a) time domain, b) frequency domain with marked possibility of filtration

A comparison of the necessary time for evaluation of result signal seems to be different at the first sight because detected components $f_2 - f_1$ and $f_2 + f_1$ of AM case have a higher frequency and shorter period in comparison with mixing principle. The more detailed discussion shows dissimilar result. A period of this signal takes the same time as differential component $f_2 - f_1$ in mixing case (Fig. 2a) as the time dependency of AM signal shows (Fig. 1a). We can say that both principles are equivalent from this point of view.

3. Pulse Excitation without Waste of its Useful Energy

This task has antagonistic aims, the dividing of excitation signals to the short burst-wave form and detection of full-period response continual signal with low difference frequency. Therefore the solution is more complicated and it is necessary to use digital signal processing (DSP). The basic principle consists in distribution of exciting signals from Fig. 2a to discrete parts (as burst-waves), which are separated by zero laps with sufficient length for solution of problems with reflections and interferences of signals. It is shown in Fig. 3. The zero laps are simplified in this figure. It is necessary to say that this time is not important for the signal processing.

On the other hand, it is necessary to remark that the changing phases of exciting signal have to be complied in separate pulses for regular sum exciting signal as it is shown in Fig. 3. If we adhere to this phase synchronisation, we obtain the result signal with the envelope form as a beat note similarly as it is in the continual wave mode (Fig. 2a) by the superposition of both pulse exciting signal pulses. The nonlinear environment changes this summed pulse signal according (1) and the result pulse signal will contain the asked differential frequency component. Further it is necessary to select the separate result pulses and to leave out zero laps for result solution. This task is quite simple because we know the time of pulses and the zero laps.

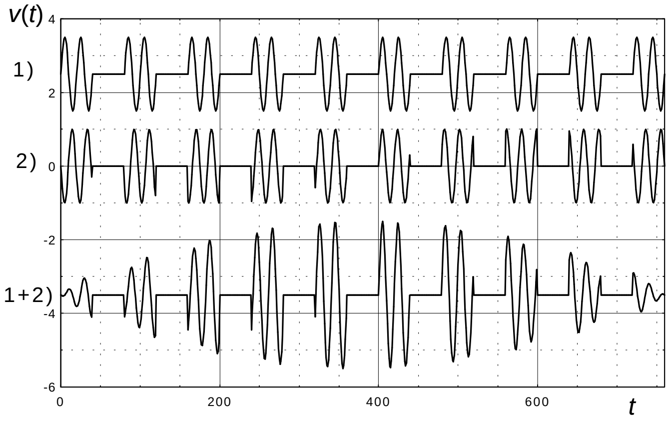

Fig. 3. Division of exciting signals to phase synchronized short pulses and summed excited signal with effect of envelope beat note.

It is evident, that we obtain partly different signals in practical use. Firstly, the selective properties of a transfer path spread the edge of impulses. It is not so much important for detecting in the case of a limited time of spreading because the sum energy of low frequency useful signal is the same. On the other hand, this effect lowers the accuracy of localization.

Secondly, the real measured signal will be delayed for limited velocity of propagation of ultrasound signals in tested sample. Therefore it is necessary to use the variable delay between both generators with phase synchronisation. It is evident that we obtain the right result signal with a correct phase shift in the place of crack and therefore we have to compensate the difference between transfer shifts of both signals by additional delay shift.

Because we do not know the difference time t_1 between transfer shifts (Fig. 4), we have to add to basic phase shift gradually short time shifts for obtaining the required differential component $f_2 - f_1$. It is simple time scanning and it offers a value of unknown time difference t_1. For a quick process of scanning we can use a two-step scanning when we firstly use a raw scanning with a greater shift and after obtaining the estimative value t_1 we can use a fine scanning for the localization with higher accuracy.

Further time shifts as a propagation time to the place of defect (t_2) and subsequently a propagation time from the place of defect to the sensor (t_3) can be detected in addition as a shift of demodulated signal and it is the second information for localization. A method of computing for localization depends on the form of tested object and on the placement of sensor and transducers.

A general block diagram of testing system is shown in Fig. 4. The way for the generation of signal is very important. It is necessary to use a defined phase and delay shift for both harmonic signals in the frame of separate impulses with high accuracy. Further it is necessary to elaborate the defined time intervals between pulses for scanning. It cannot be realised by two controlled standard generators, but it is necessary to use a system with finely digitally controlled generators and with the control unit that is synchronised with the system of DSP.

The optimum analogue pre-processor and A-D converter with high resolution have to be also used. The system of DSP realizes a detection of the useful signal and computing for localization.

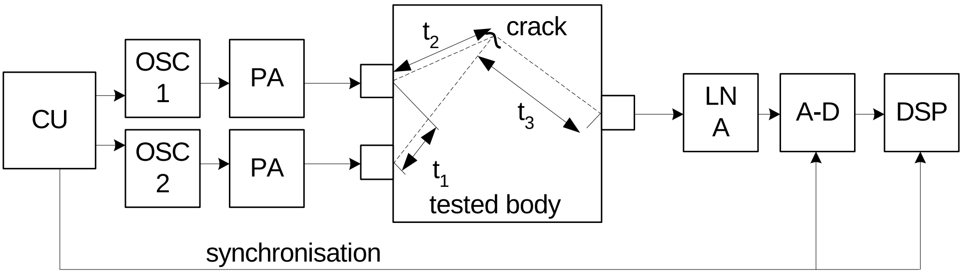

Fig. 4. Block diagram of the system for pulse testing for modulation spectroscopy. (CU - control unit, OSC - oscillator, PA - power amplifier, LN A – low noise amplifier, A-D – AD converter, DSP – digital signal processing)

4. Pulse Testing System with Higher Dynamic Range

As mentioned above, the system with pulse excitation cannot use the filter suppression of exciting components because a time constant of the frequency filter is longer than the duration of the pulse. It is a great disadvantage and therefore we try to solve this problem. The special compromise can be used as a solution of this problem. It is necessary to use such values of exciting frequencies f_1 and f_2 that the differential frequency component will have sufficiently higher frequency $f_2 - f_1$ for the result pulse response with some whole periods of this signal. On the other hand, this differential frequency of result signal has to be lower than exciting frequency. Therefore the realisable LC low-pass or band-pass filter can be used for sufficient attenuation of exciting components without non-permissible spreading of result pulse. As our experience shows, the ratio $f_1/(f_2 - f_1)$ has to be equal to or greater than 2.

These relations are shown as an example in Fig 5. We can chose the $f_1 = 1$ MHz and $f_2 = 1.5$ MHz. Then the different frequency is 500 kHz. In this case the pulse with duration 6 μs is used and the result pulse will have three periods of differential signal and it can be filtered for the suppression of exciting components.

It is necessary to mention that the design and realisation of such filter is rather complicated because it is necessary to require optimum compromise between sufficient steepness (attenuation in stop-band) and short time response for minimisation of spreading of pulse. On the other hand, the loading and matching to impedance of a sensor have to be considered. Therefore it is necessary to use a suitable program for this filter design. Also the use of the filter elements with high linearity is very important.

The result modification of pulse testing system from Fig. 4 is shown in Fig. 6. There we can see that not only addition of passive low-pas (or band-pass) filters, but also the second channel without filtration has to be used to obtain direct excitation pulses for determination of the time $t_2 + t_3$. The transfer delay of the filter has to be considered in comparison with direct signal way without filters.

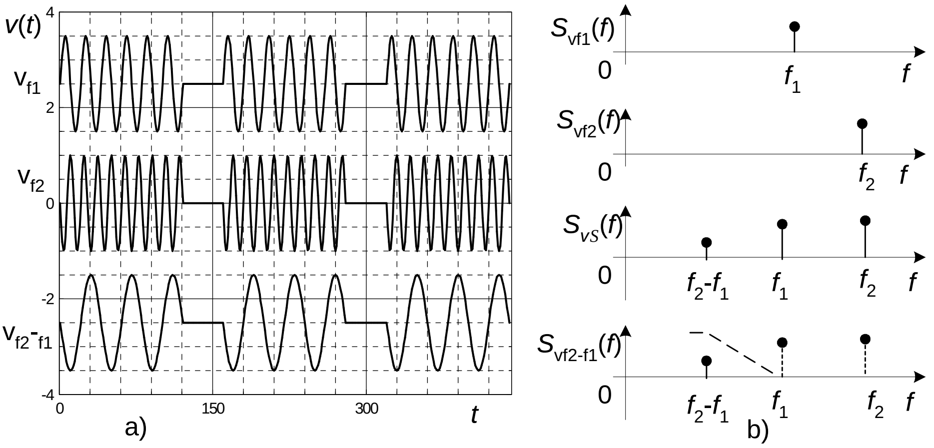

Fig. 5. Pulse excitation signals with a possibility of the use of the linear passive filters for attenuation of exciting components: a) time domain with result pulse signal, b) frequency domain with marked possibility of filtration

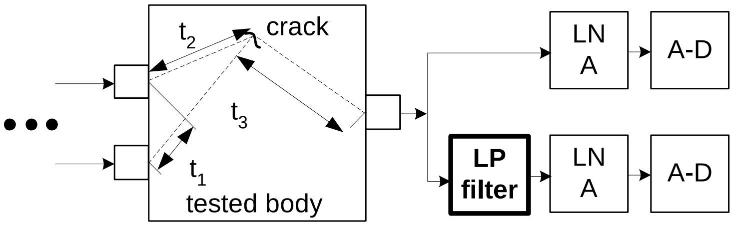

Fig. 6. A modification of the block diagram from Fig. 4 for the suppression of the exciting components by linear frequency pre-filtration (low-pass filter).

5. Conclusions

This paper discusses problems, comparison and possibility of improving of two basic methods of nonlinear ultrasound modulation spectroscopy that can be defined as amplitude modulation method and mixing method. The comparison of these two methods for continual wave excitation shows the following basic findings:

- They need the same time of detection of useful result signal.
- The mixing method enables a simpler filtration of result signal by higher attenuation of the exciting frequency components. Therefore this method enables to obtain a lower dynamic range of measured signal and a higher result sensitivity.

Further this paper shows a way to use pulse excitation for the case with longer response of result signal. This solution is applicable for the localization of defects. It needs to use a special excitation system with two digitally controlled pulse generators with phase synchronisation and added time shifting for the time scanning. On the other hand, the distribution of response pulses between zero response laps does not enable using the analogue pre-filtration to raise the sensitivity. The block diagram of this testing system is also described.

Therefore the new variant of the pulse excitation was designed, where the optimum compromise of a differential frequency for the exciting frequency components is used. This relatively high value of differential frequency enables to obtain a short response pulse with more cycles of result signal. On the other hand, it also enables to use the attenuation of exciting components by low-pas or band-pass filter because the ratio $f_1/(f_2 - f_1)$ is sufficient for the feasibility of this filter. The use of this filtration increases considerably the practical dynamic range of signal processing and also the result sensitivity. The necessary change of the pulse testing system is also described.

In further work we will direct our effort to the realization of phase synchronised two-pulse generators and consequently all system.

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